# SEEING THE BIGGER PICTURE

## VISUAL IMAGINATION AND THE SOCIAL BRAIN

Janneke van Leeuwen

This thesis is dedicated to my mother

Pita van Leeuwen

Who taught me the true spirit of imagination.

**SEEING THE BIGGER PICTURE**
**VISUAL IMAGINATION AND THE SOCIAL BRAIN**

PHD THESIS

Janneke van Leeuwen
Dementia Research Centre
Department of Neurodegenerative Disease
UCL Queen Square Institute of Neurology
University College London

In collaboration with:
Wellcome Collection, London
Gerrit Rietveld Academie, Amsterdam

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## IMPACT STATEMENT

With this study, I hope to make valuable contributions to the academic study of neuroscience and visual art and beyond.

My visualisations of the Social Brain Atlas will hopefully be of value to researchers and clinicians in the field of neuroscience, but will also enable a wider public to gain an understanding of the brain dynamics that are involved in visual imagination and other complex social behaviours in healthy ageing and in different forms of dementia.

The outcomes of this study will be submitted to peer-reviewed scientific journals and I will seek out diverse public platforms to disseminate the neuroscientific and artistic research to broad audiences to whom the findings will be of relevance. The artistic research of this study, in the form of drawings, optical instruments and visual art objects and installations was presented alongside this thesis. The aim of the artistic research was to complement the rational and reductionistic nature of neuroscientific research by an embodied approach that addressed the research questions and hypotheses in different dimensions than verbal language. By exploring the multi-layered interactions between the researcher and the subject, the research becomes contextualised in the social world, which is where I hope it will have its greatest impact.

With the art programmes that I will develop from this study I will strive to make a positive impact on people's lives by offering visual art interactions that build on the principles of the social brain dynamics to strengthen a sense of agency, social engagement, observation and communication skills.

## ABSTRACT

I studied multi-modal aspects of visual imagination in relation to visual art and complex images, defining 'visual imagination' broadly as a dynamic of complex psychological processes that integrate visual information with prior experiences and knowledge to construct internal models of oneself, others and the outside world. This reflects the ultimate aim of my work to develop engaging cultural and clinical resources that strengthen social brain networks, tailored to personal interests, age and cognitive health. I pursued two interrelated research programmes based primarily at the Wellcome Collection, as part of my interdisciplinary residency with Created Out of Mind.

I used complementary neuroscientific and visual research methods to probe relationships between visual imagination and the social brain in neurologically healthy adults and people living with various forms of dementia. The Social Brain Atlas and connectome (Alcalá López et al., Cerebral Cortex 2017) was recently computed from 3972 functional neuroimaging studies in 22712 healthy adults: to contextualise my research in the social brain, I first translated the social brain connectome to functional infographics (relational spatial representations) of the four hierarchical processing levels of the Social Brain Atlas, and generated visual imagination brain profiles in healthy adults and profiles of canonical dementia syndromes. I used these to generate hypotheses and guide analysis of my neuroscientific experiments.

I recruited three participant cohorts: 17 neurologically healthy adults aged 20-30 years; 20 neurologically healthy adults aged 50+ years; and 11 senior adults living with various forms of dementia. These research participants took part in five neuroscientific experiments that I had designed, in which I used advanced technologies to capture physiological responses and established as well as novel visual research methods to study neuropsychological responses to visual art, complex imagery and colour experiences.

I employed an arts-based facilitated conversation methodology, Visual Thinking Strategies (VTS); and I developed novel quantitative methods to analyse recorded eye tracking data, electrodermal activity and speech samples. I used both parametric and non-parametric statistical methods to compare participant cohorts.

In parallel with the neuroscientific research, I developed a series of art experiments at UCL Institute of Making, and my studio at the Limehouse Art Foundation, East London. My artistic research complemented my neuroscientific work by emphasising individual experience over generic perceptual mechanisms: by creating space for personal interactions with art, the research becomes contextualised in the social world.

The artistic research resulted in a public exhibition of optical instruments, visual artworks and installations that expanded on the two neuroscientific research projects, complementing the written thesis with the embodied language of visual art. Visitors could freely explore the perceptual effects of the optical instruments and were invited to reflect on the visual artworks with the Visual Thinking Strategies method.

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# 1. GENERAL INTRODUCTION

The human brain is an extraordinary complex universe of intricate connections. In many ways these expansive worlds inside our heads are still shrouded in mystery despite the exponential development of neuroscience over the past decades. What has changed however, is that our brains are no longer seen as purely executive organs that operate in isolation from the outside world. An increasing awareness of the profound influence of social interactions on neurological development and well-being is driving a shift towards more ecologically valid brain research.

In line with these developments, a growing number of neuroimaging studies have shown that people's personal values and their internally constructed world models are reflected in the way they respond to art. Personally strongly moving art can co-activate two major network dynamics, the so-called Default Mode and the Task-Positive (executive-control) Network, which are otherwise often anti-correlated (Cela-Conde et al., 2004; Cela-Conde et al., 2013.; Fox et al., 2005; Ishizu and Zeki, 2011; Ishizu and Zeki, 2013; Vartanian and Skov, 2014; Vessel et al., 2012; Vessel et al., 2013).
This coupling is thought to occur when integrating different memory modalities is required for optimal mental functioning. This has been found to play an important role in self-relevant and social, as well as creative thought processes (Alcalá-López et al., 2017; Amodio and Frith, 2006; Beaty et al., 2014; Beaty et al., 2018; Chatterjee & Vartanian, 2014; Ellamil et al., 2012; Margulies et al., 2016; Sestieri et al., 2011; Spreng and Grady, 2010).

Dementia has a profoundly disrupting effect on these social brain networks: the neural dynamics that regulate how we give meaning to our experiences and interact with the world around us (Buckner et al., 2008; Galvin et al., 2011; Greicius et al., 2004; Hafkemeijer et al., 2012; Sheline and Raichle, 2013; Seeley et al., 2009). This is likely to influence one's sense of self, but also interpersonal relationships. Furthermore, there are also indications that the strength of functional connectivity patterns in pre-symptomatic dementia is correlated with the extend of grey matter atrophy that will develop over time (Mandelli et al., 2016). Additionally, longitudinal studies have found that having an active social life is associated with a lower risk of developing dementia (Fabrigoule et al., 1995; Sommerlad et al., 2019).

Nurturing the social brain networks is therefore of key importance for psychological well-being and cognitive functioning in healthy ageing and could mitigate the effects of dementia. The social brain networks cover a very broad range of cognitive functions that are involved in interacting with the social world. In addition to visual perception and imagination, it includes verbal language comprehension and production, personal memories and conceptual knowledge, as well as understanding oneself and others in a social context.
Since visual imagination and complex social behaviour make use of the same brain networks, studying various aspects of visual imagination can advance our understanding of the social brain dynamics and the impact of different dementias. While insights into the complex neural dynamics of visual perception and imagination are growing rapidly, there are still many aspects that are not well understood yet.
In a recent review, Pearson (2019) discussed a range of neuropsychological disorders in which interactions between the visual cortex and higher cortical areas are disrupted, leading to various changes in people's experiences of reality and internal imagery.

In my research I set out to study multi-modal aspects of visual imagination in relation to specifically visual art and complex images. My approach to visual imagination in this study has been much broader than the common definition of imagination as the 'faculty of the mind which forms and manipulates images'. I defined visual imagination in the context of this study as a dynamic of complex psychological processes that integrate sensory information with previous experiences and knowledge to construct the internal models of oneself, others and the outside world.

This conceptualisation of visual imagination closely aligns with the ideas of the German perceptual psychologist, art and film theorist Rudolf Arnheim, who stated in his book 'Art and Visual Perception: A Psychology of the Creative Eye'(1954):

'All perceiving is also thinking, all reasoning is also intuition, all observation is also invention.'

My motivation for approaching visual imagination from this integrative perspective, was that the ultimate aim of my research is to develop engaging cultural and clinical resources that are designed to strengthen the social brain networks, tailored to personal interests, age and neurological health.

For this purpose, I designed two neuroscientific research projects which took place at the Wellcome Collection in London as part of my interdisciplinary research residency with the Created Out of Mind collective, recipient of the Hub Award 2016-2018.
I used both neuroscientific and visual research methods to investigate the close relationship between visual imagination and the social brain in neurologically healthy adults and people who are living with various forms of dementia.

In parallel with the neuroscientific research, I developed a series of art experiments at the UCL Institute of Making and my art studio in Limehouse, East London. The art experiments explored the research questions through creative material and embodied processes, allowing diverse audiences to freely explore and provide feedback of their experiences. This feedback informed the art experiments that I made for an interactive exhibition that complemented this thesis. Visual documentation of the artistic research and the resulting exhibition has been added to the Appendices chapter.

In the first chapter I have set out the theoretical framework of my research. The first section covers the Social Brain Atlas; a visual representation that I have created of the social brain connectome that was computed by Alcalá-López et al. (2017).

In the following sections I have reviewed neuroscientific literature on visual imagination and dementia syndromes and mapped these out on the Social Brain Atlas. In the last section of this chapter I have described the research questions and hypotheses.

In the second chapter I have described the experimental framework. The first section details the general methods I used in the neuroscientific experiments and statistical analysis methods that applied to both the Thinking Eyes and Colour Spaces projects. In the second section I have described the demographics and neuropsychometric contextual information of the research participants in the neuroscientific experiments. The neurologically healthy young and senior adults have been analysed on a cohort level and the senior adults living with a dementia on both a cohort and an individual level.

The third chapter covers the two neuroscientific experimental research projects: Thinking Eyes and Colour Spaces.
In the Thinking Eyes project I investigated how people engage with visual artworks and complex images, with a particular focus on the Visual Thinking Strategies method (Housen and Yenawine, 1998). The selection of visual artworks and complex images came from the Wellcome Collection in London, where the experiments took place. In the Colour Spaces project, I looked at the interaction between physical properties and psychological experiences of colours in different spatial and material contexts. For this project I created the visual stimuli myself, using model construction and wide-angle photographic techniques.
In the Summary and Conclusions section I have brought the findings of the two neuroscientific research projects together and also reflected the limitations of this study and future directions.

The Appendices chapter contains a questionnaire and analysis protocol and also the visual documentation of my artistic research, which culminated in a body of visual artworks that complements this thesis. The final two appendices present overviews of the literature references and the division of labour.

# 2. THEORETICAL FRAMEWORK

## 2.1 SOCIAL BRAIN ATLAS CONSTRUCTION

In order to contextualise my research in the social brain, I created a visual representation of the functional dynamics of the social brain atlas that was published by Alcalá López et al. in the neuroscientific journal Cerebral Cortex in 2017.
In their publication, Alcalá López et al. described in detail the neuroanatomy and functional connectivity of the social brain connectome, based on which I was able to translate it to a relational spatial representation.

The social brain connectome was computed from the largest computational meta-analysis on social cognition to date, comprising of 26 meta-analytical studies of in total 3972 functional neuroimaging studies and involving all together 22712 healthy adults. The meta-analysis included both task-dependent (meta-analytic connectivity modelling) and task-free studies (resting-state functional connectivity), using either PET (positron emission tomography) or fMRI (functional magnetic resonance imaging).
The inclusion criteria for eligible studies were defined by the authors as follows: (1) full brain coverage, (2) the absence of pharmacological manipulations, and (3) the absence of brain lesions or known mental disorders. Additionally, meta-analytic studies were only considered if they reported (4) convergence locations of whole-brain group analyses as coordinates according to the standard reference space Talairach/Tournoux or MNI (Montreal Neurological Institute). Exclusion criteria were experiments assessing neural effects in a priori defined regions of interest. Alcalá López and colleagues identified 36 consensus social brain areas through extensive qualitative analyses of the social neuroscience literature.

For the sake of visual clarity, in my Social Brain Atlas the social brain hubs have been mapped out in 2-dimensional planes. Using the MNI coordinates provided by the authors, I placed the 36 social brain areas in a fine grid in which one square unit represented a 1 x 1 MNI coordinate point.

I created the design of the Social Brain Atlas in Adobe Illustrator CC, whereby I took inspiration from astronomy maps to draw a parallel between the complexity of the human brain and the cosmos. I renamed the four hierarchical networks of the social brain connectome with the aim to communicate their core function to a wider audience beyond the neuroscience community.

The first network level was described by the authors of the social brain connectome as the Lower Sensory Network, which I renamed into the Perception Network as it involves brain areas that are primarily responsible for the translation of sensory input to visual percepts in the brain.
The second processing level, described as the Limbic Network was renamed into the Animation Network, as core nodes in this network regulates the dynamics of our emotional states, as well as the navigation through spatial and conceptual internal representations of the world we live in.
The third processing level, called the Intermediate Network by the authors of the social brain connectome, was renamed into the Interaction Network because this network is crucial in weighing up internal states against external observations to plan and execute our interactions with the outside world.
Finally, the fourth and highest processing level was referenced by the social brain connectome authors as the Higher Associative Network. This network aligns anatomically with the so-called Default Mode Network, which in my opinion is a misnomer as it incorrectly suggests a predefined and static state. In the spirit of Jerome Bruner I renamed this network into the Construction Network, because the core function of this network is to integrate multiple memory systems to construct internal models of the self, others and the worlds we inhabit.

The social brain connectome by Alcalá López et al. (2017) describes both task-dependent and resting state functional connectivity patterns between the 36 social brain hubs across the 4 hierarchical processing levels. In my Social Brain Atlas these functional connections have been drawn with lines, whereby a

solid line indicates a functional connection independent of the brain state; a wide dotted line indicates a task-dependent functional connection and a narrow dotted line indicates a functional connection during a brain state when no task has been given, described as the resting state. For each social brain area, the authors also generated functional profiles, both by means of forward and reverse inference. In reverse inference, likely psycho-logical functions are derived from observed brain area activity during a neuroimaging experiment, whereas forward inference predicts neural network dynamics based on theories about the nature of psychological processes. Alcalá López et al. (2017) based their classification system of the functional profiles on the Behavioural Domain (mental operations) and Paradigm Class (functional tasks) categories from the BrainMap taxonomy. In my Social Brain Atlas I only represented the functional profiles that were derived by reversed inference, because it gave the broadest range of cognitive functions. Alcala-Lopez et al. arrived at the functional annotations in the social brain connectome by using very similar methods as described by Yarkoni et al. (2011). The reverse inference calculations looked at the probability of a term occurring in an article given the presence of activation in a particular brain region, defined as (P(Term|Activation). I only included mental operations or functional tasks with a computed likelihood ratio of 4 or higher, which I placed in word clouds adjacent to each social brain hub. The larger the word size, the higher the likelihood of a particular psychological process being recruited given an observed brain activity increase (Alcalá López et al., 2017). There were too many functional profiles to be able to include them all in word clouds around the Social Brain Atlas drawings. For this reason, I made a selection based on the mental operations and functional tasks that I wanted to investigate in my experimental research projects. In each network map, the anatomical labels and functional profiles of the core nodes are shown, as well as the anatomical labels of the social brain areas they connect to. A magnifying glass is provided with this thesis to make the small word clouds more readable, as also used in the compact edition of the Oxford English dictionary (1971).

An online version of the Social Brain Atlas has been published at: http://www.thinkingeye.org/social-brain-atlas.

With respect to the Brainmap.org taxonomy system that was applied to the social brain connectome (Alcalá López et al., 2017), I discarded the categorical distinction between social and non-social behaviours that was made by the authors. Alcalá López et al. made that distinction to demonstrate that no social brain hub was solely involved in social cognition. I would even argue that what distinguishes social cognition from non-social cognition is mostly determined by the degree of personal/social engagement, which will effect the network dynamics involved.
A limitation of the used taxonomy system was that it only defined 3 memory domains: working memory, explicit and implicit memory. It didn't distinguish between semantic and episodic memory, which are both considered to be part of the explicit memory system. Especially in the context of dementia syndromes a greater nuance within the memory domains would be beneficial. For instance, in typical Alzheimer's Disease increasing difficulties with recent episodic memory is a characteristic early symptom, whereas in Semantic Primary Progressive Aphasia the semantic memory system is markedly affected early on.
To address this matter, I have added where relevant memory domain nuances to the functional profiles of the social brain maps that I created for various forms of dementia. Further limitations of the Social Brain Atlas that have been pointed out by the authors of the social brain connectome include a likely under-representation of orbitofrontal hubs due to an increase in signal drop-out near these brain regions.
Furthermore, local level functional nuances are not represented in this atlas, which focuses on large scale social network dynamics. The authors also warned that semantic language could be over-represented in their social brain connectome, due to the strong reliance on semantic processing in the vast majority of task-dependent functional neuroimaging studies to date (Alcalá López et al., 2017). Figures 1 – 15 show the four hierarchical functional network profiles of the Social Brain Atlas in top (axial) and hemispheric side (sagittal) views.

Figure 1

# SOCIAL BRAIN ATLAS

## OVERVIEW NETWORKS

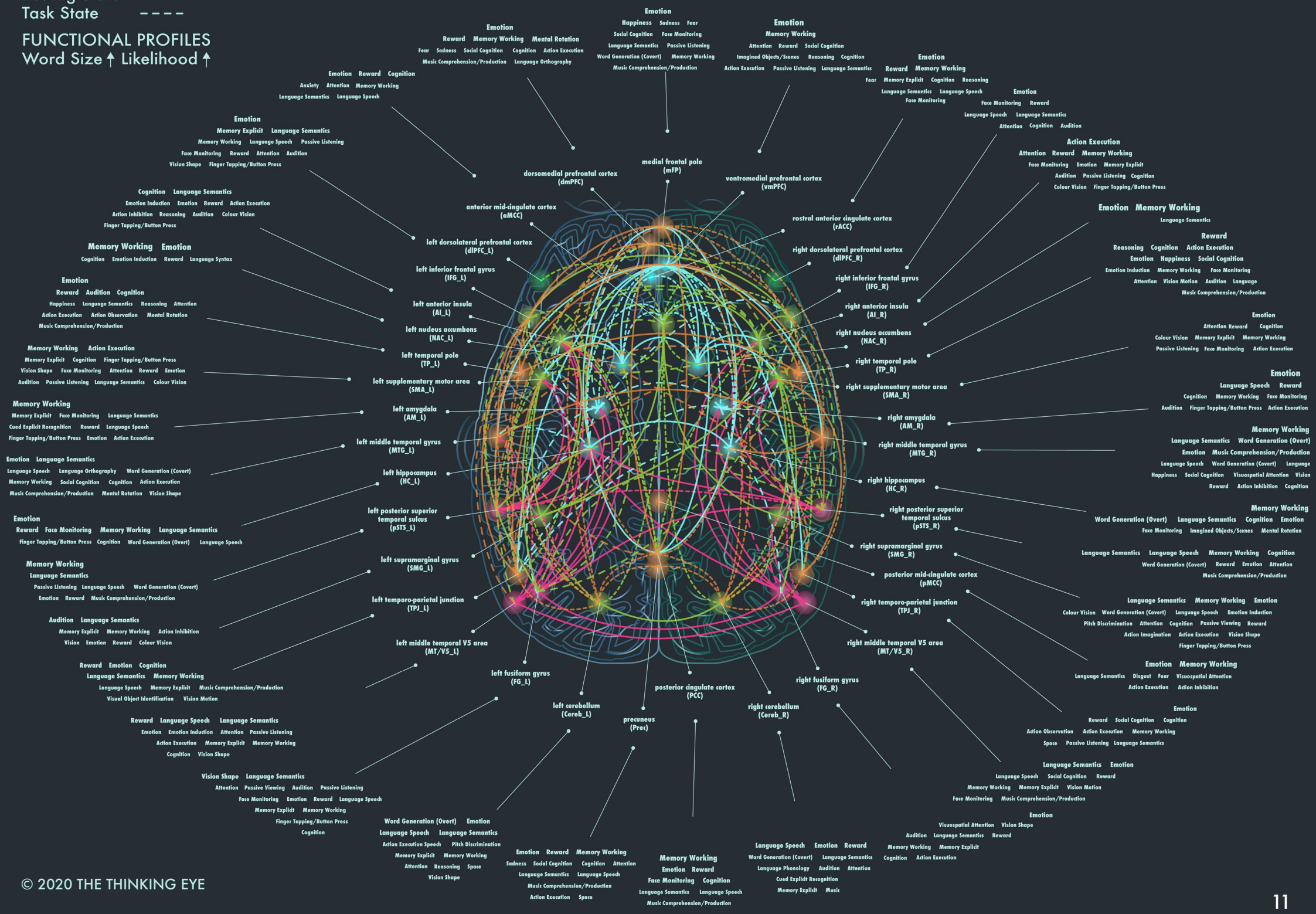
### AXIAL PLANE

x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 2

# SOCIAL BRAIN ATLAS

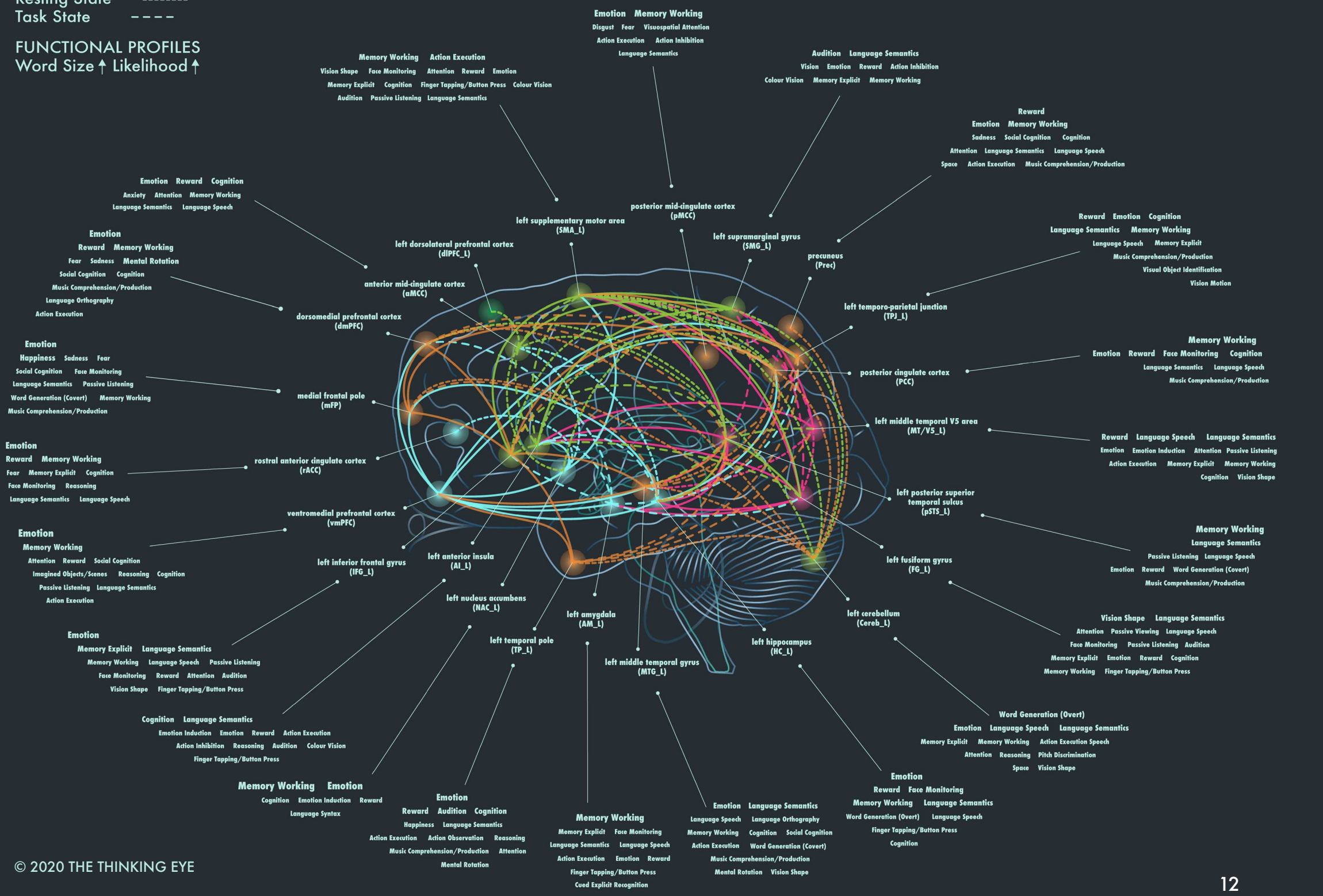
## OVERVIEW NETWORKS

LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 3

# SOCIAL BRAIN ATLAS

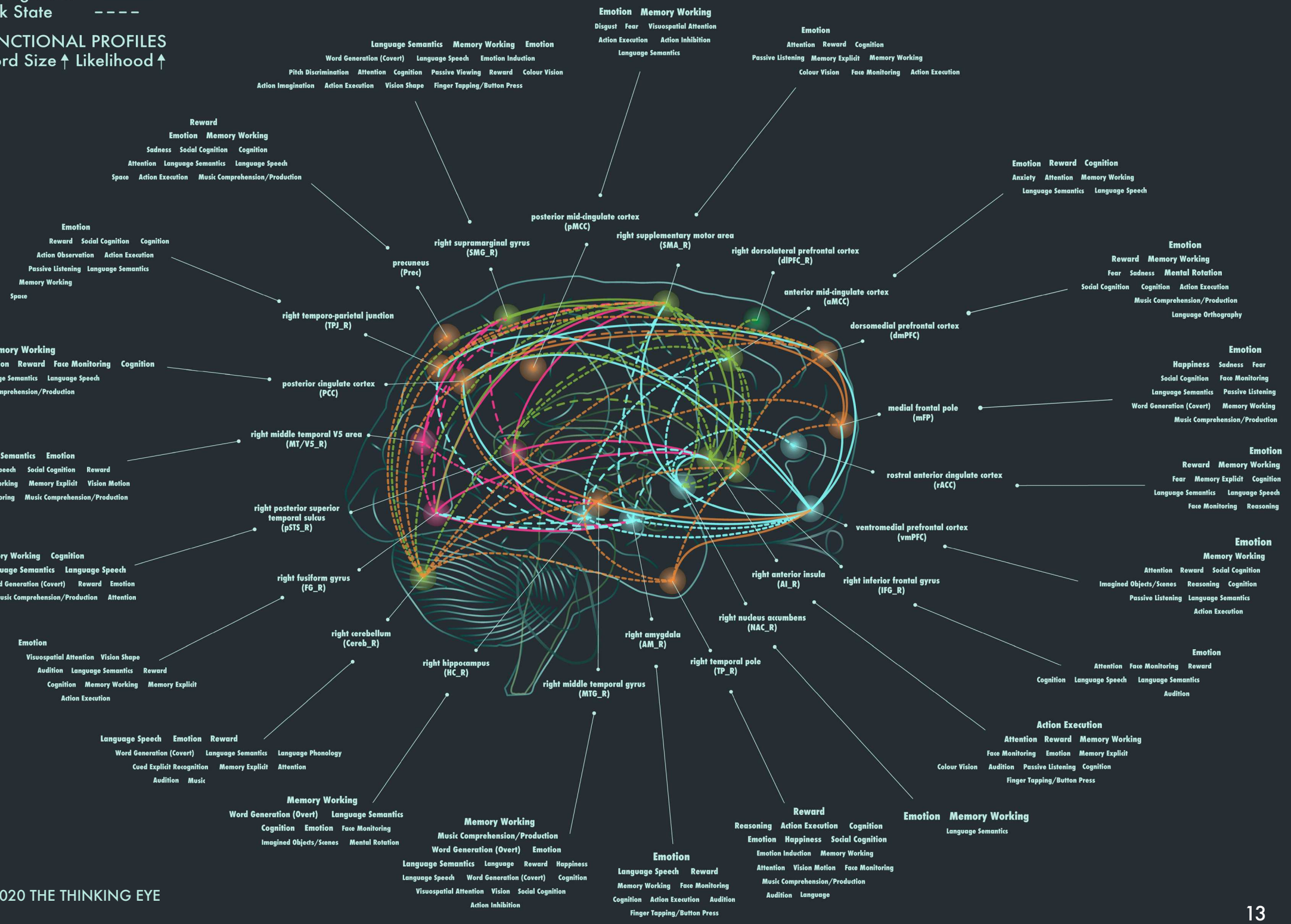
## OVERVIEW NETWORKS

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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### 2.1.1 PERCEPTION NETWORK

The Perception Network, shown in magenta, is the first processing level in the Social Brain Atlas and contains the following brain areas:

- Bilateral fusiform gyrus (FG)
- Bilateral middle temporal V5 area (MT/V5)
- Bilateral posterior superior temporal sulcus (pSTS)

The posterior superior sulcus is also part of the Interaction Network and is the only area in the social brain connectome that is grouped with two different network dynamics, which is possibly a reflection of its function in connecting bottom-up sensory information with top-down interpretative processes.

The social brain hubs in the Perception Network are specialised in analysing sensory and spatial features of social behaviour, with an emphasis on visual processes.

Figure 4: Perception Network Axial
Figure 5: Perception Network Left
Figure 6: Perception Network Right

Figure 4

# SOCIAL BRAIN ATLAS

## PERCEPTION NETWORK

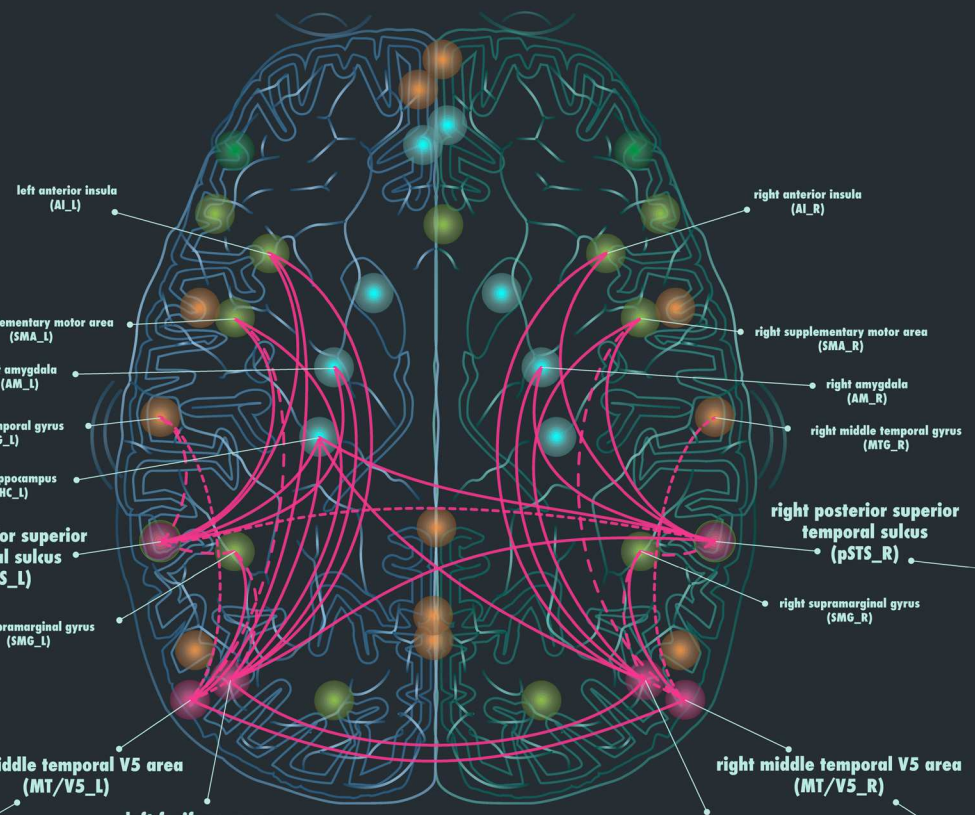
### AXIAL PLANE

x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




**Memory Working**
**Language Semantics**
Passive Listening Language Speech Word Generation (Covert)
Emotion Reward Music Comprehension/Production

**Memory Working**
**Language Semantics Language Speech Cognition**
Word Generation (Covert) Reward Emotion Attention
Music Comprehension/Production

**Reward Language Speech Language Semantics**
Emotion Emotion Induction Attention Passive Listening
Action Execution Memory Explicit Memory Working
Cognition Vision Shape

**Language Semantics Emotion**
Language Speech Social Cognition Reward
Memory Working Memory Explicit Vision Motion
Face Monitoring Music Comprehension/Production

**Vision Shape Language Semantics**
Attention Passive Viewing Audition Passive Listening
Face Monitoring Emotion Reward Language Speech
Memory Explicit Memory Working
Finger Tapping/Button Press
Cognition

**Emotion**
Visuospatial Attention Vision Shape
Audition Language Semantics Reward
Memory Working Memory Explicit
Cognition Action Execution

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Figure 5

# SOCIAL BRAIN ATLAS

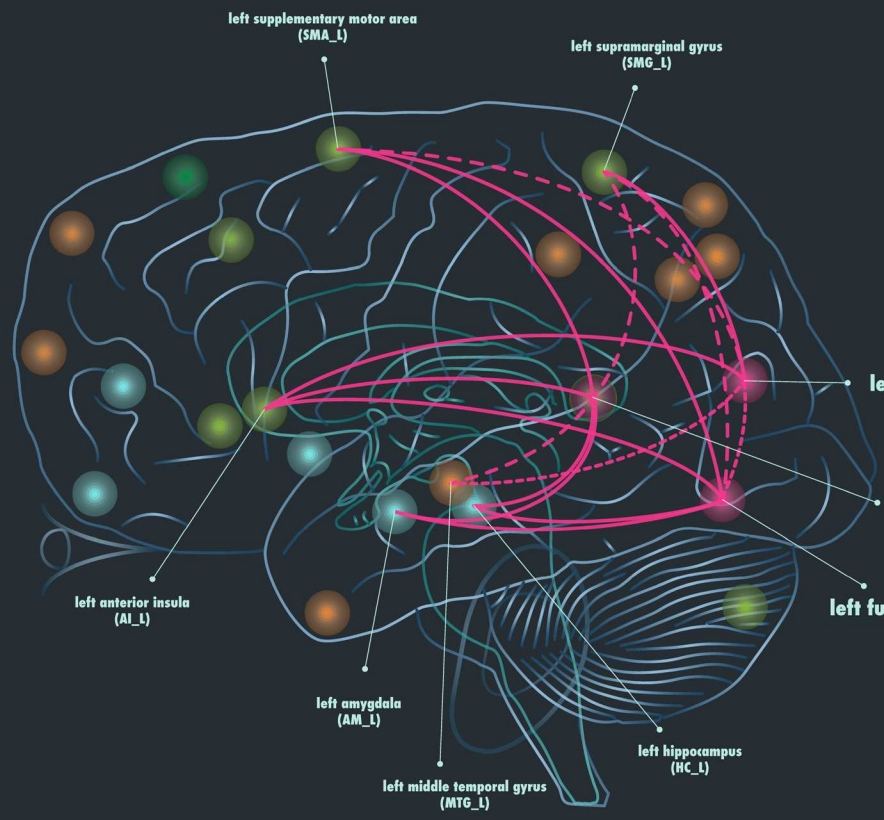
## PERCEPTION NETWORK

LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




**Reward**
**Language Speech** **Language Semantics**
**Emotion** **Emotion Induction** **Attention** **Passive Listening**
**Action Execution** **Memory Explicit** **Memory Working**
**Cognition** **Vision Shape**

**Memory Working**
**Language Semantics**
**Passive Listening** **Language Speech**
**Emotion** **Reward** **Word Generation (Covert)**
**Music Comprehension/Production**

**Vision Shape** **Language Semantics**
**Attention** **Passive Viewing** **Language Speech**
**Face Monitoring** **Passive Listening** **Audition**
**Memory Explicit** **Emotion** **Reward** **Cognition**
**Memory Working** **Finger Tapping/Button Press**

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Figure 6

# SOCIAL BRAIN ATLAS

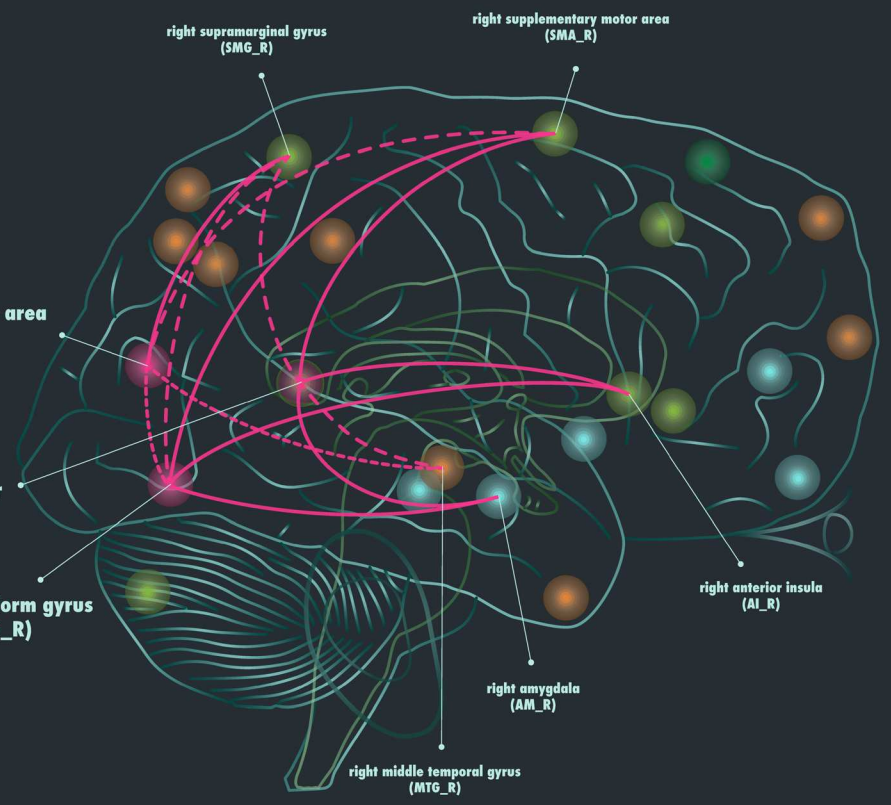
## PERCEPTION NETWORK

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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### 2.1.2 ANIMATION NETWORK

The Animation Network, shown in cyan, is the second processing level in the Social Brain Atlas and consists of the following hubs:

- Bilateral hippocampus (HC)
- Bilateral amygdala (AM)
- Bilateral nucleus accumbens (NA)
- Rostral anterior cingulate cortex (rACC)
- Ventromedial prefrontal cortex (vmPFC)

This network plays an important role in attributing personal and emotional value to our experiences as well as creating, retrieving and updating dynamic internal representations and multi-modal memories.

Figure 7: Animation Network Axial
Figure 8: Animation Network Left
Figure 9: Animation Network Right

Figure 7

# SOCIAL BRAIN ATLAS

## ANIMATION NETWORK

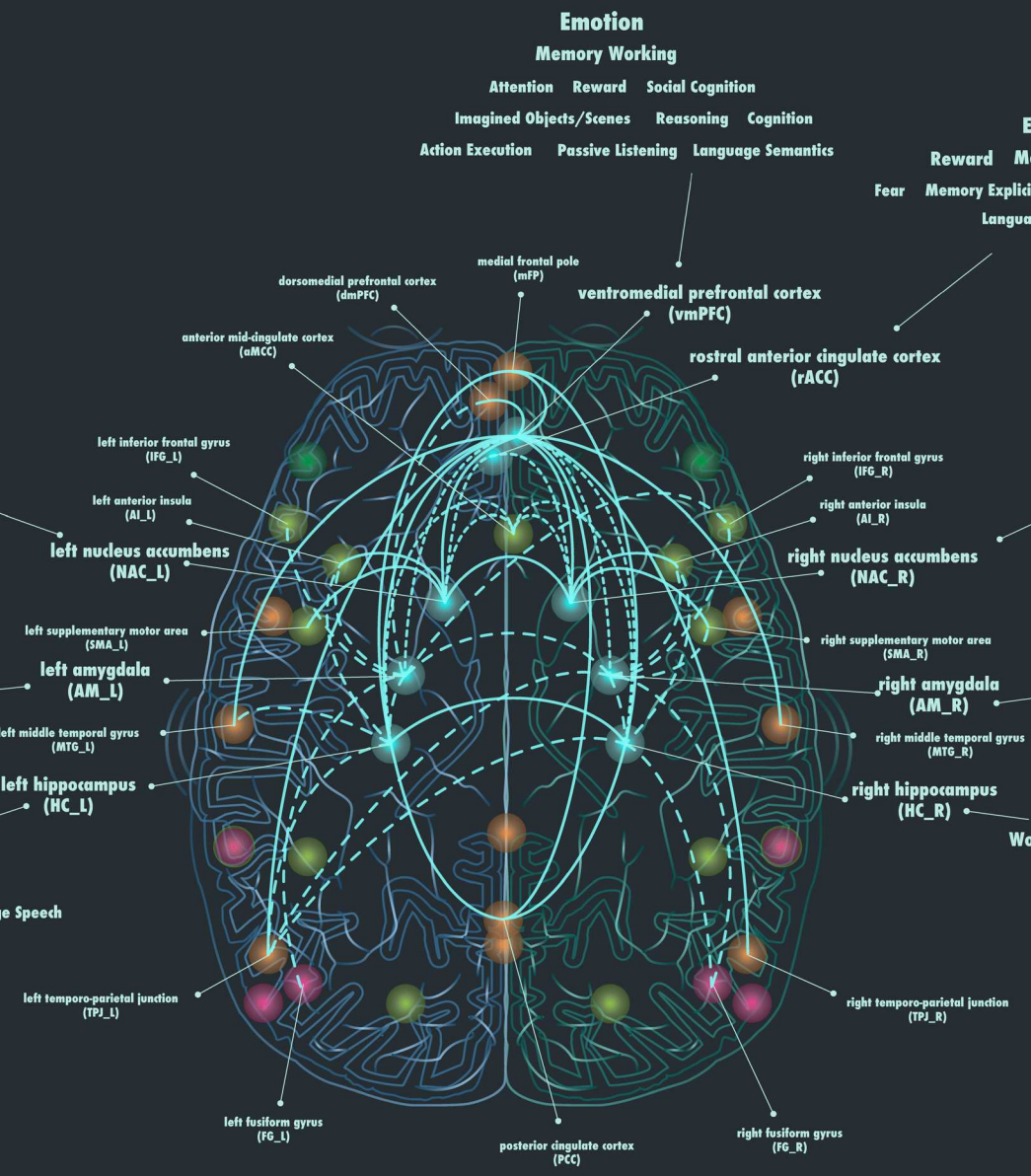
### AXIAL PLANE

x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 8

# SOCIAL BRAIN ATLAS
## ANIMATION NETWORK

LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




**Emotion**
Reward Memory Working
Fear Memory Explicit Cognition
Face Monitoring Reasoning
Language Semantics Language Speech

**Emotion**
Memory Working
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Passive Listening Language Semantics
Action Execution

**Memory Working Emotion**
Cognition Emotion Induction Reward
Language Syntax

**Memory Working**
Memory Explicit Face Monitoring
Language Semantics Language Speech
Action Execution Emotion Reward
Finger Tapping/Button Press
Cued Explicit Recognition

**Emotion**
Reward Face Monitoring
Memory Working Language Semantics
Word Generation (Overt) Language Speech
Finger Tapping/Button Press
Cognition

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Figure 9

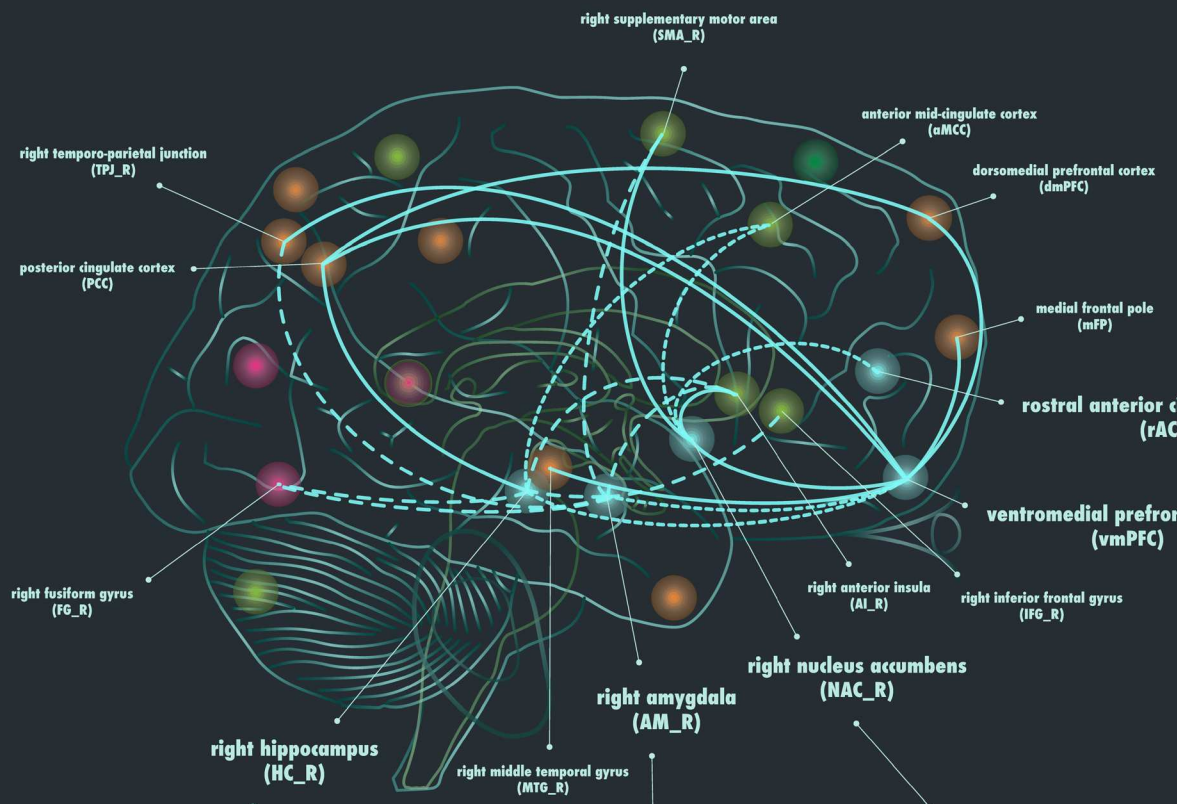
# SOCIAL BRAIN ATLAS
## ANIMATION NETWORK

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




**Emotion**
Reward Memory Working
Fear Memory Explicit Cognition
Language Semantics Language Speech
Face Monitoring Reasoning

**Emotion**
Memory Working
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Passive Listening Language Semantics
Action Execution

**Memory Working**
Word Generation (Overt) Language Semantics
Cognition Emotion Face Monitoring
Imagined Objects/Scenes Mental Rotation

**Emotion**
Language Speech Reward
Memory Working Face Monitoring
Cognition Action Execution Audition
Finger Tapping/Button Press

**Emotion Memory Working**
Language Semantics

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### 2.1.3 INTERACTION NETWORK

The Interaction Network, shown in lime, is the third processing level in the Social Brain Atlas and consists of the following hubs:

- Bilateral cerebellum (Cereb)
- Bilateral posterior superior sulcus (pSTS)
- Bilateral supramarginal gyrus (SMG)
- Bilateral  supplementary motor area (SMA)
- Bilateral inferior frontal gyrus (IFG)
- Bilateral anterior insula (AI)
- Anterior mid-cingulate cortex (aMCC)

The posterior superior sulcus is also part of the Perception Network and is the only area in the social brain connectome that is grouped with two different network dynamics, which is possibly a reflection of its function in connecting bottom-up sensory information with top-down interpretative processes.

The Interaction Network contains core hubs of the so-called Salience Network (including AI and aMCC; connecting to vmPFC and other core nodes from the Animation Network) which weighs internal states against incoming sensory information to regulate social behaviour.

It also consists of brain areas which regulate speech production (including IFG, SMA) and a mirroring behaviour system involving parietal areas (including SMA, SMG) that is thought to underpin empathy and mentalising skills.

Figure 10: Interaction Network Axial
Figure 11: Interaction Network Left
Figure 12: Interaction Network Right

Figure 10

# SOCIAL BRAIN ATLAS

## INTERACTION NETWORK

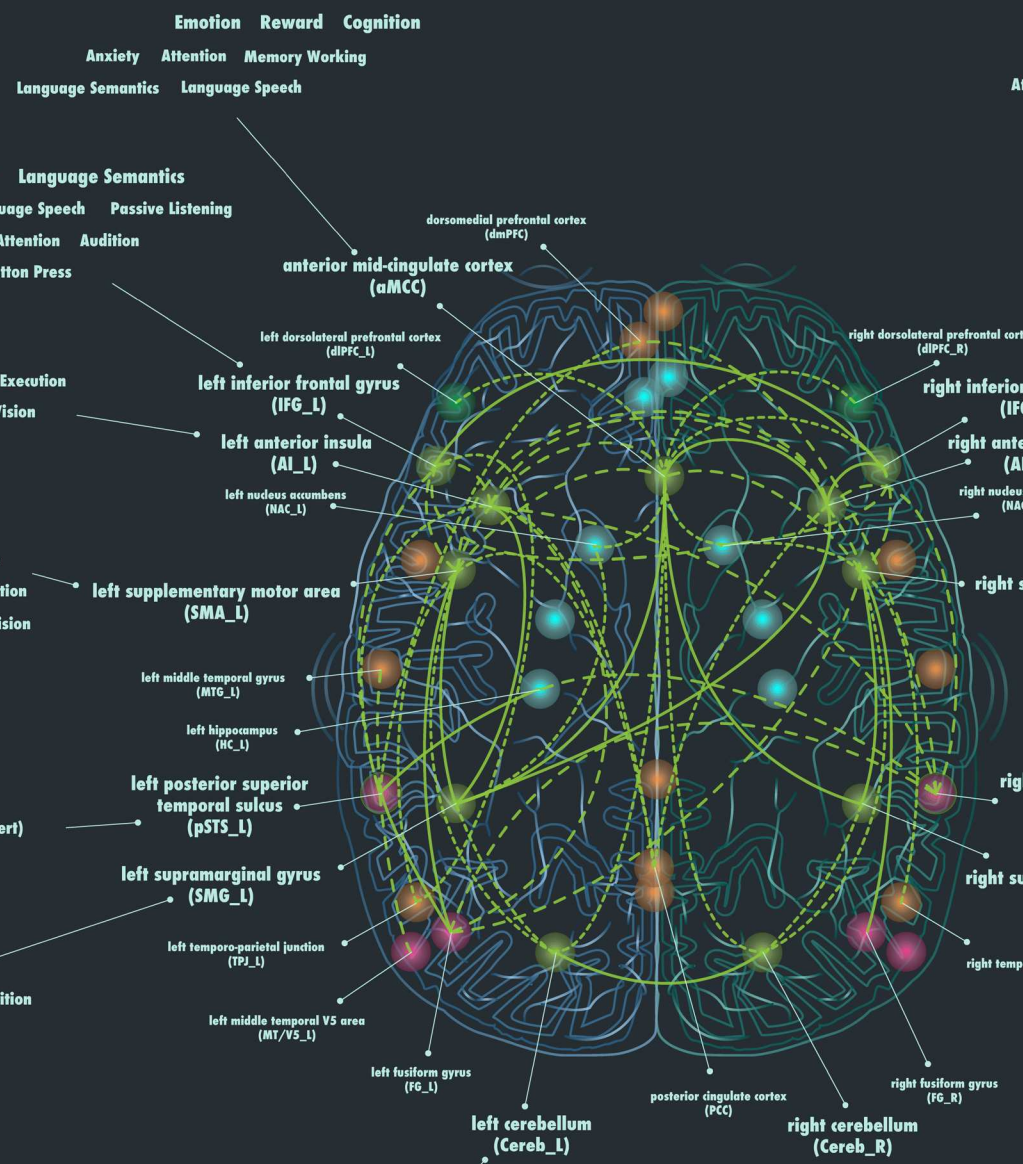
### AXIAL PLANE

x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 11

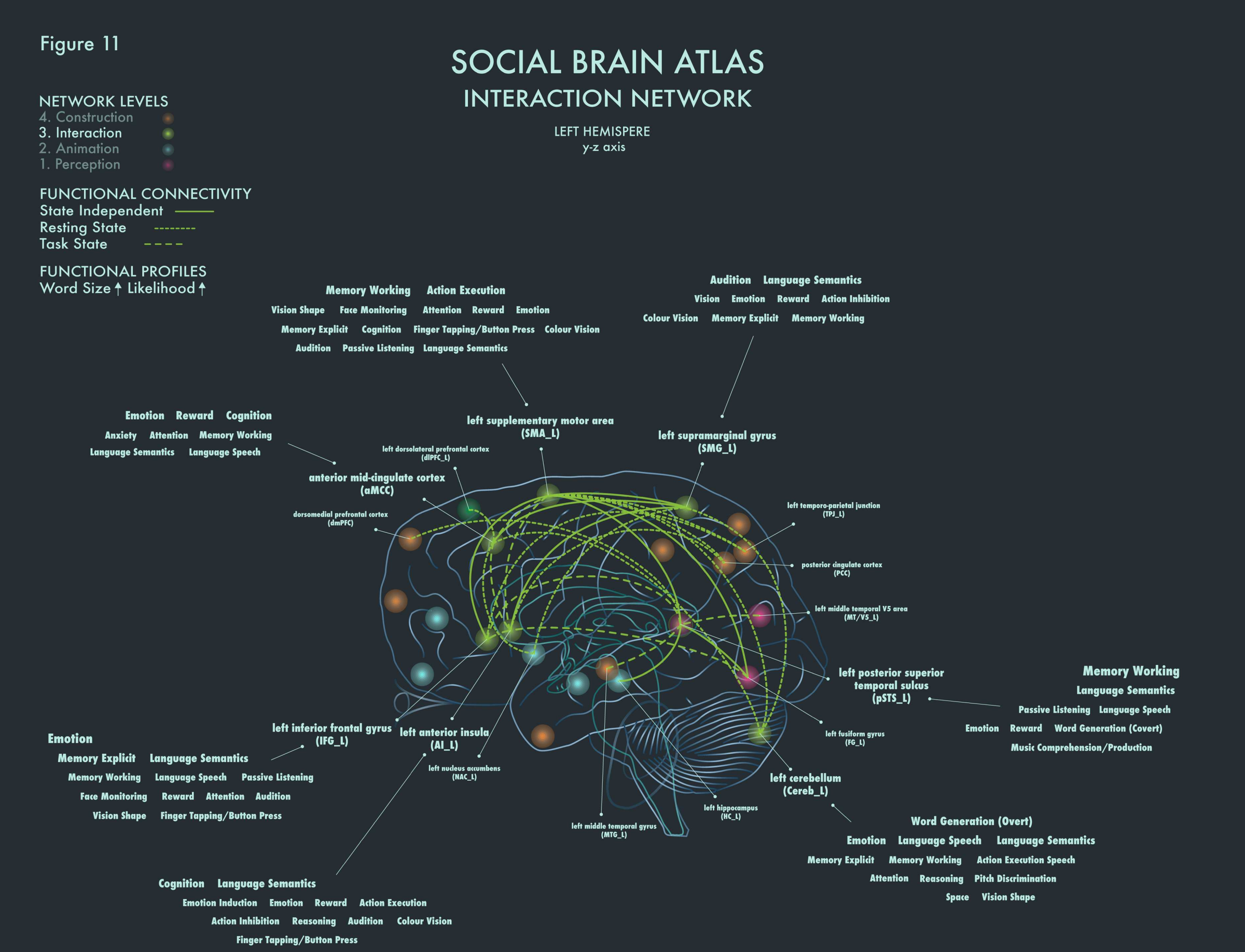
# SOCIAL BRAIN ATLAS
## INTERACTION NETWORK

LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 12

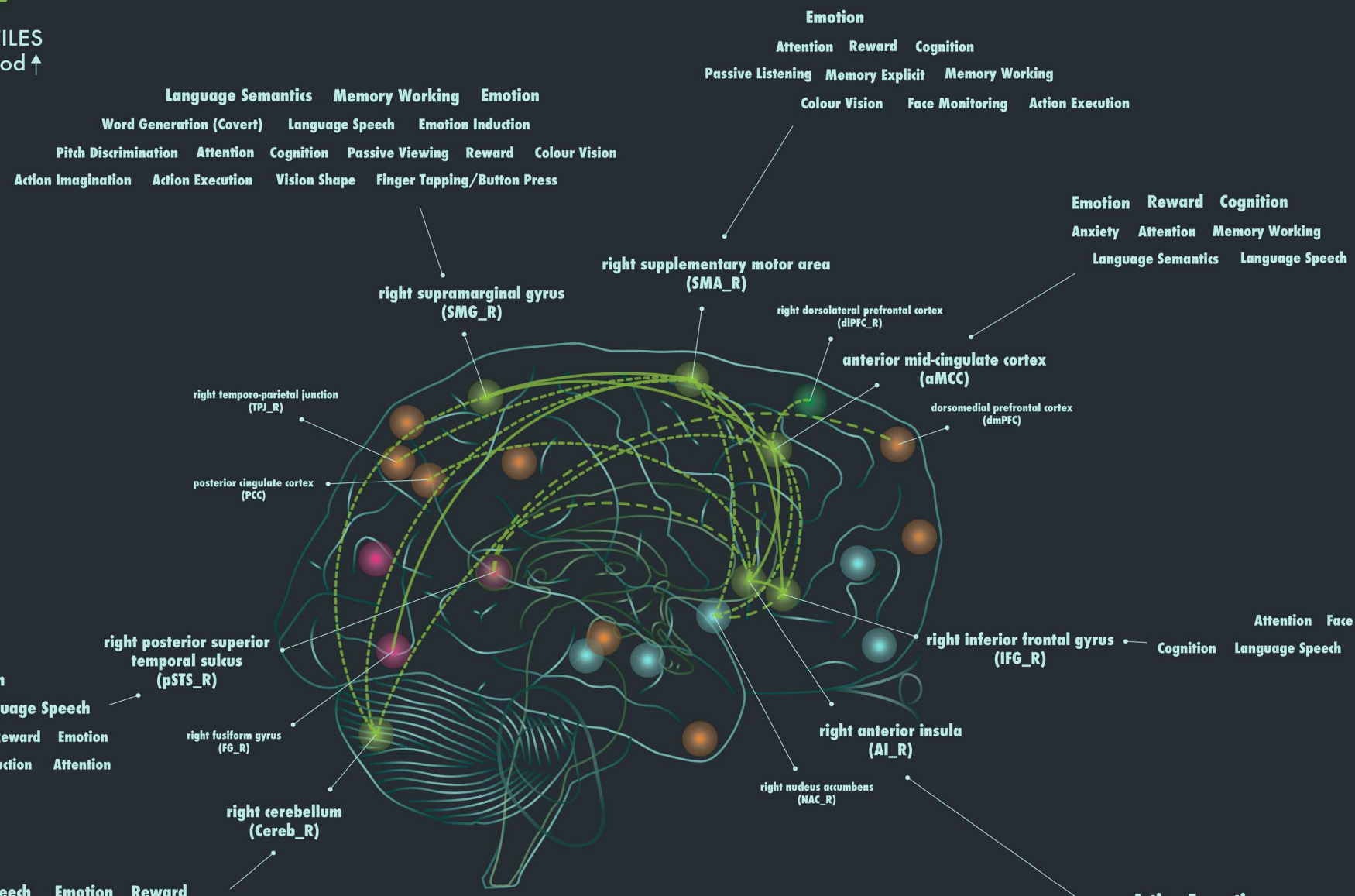
# SOCIAL BRAIN ATLAS
## INTERACTION NETWORK

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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### 2.1.4 CONSTRUCTION NETWORK

The Construction Network, shown in ochre, is the fourth processing level in the Social Brain Atlas and consists of the following hubs:

- Bilateral temporoparietal junction (TPJ)
- Bilateral middle temporal gyrus (MTG)
- Bilateral temporal pole (TP)
- Precuneus (Prec)
- Posterior cingulate cortex (PCC)
- Posterior mid-cingulate cortex (pMCC)
- Dorsomedial prefrontal cortex (dmPFC)
- Medial frontal pole (mFP)

The Construction Network corresponds anatomically with the so-called Default Mode Network and plays a crucial role in creating internal models of ourselves and others in relationship to the world around us. This network also contains the semantic language system, which regulates our knowledge of the symbolic meaning of things.

Figure 13: Construction Network Axial
Figure 14: Construction Network Left
Figure 15: Construction Network Right

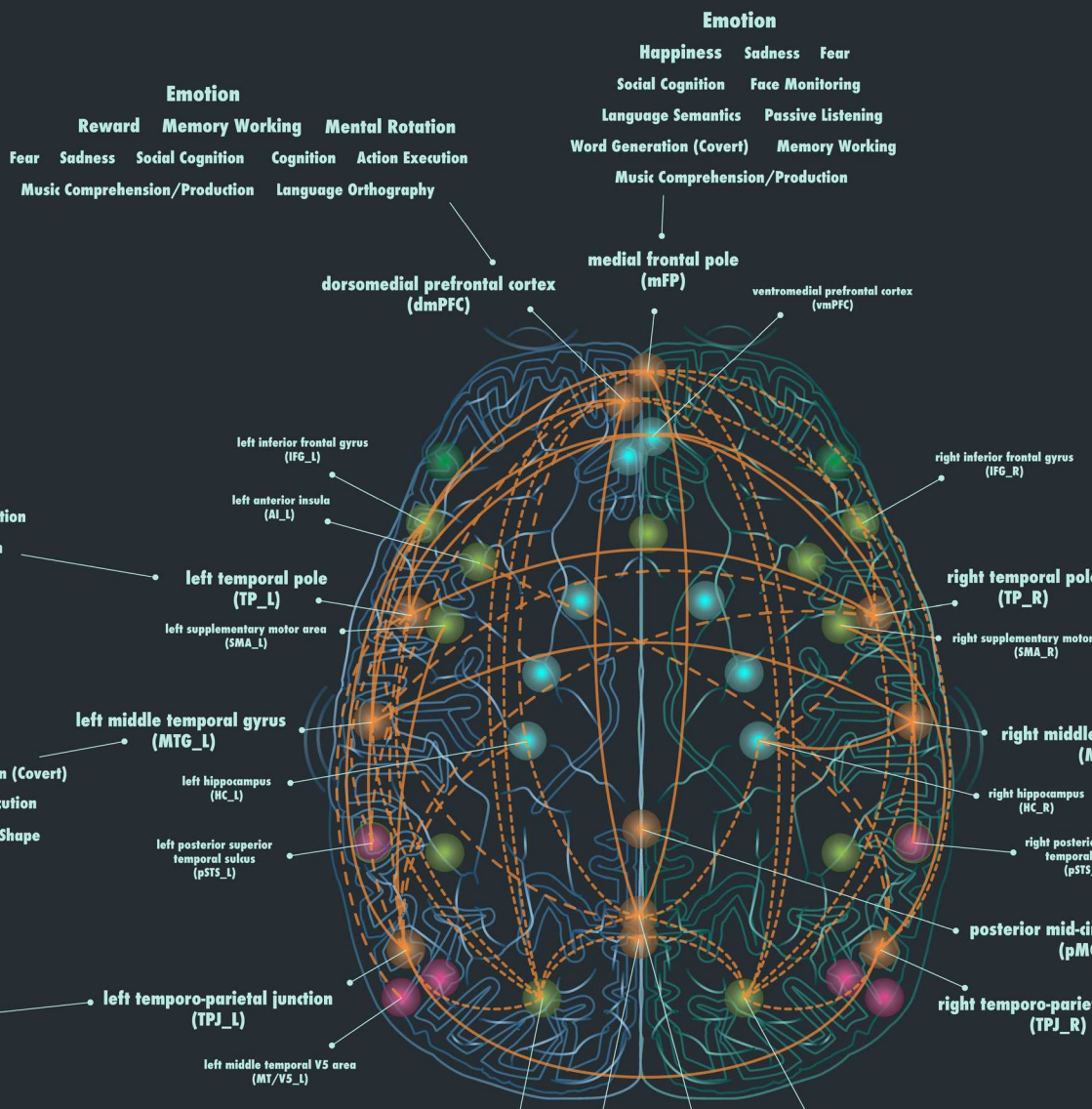
Figure 13

# SOCIAL BRAIN ATLAS
## CONSTRUCTION NETWORK
### AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 14

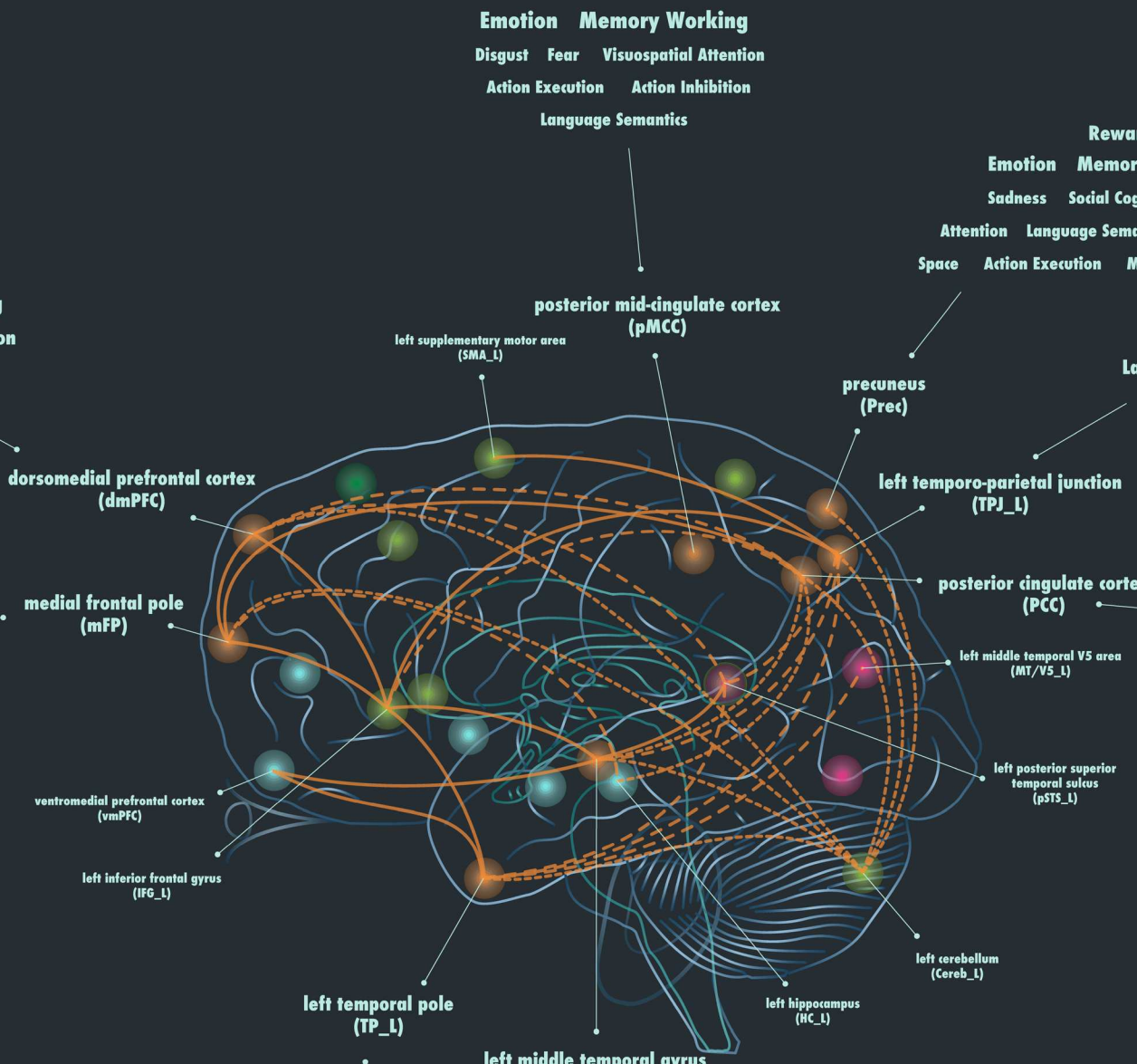
# SOCIAL BRAIN ATLAS
## CONSTRUCTION NETWORK

LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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Figure 15

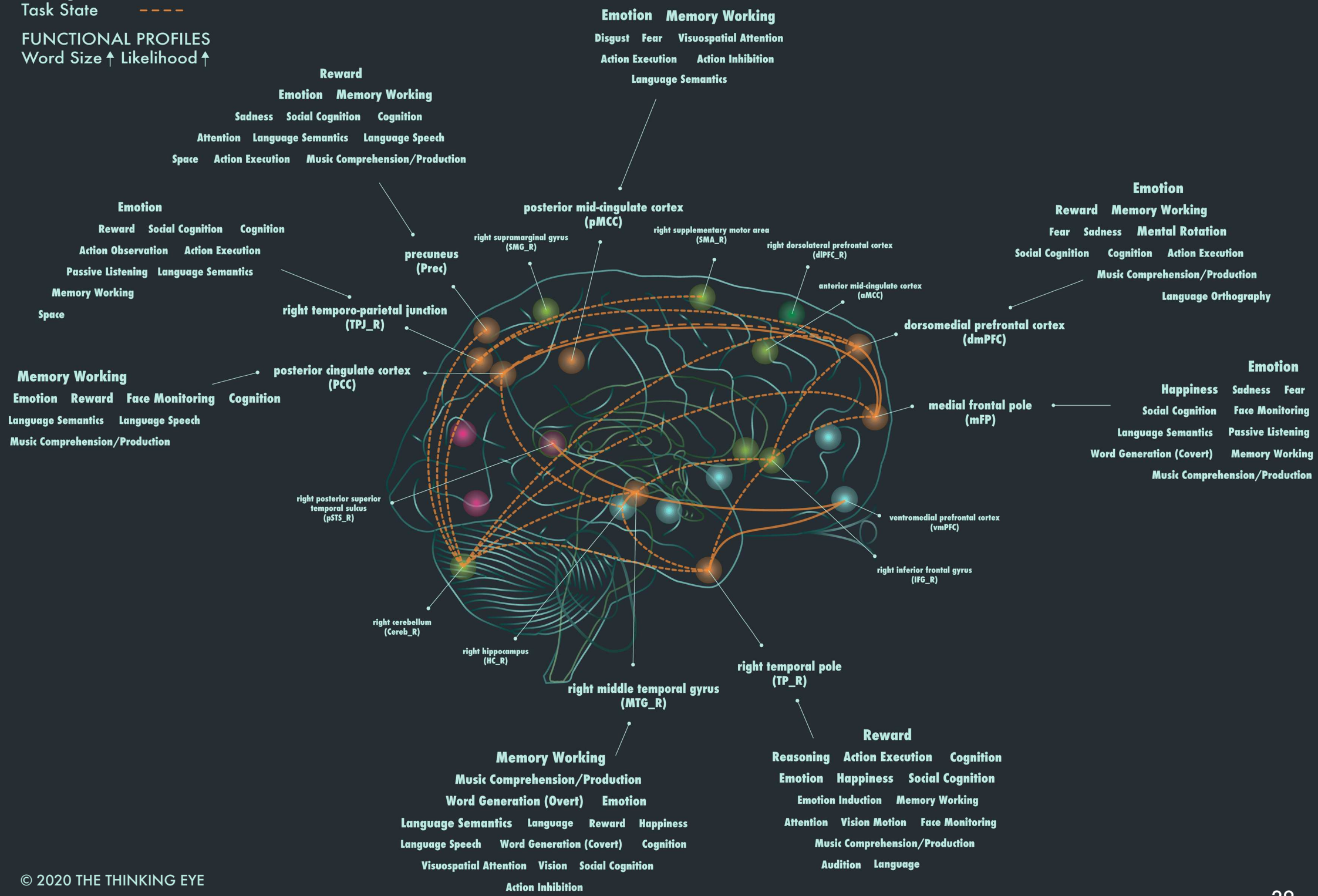
# SOCIAL BRAIN ATLAS
## CONSTRUCTION NETWORK

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑




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## 2.2 VISUAL IMAGINATION IN THE SOCIAL BRAIN

### Conceptual definitions

After I had constructed the visual representations of the four hierarchical processing levels of the Social Brain Atlas, I set out to map out various aspects of visual imagination onto the Social Brain Atlas. My aim was to elucidate the functional neuroanatomy of visual imagination processes and their links with other complex social behaviours. For this purpose, I first defined the concepts 'visual art', 'colour experiences' and 'creativity' in the context of this study.

What is visual art? This question is very difficult to answer. Since the late 19th century, artists and curators have progressively challenged our understanding of visual art and its place in the social world. Today the only consensus seems to be: Visual art can be anything.
But if art can be anything, how can it be identified?
I believe that the answer to this question will always be dependent on the context in which it is being asked.
The curator of a contemporary fine art museum for instance, will have a very different understanding of visual art, compared to a medical professional who takes an interest in the artistic self-expressions of a patient. The point of view I have therefore taken in this study, is that visual art is a social construct which only has meaning in relation to the dynamics of a social and cultural context.

With this in mind, I identified two conditions that have to be met for something to be considered visual art in this study:

1. It is presented with an artistic intent in a cultural context

2. It is validated as visual art within a cultural context

By this definition, visual art is always an interaction between the intentions and qualities of an artistic expression and the cultural values of the community (or authority) which accepts it as art.

For this reason, visual art can offer us an opportunity to critically reflect on how we personally and culturally relate to the world we inhabit. In this spirit, the visual artworks and complex images that I selected from the Wellcome Collection for this study were perceptually ambiguous and conceptually multi-layered.

Colour experiences are equally challenging to define.
Is a colour experience caused by the sensory stimulation of the retina and the electrical signals received by the visual cortex, or is it instead driven by affective and symbolic representations inside the mind? In this study I was interested in the relationship between the material and immaterial elements of colour experiences. My definition of colour experiences therefore includes both physiological and psychological aspects.

Finally, a word on creativity. Creativity is an elusive ability, which in the context of neuroscientific research is often conflated with 'creating' (Zaidel, 2014). Creating something can enhance a sense of self-agency and when done in a social context it can also nurture interpersonal connectivity, both of which are important core values of participatory art projects.
However, the designation 'creative' implies a degree of originality of thought and/or execution which the act of creating in itself doesn't. The act of creating can be creative, but not everything that is created is creative. It is important to recognise this difference, because failing to appropriately conceptualise creativity will stand in the way of gaining a deeper understanding of its complex nature. In this study, I have defined creativity as an adaptive behaviour that comes about in a dynamic exchange with the social environment, whereby intent, skill and cultural context are intricately intertwined.

With the conceptual definitions in place, I conducted a literature review in PubMed, the online publication database on biomedical and life sciences topics. I searched for functional neuroimaging studies (PET, MEG and fMRI) on visual imagination in the social brain using various combinations of the keywords 'brain'; 'functional connectivity'; 'social'; 'visual art',

'colours'; 'creativity'; 'healthy'; and 'dementia'.
I was particularly interested in studies that approached art from a social perspective, looking beyond the neural networks and physiological processes involved. Studies that treated colours and visual art simply as material stimuli who's visual properties were manipulated to make inferences about their psychological effects were excluded for instance. I found 42 publications that met my criteria for a holistic social (brain) approach to colours and visual art experiences (Table x, page x). I conducted a qualitative analysis on the reported results in these studies. When visual imagination functions where associated with any of the 36 core hubs of the Social Brain Atlas, I added these in a second tier to the word clouds in the Social Brain Atlas Figures. Since my analysis method was qualitative in nature, I based the findings reported in my literature review in the next sub-sections on the labels of brain areas as described by the authors of the publications, rather than any reported MNI coordinates.

**Visual imagination in the Perception Network**

The Perception Network plays an important role in analysing the spatial qualities and meaning of the perceptual features of colours and visual art. For a review on the role of areas 1 to 4 of the visual cortex in colour processing -which are not part of this network- see the introduction to the Colour Spaces project in the Experimental Research chapter.

Cela-Conda et al. (2013) found that within 750 ms after the presentation of a visual stimuli, the brain makes an assessment whether it is beautiful or not. The authors named this phase the Initial Aesthetic Network, which covers occipital, temporal and parietal areas. Anatomically the so-called Initial Aesthetic Network corresponds with the core nodes of the Perception Network, extending to the ventromedial prefrontal cortex which is part of the Animation Network. After this first gist evaluation has been made, Cela-Conda et al. found that when the artwork was considered beautiful, the Default Mode Network was then activated, which corresponds with the Construction Network in the Social Brain Atlas.

The authors called this dynamic the Delayed Aesthetic Network. This will be further elaborated on under the section on visual imagination in the Construction Network. If the visual stimulus was considered ugly, brain regions associated with executive and control functions became more active (Cela-Conde et al., 2013). The functional connectivity patterns of the Perception Network correspond with both the ventral (lower) and dorsal (upper) streams of visual processing. The ventral stream is concerned with the 'What?' of visual information to guide the meaning making process, whereas the dorsal stream is focused on the 'Where?' to guide action (Goodale and Milner, 1992; Ungerleider and Mishkin, 1982).

Photographic images of naturally and unnaturally coloured objects have been found to activate areas V1 to V4 of the visual cortex in equal manner. However, images of naturally coloured objects have been reported to engage more with the ventral stream, including the anterior regions of the fusiform gyrus, the hippocampus and the ventrolateral frontal cortex, whereas images of unusually coloured objects have been found to recruit the anterior mid-cingulate cortex and the dorsolateral prefrontal cortex, which is connected to the dorsal route (Zeki and Marini, 1998). These findings could suggest that naturally coloured objects are more likely to trigger a familiarity response, whereas unnaturally coloured objects might need further examination to decide their value.

The bilateral fusiform gyrus has been associated with object perception and recognition – including faces – when viewing pictorial representations (Kawabata and Zeki, 2004; Vartanian and Skov, 2014). This is largely congruent with the functional profiles of these structures in the Social Brain Atlas. Both the left and right fusiform gyrus are associated with shape vision and the right fusiform gyrus is likely to be activated during visuospatial attention. However, surprisingly, only the left fusiform gyrus is implicated in face monitoring in the Social Brain Atlas (Alcalá-López et al., 2017).

**Table 1: Studies included in the literature review on visual imagination and the social brain**

| Study | Cohort | Subjects |
|---|---|---|
| Beaty et al. (2014) | Neurologically healthy; adults | 24 |
| Beaty et al. (2018) | Neurologically healthy; adults | 163 |
| Belfi et al. (2019) | Neurologically healthy; adults | 25 |
| Boccia et al. (2016) | Neurologically healthy; adults | 286 |
| Cela-Conde et al. (2013) | Neurologically healthy; adults | 24 |
| Cela-Conde et al. (2004) | Neurologically healthy; adults | 8 |
| Chakravarty (2011) | Typical Alzheimer's Disease; adult | 1 |
| Cohen et al. (2016) | Frontotemporal Dementias (N=24) and Neurologically healthy (N=39); adults | 63 |
| Crutch et al. (2001) | Typical Alzheimer's Disease; adult | 1 |
| Crutch and Rossor (2006) | Typical Alzheimer's Disease; adults | 2 |
| Cupchik et al. (2009) | Neurologically healthy; adults | 16 |
| De Pisapia et al. (2016) | Neurologically healthy; adults | 24 |
| Dittmar (2001) | Neurologically healthy; adults | 842 |
| Ellamil et al. (2012) | Neurologically healthy; adults | 15 |
| Elliott et al. (2000) | Neurologically healthy; lesion studies; adults | Data not provided |
| Fairhall and Ishai (2008) | Neurologically healthy; adults | 12 |
| Fornazzari (2005) | Typical Alzheimer's Disease; adult | 1 |
| Gonen-Yaacovi et al. (2013) | Neurologically healthy; adults | 622 |
| Gretton and ffytche (2014) | Various dementias; adults | 14 |
| Hassabis et al. (2007) | Neurologically healthy; adults | 21 |
| Huang et al. (2011) | Neurologically healthy; adults | 14 |
| Ishizu and Zeki (2013) | Neurologically healthy; adults | 21 |
| Ishizu and Zeki (2017) | Neurologically healthy; adults | 21 |
| Ishizu and Zeki (2011) | Neurologically healthy; adults | 20 |
| Jonauskaite et al. (2016) | Neurologically healthy; adults | 88 |
| Kawabata and Zeki (2004) | Neurologically healthy; adults | 10 |
| Kim and Blake (2007) | Neurologically healthy; adults | 14 |
| Kowatari Yasuyuki et al. (2009) | Neurologically healthy; adults | 40 |
| Lacey et al. (2011) | Neurologically healthy; adults | 8 |
| Liu et al. (2009) | Frontotemporal Dementia; adult | 1 |
| Mullally et al. (2012) | Severe amnesia (N=1); Neurologically healthy (N=21); adults | 22 |
| Palmer and Schloss (2010) | Neurologically healthy; adults | 48 |
| Rankin et al. (2007) | Typical Alzheimer's Disease (N=18); Frontotemporal Dementia (N=18); Neurologically healthy (N=15); adults | 51 |
| Rogers et al. (2007) | Semantic Primary Progressive Aphasia (N=26); Neurologically healthy (N=10); adults | 36 |
| Schloss et al. (2013) | Neurologically healthy; adults | 48 |
| Taylor et al. (2013) | Neurologically healthy; infants | 30 |
| Vartanian and Skov (2014) | Neurologically healthy; adults | 330 |
| Vessel et al. (2012) | Neurologically healthy; adults | 16 |
| Vessel et al. (2013) | Neurologically healthy; adults | 16 |
| Wijk et al. (1999) | Typical Alzheimer's Disease; adults | 50 |
| Zeki and Marini (1998) | Neurologically healthy; adults | 9 |
| Zeman et al. (2015) | Neurologically healthy; adults | 21 |

The perception of implied motion in photographs and paintings has been associated with an increased activity of the bilateral MT/V5 areas, but with respect to abstract art this effect was only present in viewers with previous knowledge of the use of implied motion in abstract art (Kim and Blake, 2007). These findings are supported by the functional profile of MT/V5 in the Social Brain Atlas. While only the functional profile of the right MT/V5 area includes a likelihood of involvement in motion vision, both left and right MT/V5 are implicated in working and explicit memory tasks (Alcalá-López et al., 2017). This supports the finding by Kim and Blake that perceiving implied motion in abstract art is dependent on prior knowledge of abstract art. Different emotional processing of manipulations of abstract art in variants of frontotemporal dementias, compared to neurologically healthy adults, has been associated with atrophy in the right MT/V5 area (Cohen et al., 2016). This finding is congruent with the functional profile of this area in the Social Brain Atlas, which reports a likelihood for recruitment during emotion processing in the right but not the left MT/V5 area (Alcalá-López et al., 2017).

**Visual imagination in the Animation Network**

The Animation Network is associated with people's imaginative abilities and their affective responses to viewing art and colours.

The ventromedial prefrontal cortex is considered the end-point of the ventral visual pathway (Goodale and Milner, 1992; Ungerleider and Mishkin, 1982). It receives information about the perceptual qualities of incoming visual information and evaluates its potential reward value (Elliot et al., 2000).
It has also been implicated in the aesthetic evaluations of artworks (Cela-Conde et al., 2004, 2013; Ishizu and Zeki, 2011, 2013; Kawabata and Zeki, 2004; Lacey et al., 2011). This area has also been found to be engaged when judging a personally considered beautiful picture as simultaneously joyful (Ishizu and Zeki, 2017). The reported key role of the ventromedial prefrontal cortex in the evaluation of the personal value of artworks is congruent with its functional profile in the Social Brain Atlas, which indicates a strong involvement of this brain region in emotion, working memory, attention, reward, social cognition, imagined objects/scenes and reasoning (Alcalá-López et al., 2017). The bilateral amygdala is functionally connected to the ventromedial prefrontal cortex during resting states (Alcalá-López et al., 2017) and has been found to drive the emotional component of reward attribution during aesthetic evaluations (Cela-Conde et al., 2013; Jacobs et al., 2012). The bilateral amygdala has also been found to be specifically engaged when watching portrait paintings, an activation which is also consistently found in facial perception (Kawabata and Zeki, 2004). These findings are supported by the functional profiles of the amygdala in the Social Brain Atlas, as a significant likelihood for involvement in face monitoring is reported for both the left and the right amygdala. In the Social Brain Atlas, the functional profiles of both the right and the left amygdala include reward related behaviour. The left amygdala is also implicated in explicit and working memory and the right amygdala in emotion (Alcalá-López et al., 2017). In non-related research, it was found that direct stimulations of the right amygdala always induced negative emotions (fear, anxiety and sadness), whereas stimulations of the left amygdala could evoke both negative and pleasant emotions (Lanteaume et al., 2007).
It is relevant to consider these findings in relation to the functional profiles of the left and right amygdala in the Social Brain Atlas, as they underline that the broad categorisations do not provide any information on either content or emotional valence. In the general methods chapter I have further elaborated on the study by Lanteaume et al., (2007) in the context of the electrodermal activity measurements in this study.

The left hippocampus has been found to be engaged when viewing highly moving artworks (Vessel et al., 2012).
A selective activation of the right hippocampus has been found when viewing landscape paintings (Kawabata and Zeki, 2004). Bilateral hippocampus activation has been reported during visuospatial creative production (Ellamil et al., 2012; Kowatari Yasuyuki et al., 2009). It has also been found that people with

bilateral hippocampal damage, causing anterograde amnesia, have difficulties imagining scenes and objects in their mind's eye (Hassabis et al., 2007; Mullally et al., 2012). Additionally, people who experience little to no voluntary visual imagination, a condition coined 'Aphantasia', often also report having a poor autobiographical memory (Zeman et al., 2015).
These finding are compatible with the functional profiles of the bilateral hippocampus in the Social Brain Atlas, which report a strong activation likelihood for working memory, with a selective likelihood for recruitment of the right hippocampus when imagining objects and scenes (Alcalá-López et al., 2017).
The bilateral hippocampus has also been found to be activated when viewing pictures of naturally coloured objects, but not when viewing pictures of unnaturally objects (Zeki and Marini, 1998). The resting-state functional connectivity in the Social Brain Atlas between the bilateral hippocampus and the anterior mid-cingulate cortex might be of interest in this context, as this structure – together with the dorsolateral prefrontal cortex – has been found to be activated by pictures of unnaturally coloured objects. (Zeki and Marini, 1998), but also during critical evaluation of creative thought and production processes (Beaty et al., 2018; De Pisapia et al., 2016, Ellamil et al., 2012).
In the next sub-section I will further elaborate on this.

**Visual imagination in the Interaction Network**

The Interaction Network is considered to play an important role in mediating between incoming sensory information and the construction of meaning. It is involved in evaluating the subjective value of colours, artworks and creative output.

The bilateral anterior insula and the bilateral supplementary motor area have been linked to making judgements on both the brightness and the aesthetic value of paintings (Ishizu and Zeki, 2013). The anterior mid-cingulate gyrus has been found to be engaged during the perception of unnaturally coloured objects (Zeki and Marini, 1998). This region is thought to play a mediating role in evaluating the internal valence of aesthetic experiences, compared to a neutral state (Boccia et al., 2016; Kawabata and Zeki, 2004). The anterior mid-cingulate gyrus, together with the bilateral supplementary motor area have also been found to connect more strongly with the ventromedial prefrontal cortex in the Animation Network when a photographic image was judged as both beautiful and sad. The authors explained this finding by the implicated involvement of these areas in empathy studies (Ishizu and Zeki, 2017). This is congruent with the functional profiles in the Social Brain Atlas of the anterior mid-cingulate gyrus and the bilateral supplementary motor area, which are associated with emotion, reward and cognition. The functional profiles for these areas do not mention a specific association with sadness however, but there is a likelihood for anxiety-related activation in the anterior mid-cingulate gyrus (Alcalá-López et al., 2017).

The left supplementary motor area (likelihood 1.2), as well as the left supra-marginal gyrus (likelihood 0.6) and the left anterior insula (likelihood 0.3) are also linked to colour vision related behaviour in the social brain connectome (Alcalá-López et al., 2017). Despite the low likelihood ratios, I did include these associations in the functional profiles of my representation of the Social Brain Atlas because of their relevance to visual imagination. The fact that none of these social brain areas are part of the visual cortex, could indicate that the Interaction Network regulates internal representations and value systems of colours. Ishizu and Zeki (2013) found increased activation of the bilateral anterior insula and supplementary motor area in both aesthetic and brightness judgements of paintings, which aligns with the suggestion of a central colour evaluation system. It is also relevant to consider these findings in the context of dementia syndromes, as they commonly lead to changes in colour experiences.

Whether humans are born with intrinsic categories and values for colour processing is a long-standing debate in the scientific community going back at least to 1894 when Johan Cohn published the first attempt to systematically study human colour preferences (Cohn, 1894). Behavioural research has

found that colour preferences are to a certain extend age-related and are modulated by variations in lightness, saturation and context (Jonauskaite et al., 2016; Schloss et al., 2013, Taylor et al., 2013). Taylor et al. (2013) found that adults expressed both an explicit and a looking preference for light blue, while infants had a stronger looking preference for dark yellow, a colour generally disliked by adults. The ecological valence theory of human colour preference offers a possible explanation for these differences in colour preferences between infants and adults, by proposing that colour preferences arise from people's average responses to colour-associated objects (Palmer and Schloss, 2010). The preference for light blue could be linked in adults to positive associations such as water and the sky, while dark yellow often brings up associations of faeces or decay for instance. The study by Taylor et al. (2013) described above echoed an earlier colour preference study by Dittmar (2001), which reported a strong preference for saturated blue and a dislike of yellow in both young and senior adults, although the blue preference decreased and the preference for red and green increased with age. Dittmar suggested that alterations in colour discrimination, the yellowing of the crystalline lens and the decreased function of the blue cones in the retina in older adults could offer a possible explanation for the reported differences in colour preferences between young and senior adults.

The findings of an effect of ageing on colour preferences are also of interest in relation to neurodegenerative diseases, as the visual, physiological and emotional responses to a broad range of colours have not yet been studied rigorously from a social neuroscientific perspective yet in people living with various forms of dementia. A number of case studies have reported a strong preference for bright and saturated colours in variants of Frontotemporal dementias, while there are more conflicting reports in the neuropsychological literature on possible disease-related changes in colour preference or expression in typical Alzheimer's Disease (Chakravarty, 2011; Crutch et al., 2001; Crutch and Rossor, 2006; Fornazzari, 2005; Gretton and Ffytche, 2015; Liu et al., 2009, Rankin et al., 2007, Wijk et al., 1999). The lack of consistent findings in these studies that aimed to investigate possible effects of dementia syndromes on colour use in artistic production could be related to a misguided approach of attempting to reduce the complex multimodal processes that are involved in artistic creation to a closely controlled executive task. The reason I have included these studies in this review nonetheless, is to underline the need for a more holistic social brain approach in both cohort and case studies that aim to investigate the relationship between artistic experiences or creation and brain functioning.

Semantic Primary Progressive Aphasia often presents with a loss of conceptual colour knowledge of real world objects, which is associated with left anterior and inferior temporal lobe atrophy. It has been found that semantic knowledge of and perceptual ability to identify basic colours that are part of the opponent-process system – which consists of red/green; blue/yellow and black/white – is longer preserved than non-primary colours such as brown, orange and pink (Rogers et al., 2007; 2015). A case study by Chan et al (2001) demonstrated that Posterior Cortical Atrophy can cause changes in colour perception as well as prolonged colour after-images, which the authors attributed to an impairment of colour wavelength processing in the primary visual cortex. Taken together, these reports of altered colour experiences in people living with dementia offer valuable insights into the social brain dynamics of colour processing and emphasise the central role that colours play in the creation of internal representations of the external world.

The left anterior insula has been implicated in flexibly switching between divergent and convergent thought processes, which is considered to be a key neural mechanism underlying creativity (Beaty et al., 2018; De Pisapia et al., 2016; Ellamil et al., 2012). Cela-Conde et al (2013) also reported they had found that the left anterior insula mediated between the Initial and Delayed Aesthetic Network during the aesthetic evaluation of visual stimuli. These findings are supported by the functional profile of the left anterior insula in the Social Brain Atlas, which includes

semantic language, emotion induction, emotion, reward, action execution, action inhibition and reasoning. Creative ability has been linked to increased functional connectivity between the bilateral anterior insula, the anterior mid-cingulate cortex and the Default Mode Network (corresponding with the Construction Network) in relation to verbal creative thought generation (Beaty et al., 2018). An earlier study had found an increased functional connectivity between the right inferior prefrontal gyrus and the Default Mode Network during visuospatial creative thought generation and highly creative verbal thought processes (Beaty et al., 2014; De Pisapia et al., 2016; Ellamil et al., 2012; Kowatari Yasuyuki et al., 2009).

These findings are supported by the functional profiles of the frontal areas of the Interaction Network in the Social Brain Atlas, which report likelihoods for recruitment during behaviours that involve semantic language, reasoning, working and explicit memory, attention, action inhibition and execution. However, only a likely recruitment of the left inferior prefrontal gyrus is reported for vision shape tasks, which goes against the neuroscientific consensus of a right hemispheric dominance in visuospatial related behaviour.

Finally, the right dorsolateral prefrontal cortex has been found to be engaged when watching pictures of unnaturally coloured objects (Zeki and Marini, 1998). It has also been shown to play an important role in critical self-evaluation of verbal creative thought or expressions (Beaty et al., 2018), while in visuospatial creative thought generation bilateral activation of the dorsolateral prefrontal cortex has been reported (De Pisapia et al., 2016, Ellamil et al., 2012). The dorsolateral prefrontal cortex is functionally connected to the anterior mid-cingulate cortex, but as it is not part of the Social Brain Atlas, it has not been functionally profiled within the social connectome by Alcalá-López et al. (2017).

**Visual imagination in the Construction Network**

The Construction Network integrates multi-modal memory systems to give personal and symbolic meaning to the world around us. It plays a key role in the appreciation of colours and artworks, as well as generating and critically evaluating creative thoughts and artistic expressions.

Posterior and anterior medial regions of the so-called Default Mode Network, which correspond to the precuneus, the posterior cingulate cortex, the temporoparietal junction and the dorsomedial prefrontal cortex in the Construction Network, have been identified by Cela-Conde and colleagues (2013) to form what they described as the Delayed Aesthetic Network.
It was found that these regions are only engaged when the Initial Aesthetic network has judged an artwork as beautiful. In line with these findings, Vessel and colleagues have also reported an engagement of both posterior and anterior regions of the Construction Network when people felt strongly moved by an artwork (Vessel et al., 2012; Vessel et al., 2013). Belfi et al. (2019) have suggested that Default Mode Network dynamics track the internal state of participants during aesthetic experiences.

The dorsomedial prefrontal cortex, posterior cingulate cortex, and bilateral middle temporal gyrus have also been found to be highly co-activated with other social brain networks in divergent and creative thought processes, as well as in the generation of artistic expressions (Beaty et al., 2014; Beaty et al., 2018; De Pisapia et al., 2016; Ellamil et al., 2012; Gonen-Yaacovi et al., 2013). The precuneus has been implicated in exploring the visuospatial qualities of pictorial representations (Cupchik et al., 2009; De Pisapia et al., 2016; Fairhall and Ishai, 2008; Kawabata and Zeki, 2004; Vartanian and Skov, 2014).

These findings are aligned with the precuneus' functional profile in the Social Brain Atlas, which includes a significant likelihood of engagement in attention and space related behaviour (Alcalá-López et al., 2017). The posterior cingulate

cortex has consistently been found to be engaged when people imbue an artwork with personal and symbolic meaning, regardless of its artistic category or style (Boccia et al., 2016). This is congruent with its functional profile in the Social Brain Atlas, which reports a very strong likelihood of working memory related activation in combination with strong activation likelihoods for emotion, cognition and reward related psychological processes.

Activation of the frontal pole has been found to be engaged during the evaluation of authenticity of visual art, especially when an artwork is thought to be inauthentic (Huang et al., 2011). The frontal pole is also implicated to be engaged when judging a personally considered beautiful picture as joyful (Ishizu and Zeki, 2017). Both findings are compatible with the medial frontal pole's functional profile in the Social Brain Atlas, which includes strong likelihoods for involvement in emotion, happiness, social cognition and working memory. (Alcalá-López et al., 2017). The implied involvement in authenticity evaluations is more difficult to relate specifically to the functional profile of the medial frontal pole, but its connections to multiple other areas in the Social Brain Atlas with strong links to emotion, working memory and reward might further elucidate its suggested role in critical social and cultural value judgements.

Figures 16 – 18 show the visual imagination functions that are associated with core nodes in the Social Brain Atlas.

Figure 16

# SOCIAL BRAIN ATLAS

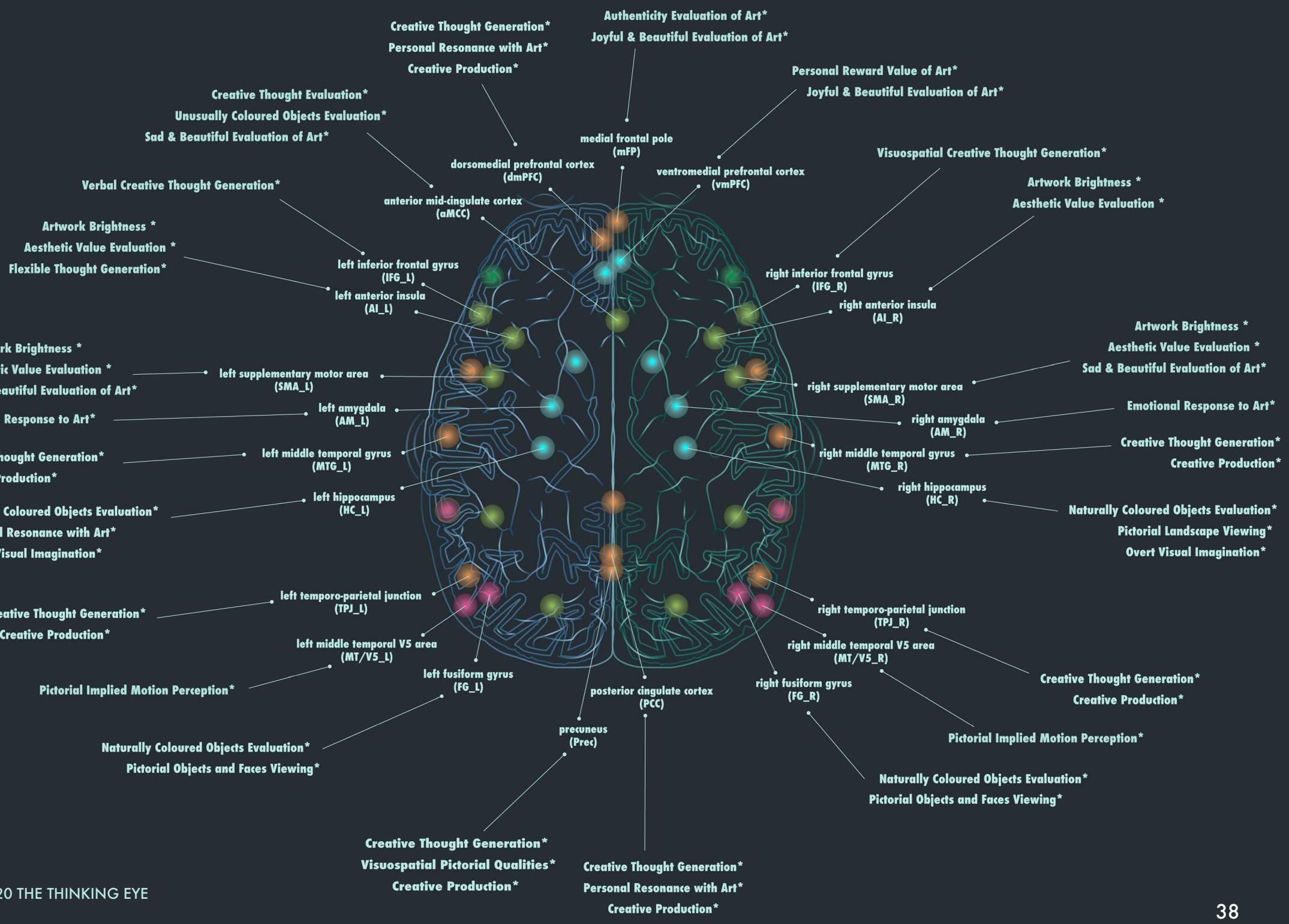
## VISUAL IMAGINATION PROFILES

### AXIAL PLANE

x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL PROFILES
*Indeterminate likelihood




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Figure 17

# SOCIAL BRAIN ATLAS

## VISUAL IMAGINATION PROFILES

LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL PROFILES
*Indeterminate likelihood




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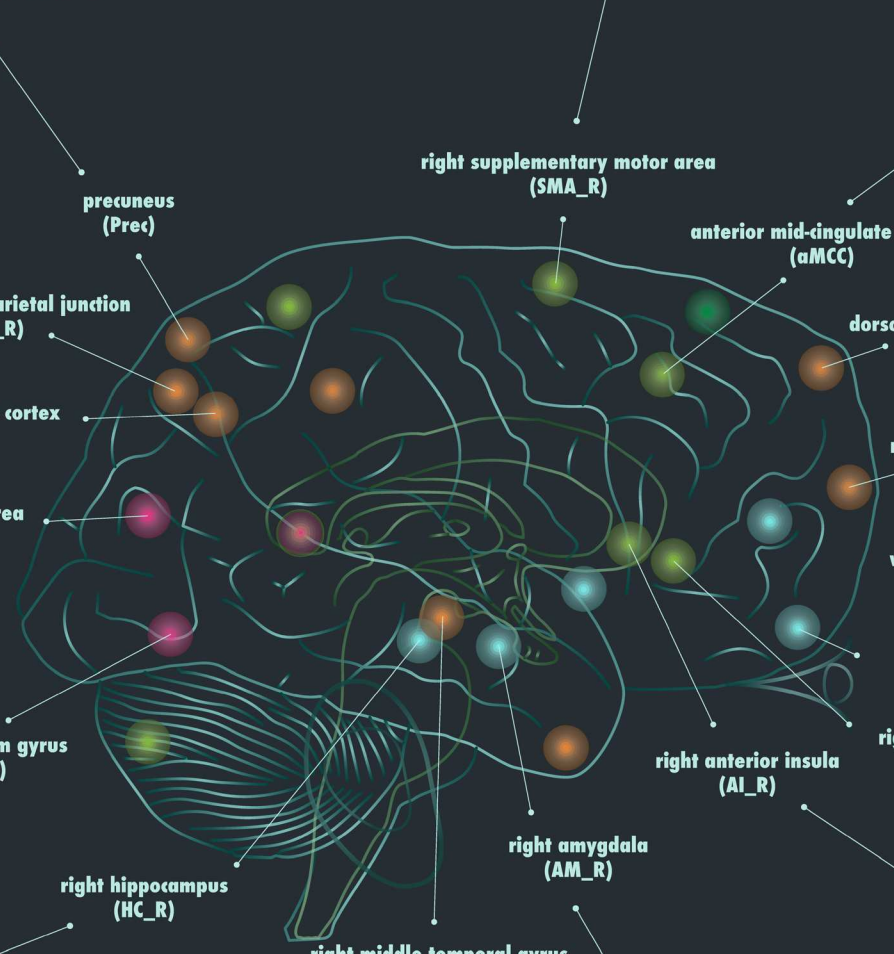
Figure 18

# SOCIAL BRAIN ATLAS
## VISUAL IMAGINATION PROFILES

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood




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## 2.3 DEMENTIA IN THE SOCIAL BRAIN

### Introduction

It is thought that pathogenic proteins that cause dementia might spread preferentially through the brain via specific intrinsic large-scale neural networks (Brettschneider et al., 2015; Goedert, 2015; Warren et al., 2012, 2013; Seeley et al., 2009; Zhou et al., 2010, 2012). This proposed mechanism has been named the nexopathy theory of neurodegenerative diseases (Warren, 2013). In support of this theory, it has been demonstrated that differential pathways of dementia syndromes can be successfully predicted from intrinsic network connectivity patterns in healthy control participants (Seeley et al., 2009; Zhou et al., 2012). Marshall et al. (2019) found disease-specific functional connectivity patterns in people with various forms of frontotemporal dementias in response to dynamic facial emotions, which aligned with core hubs in the Social Brain Atlas in brain regions that are known to be affected in these dementia syndromes.

In this study I mapped various dementia syndromes onto the Social Brain Atlas, based on a qualitative analysis of the neuroimaging literature on the pathology patterns of dementia syndromes, with a focus on functional connectivity.
In the Social Brain Atlas the dementia syndromes are shown in white overlay patterns and each disease type has been given a unique symbol. The connectivity patterns indicate the likely pathways of the disease pathogens. An increased likelihood of hypo-metabolism in a social brain hub that is likely to be affected by that type of dementia is represented by a larger symbol. The social brain profiles for each dementia syndrome show the primary networks that are affected, the brain areas that are involved early on and the behavioural functions those brain areas are involved in.

### Functional profiles of dementia syndromes

I complemented the behavioural functions that Alcalá-López et al. (2017) computed for the core 36 social brain areas with the memory domain nuances that I addressed in the introduction of the Social Brain Atlas and I also added the visual imagination functions based on my qualitative analysis of the neuroimaging literature. The resulting functional profiles contain behaviours that have well-known connections with dementias, but also cover functions that are less commonly linked to specific brain networks and hubs that are affected in dementias, such as objects/scenes imagination and artistic production for instance.
These behavioural profiles are at this stage mainly of value in the development of research hypotheses, but can hopefully eventually also be of aid in identifying and differentiating dementia syndromes and offer guidelines for therapeutic interventions aimed at stimulating these functions to counterbalance the patterns of reduced brain metabolism.

The behavioural functions are organised in two sections: the first part summarises the functional profiles associated with the social brain areas from the social brain connectome by Alcalá-López et al. (2017), the second part gives an overview of visual imagination functions based on my literature review described in the previous section.

The consensus phenotype descriptions of the frontotemporal dementias include the word ‘variant’, for example ‘behavioural variant Frontotemporal Dementia’. For the sake of brevity, I have left the word ‘variant’ out of the frontotemporal dementia phenotype descriptions in the following subsections.

The different dementia profiles in the Social Brain Atlas are shown in Figures 19 – 39.

### 2.3.1 TYPICAL ALZHEIMER'S DISEASE

Typical Alzheimer's Disease causes increasing problems with episodic memory and word finding, as well as difficulties to orientate oneself in space and time. Caused by a combination of accumulating amyloid plaques and neurofibrillary tangles throughout the brain, Typical Alzheimer's Disease is the most prevalent dementia.

Mapped onto the Social Brain Atlas, Alzheimer's Disease shows a pattern of reduced metabolism in bilateral hubs throughout the Construction Network, which anatomically corresponds with the Default Mode Network. This reduced metabolism is already present in pre-clinical stages. Early in the disease process, decreased functional connectivity can be detected between medial posterior regions (the precuneus and the posterior cingulate cortex) and the bilateral hippocampus, which is part of the Animation Network (Buckner et al., 2005; Caroli et al., 2012; Greicus et al., 2004; Minoshima et al., 1997; Ossenkoppele et al., 2015; Sheline and Raichle, 2013).
A stronger involvement of left lateral posterior hubs of the Construction Network is thought to relate to the severity of semantic language problems, which has been reported to affect women with Alzheimer's Disease more than men (Harasty et al., 1999).

Figure 19: Typical Alzheimer's Disease Axial
Figure 20: Typical Alzheimer's Disease Left
Figure 21: Typical Alzheimer's Disease Right

PRIMARY SOCIAL BRAIN NETWORKS
- Construction
- Animation

EARLY AFFECTED AREAS
- Bilateral hippocampus
- Posterior cingulate cortex
- Precuneus

ASSOCIATED BEHAVIOURAL FUNCTIONS
*Social brain profile*
- Working memory
- Emotion (especially sadness)
- Reward
- Language semantics and speech
- Overt word generation
- Social cognition and face monitoring
- Imagined objects/scenes and mental rotation
- Space representation
- Music comprehension/production

EARLY AFFECTED MEMORY DOMAINS
- Episodic memory
- Semantic memory

*Visual imagination profile*
- Creative thought generation and production
- Naturally coloured objects evaluation
- Overt visual imagination
- Personal resonance with art
- Visuospatial pictorial qualities

Figure 19

# SOCIAL BRAIN ATLAS

## TYPICAL ALZHEIMER'S DISEASE PROFILE

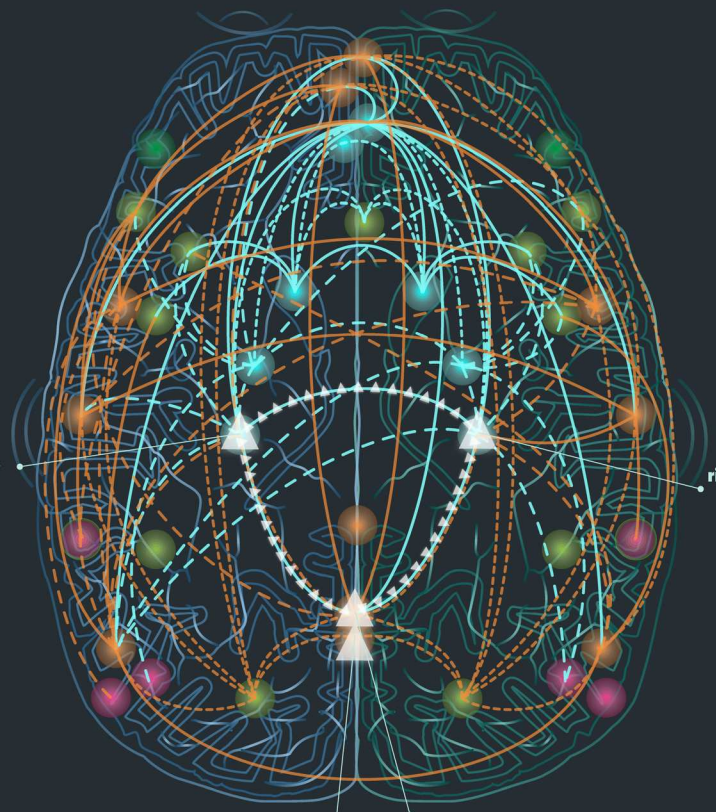
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease ▲
Semantic Primary Progressive Aphasia ▌
Nonfluent Primary Progressive Aphasia ✖
Logopenic Promary Progressive Aphasia ◤
Behavioural Frontotemporal Dementia ■
Dementia with Lewy Bodies ★
Posterior Cortical Atrophy ⮝



left hippocampus (HC_L)

Emotion
Reward Face Monitoring Memory Working Language Semantics
Finger Tapping/Button Press Cognition Word Generation (Overt) Language Speech
Naturally Coloured Objects Evaluation* Overt Visual Imagination*
Personal Resonance with Art*

right hippocampus (HC_R)

Word Generation (Overt) Language Semantics Cognition Emotion
Face Monitoring Imagined Objects/Scenes Mental Rotation
Memory Working
Naturally Coloured Objects Evaluation*
Pictorial Landscape Viewing*
Overt Visual Imagination*

posterior cingulate cortex (PCC)

precuneus (Prec)

Emotion Reward Memory Working
Sadness Social Cognition Cognition
Language Semantics Language Speech
Music Comprehension/Production
Action Execution Space Attention
Creative Thought Generation*
Visuospatial Pictorial Qualities*
Creative Production*

Memory Working
Emotion Reward
Face Monitoring Cognition
Language Semantics Language Speech
Music Comprehension/Production
Creative Thought Generation*
Personal Resonance with Art*
Creative Production*

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Figure 20

# SOCIAL BRAIN ATLAS

## TYPICAL ALZHEIMER'S DISEASE PROFILE

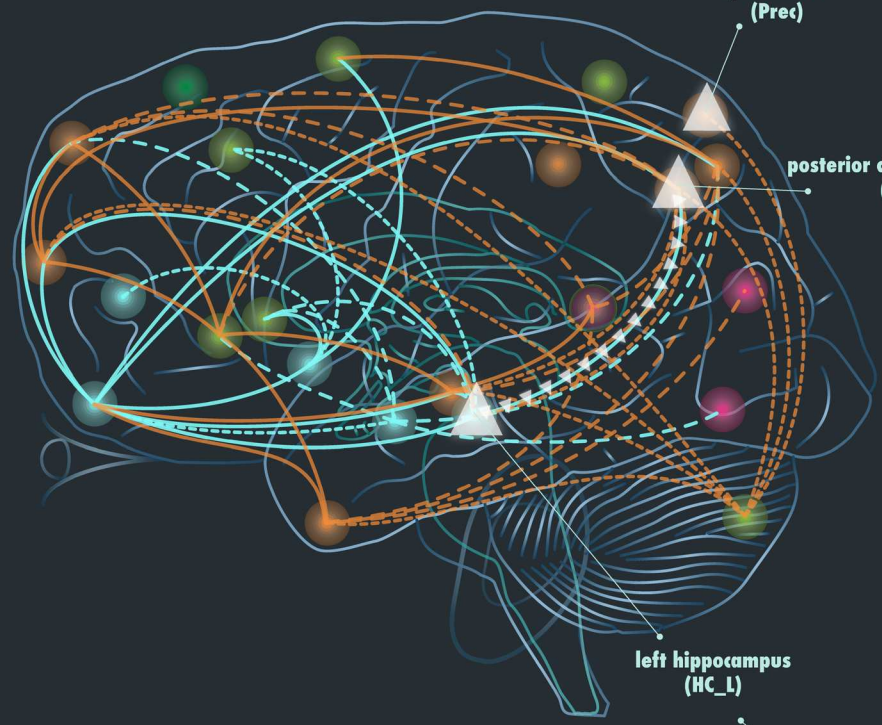
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

LEFT HEMISPERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




**Reward**
**Emotion** **Memory Working**
**Sadness** **Social Cognition** **Cognition**
**Attention** **Language Semantics** **Language Speech**
**Space** **Action Execution** **Music Comprehension/Production**
**Creative Thought Generation***
**Visuospatial Pictorial Qualities***
**Creative Production***

**Memory Working**
**Emotion** **Reward** **Face Monitoring** **Cognition**
**Language Semantics** **Language Speech**
**Music Comprehension/Production**
**Creative Thought Generation***
**Personal Resonance with Art***
**Creative Production***

**Emotion**
**Reward** **Face Monitoring**
**Memory Working** **Language Semantics**
**Word Generation (Overt)** **Language Speech**
**Cognition** **Finger Tapping/Button Press**
**Naturally Coloured Objects Evaluation***
**Personal Resonance with Art***
**Overt Visual Imagination***

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Figure 21

# SOCIAL BRAIN ATLAS

## TYPICAL ALZHEIMER'S DISEASE PROFILE

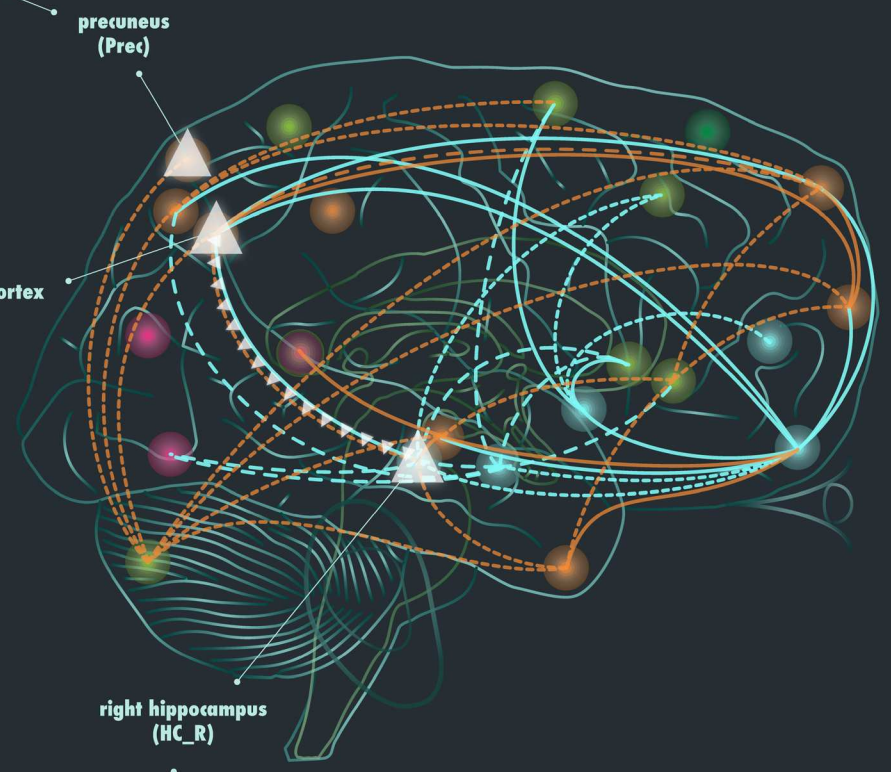
RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




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### 2.3.2 SEMANTIC PRIMARY PROGRESSIVE APHASIA

Semantic Primary Progressive Aphasia is characterised by difficulties with word finding and grasping the meaning of words and objects that were previously known, while initially maintaining the ability to speak fluently (Mesulam et al., 2014; Neary et al., 1998; Seeley et al., 2014). Semantic Primary Progressive Aphasia is caused by TDP 43 protein aggravates in most cases, but it can also have different causes such as underlying Alzheimer's pathology and occasionally microtubule-associated protein tau (Grossman, 2013).
The disease is associated with left-dominant bilateral atrophy and decreased functional connectivity in the left fusiform gyrus, amygdala and temporal pole, extending to the orbitofrontal cortex (Mesulam et al., 2014; Rohrer et al., 2011; Seeley et al., 2009). Atrophy levels in the right temporal pole is associated with the extend of changes in social behaviour (Landin-Romero et al., 2016).
If the right temporal pole is affected first, the disease presents itself as right-variant Behavioural Frontotemporal Dementia. In this phenotype of Behavioural Frontotemporal Dementia prominent changes in behaviour and personality occur early on in the disease. Using magneto-encephalographic (MEG) imaging, reduced synchronisation in the alpha and beta frequencies has also been reported in the left temporoparietal junction in Semantic Primary Progressive Aphasia (Ranasinghe et al., 2017).

Mapped onto the Social Brain Atlas, Semantic Primary Progressive Aphasia affects core hubs that are part of the Perception Network, the Animation Network and the Construction Network, indicating that both bottom-up and top-down processes are affected early on in the disease.

Figure 22: Semantic Primary Progressive Aphasia Axial
Figure 23: Semantic Primary Progressive Aphasia Left
Figure 24: Semantic Primary Progressive Aphasia Right

PRIMARY SOCIAL BRAIN NETWORKS
- Construction
- Animation
- Perception

EARLY AFFECTED AREAS
- Left fusiform gyrus
- Left amygdala
- Left temporal pole
- Ventromedial prefrontal cortex

EARLY AFFECTED MEMORY DOMAINS
- Semantic memory

ASSOCIATED BEHAVIOURAL FUNCTIONS
*Social brain profile*
- Emotion (especially happiness)
- Reward
- Working memory
- Language semantics
- Shape vision
- Cognition and reasoning
- Action execution and observation
- Imagined objects/scenes and mental rotation
- Explicit memory and cued explicit recognition
- Audition and passive listening
- Visuospatial attention and passive viewing
- Music comprehension/production
- Social cognition and face monitoring

*Visual imagination profile*
- Emotional response to art
- Joyful and beautiful evaluation of art
- Naturally coloured objects evaluation
- Personal reward value of art
- Pictorial faces and objects viewing

Figure 22

# SOCIAL BRAIN ATLAS

## SEMANTIC PRIMARY PROGRESSIVE APHASIA

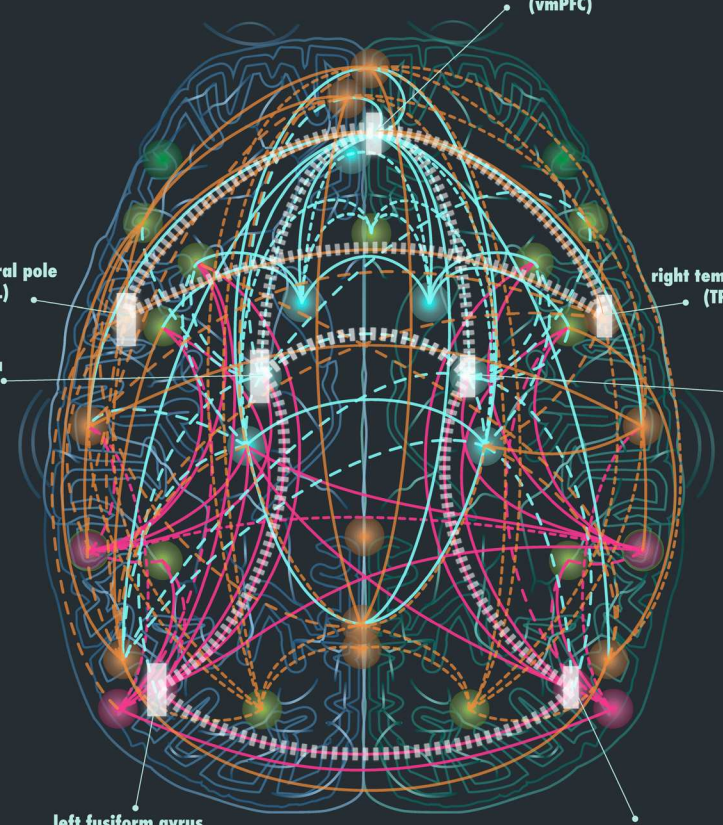
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




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Figure 23

# SOCIAL BRAIN ATLAS

## SEMANTIC PRIMARY PROGRESSIVE APHASIA PROFILE

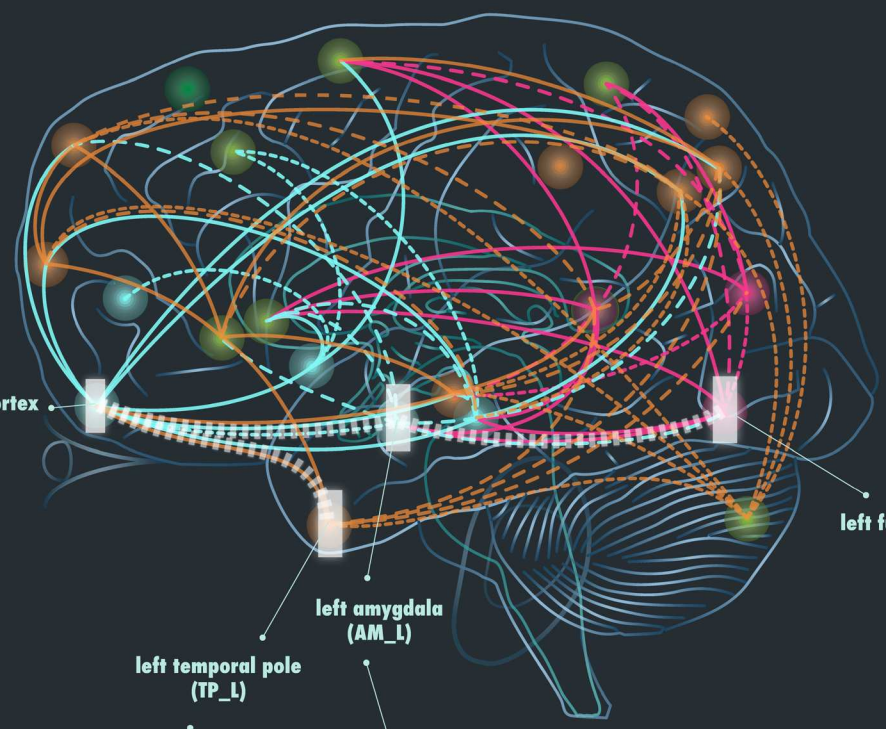
LEFT HEMISPERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



**Emotion**
**Memory Working**
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Passive Listening Language Semantics Action Execution
**Personal Reward Value of Art***
**Beautiful/Joyful Evaluation of Art***

ventromedial prefrontal cortex (vmPFC)

left fusiform gyrus (FG_L)

Vision Shape Language Semantics
Attention Passive Viewing Language Speech
Face Monitoring Passive Listening Audition
Memory Explicit Emotion Reward Cognition
Memory Working Finger Tapping/Button Press
**Naturally Coloured Objects Evaluation***
**Pictorial Objects and Faces Viewing***

left amygdala (AM_L)

left temporal pole (TP_L)

**Emotion**
Reward Audition Cognition
Happiness Language Semantics
Action Execution Action Observation Reasoning
Music Comprehension/Production Attention
Mental Rotation

**Memory Working**
Memory Explicit Face Monitoring
Language Semantics Language Speech
Action Execution Emotion Reward
Finger Tapping/Button Press
Cued Explicit Recognition
**Emotional response to art***

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Figure 24

# SOCIAL BRAIN ATLAS

## SEMANTIC PRIMARY PROGRESSIVE APHASIA PROFILE

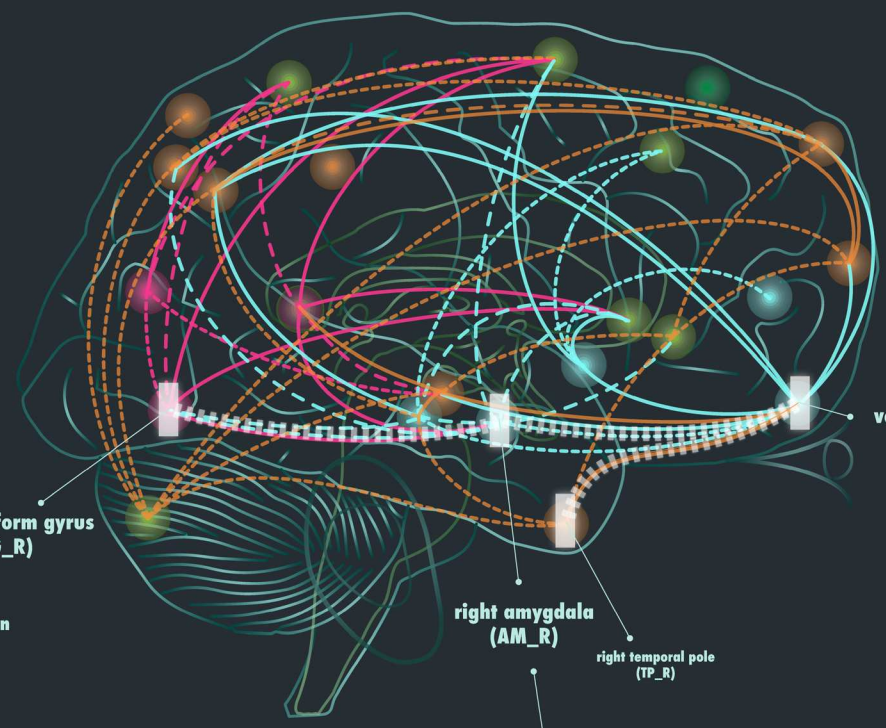
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

RIGHT HEMISPHERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



right fusiform gyrus (FG_R)

**Emotion**
Visuospatial Attention Vision Shape
Audition Language Semantics Reward
Cognition Memory Working Memory Explicit Action Execution
**Naturally Coloured Objects Evaluation***
**Pictorial Objects and Faces Viewing***

ventromedial prefrontal cortex (vmPFC)

**Emotion**
Memory Working
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Action Execution Passive Listening Language Semantics
**Personal Reward Value of Art***
**Beautiful/Joyful Evaluation of Art***

right amygdala (AM_R)

right temporal pole (TP_R)

**Emotion**
Language Speech Reward
Memory Working Face Monitoring
Cognition Action Execution Audition
Finger Tapping/Button Press
**Emotional response to art***

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### 2.3.3 NONFLUENT PRIMARY PROGRESSIVE APHASIA

In Nonfluent Primary Progressive Aphasia increasing difficulties with speech production (fluency) and grammar are initially most prominent, while speech comprehension remains relatively intact (Mesulam et al., 2014; Neary et al., 1998; Seeley et al., 2014). Underlying pathogenic proteins include microtubule-associated protein tau (MAPT), Alzheimer's pathology and TDP-43 (Grossman, 2013).
Nonfluent Primary Progressive Aphasia is associated with decreased functional connectivity in frontal hubs in the Interaction Network with a left hemispheric dominance.
The inferior frontal cortex has been identified as one of the earliest affected areas, extending to the anterior insula, the anterior mid-cingulate cortex, the supplementary motor area and the supramarginal gyrus (Mesulam et al., 2014; Mandelli et al., 2016; Ranasinghe et al., 2017; Seeley et al., 2009).

Mapped onto the Social Brain Atlas, Nonfluent Primary Progressive Aphasia predominantly affects frontal hubs of the Interaction Network, with a more lateral pattern compared to Behavioural Frontotemporal Dementia. The inferior frontal gyrus is connected to the middle temporal lobe and temporal pole of the Construction Network. Given these functional connectivity patterns, it appears to be likely that especially top-down cognitive processes are affected early on in Nonfluent Primary Progressive Aphasia.

Figure 25: Nonfluent Primary Progressive Aphasia Axial
Figure 26: Nonfluent Primary Progressive Aphasia Left
Figure 27: Nonfluent Primary Progressive Aphasia Right

PRIMARY SOCIAL BRAIN NETWORK
- Interaction

EARLY AFFECTED BRAIN AREAS
- Left inferior frontal cortex
- Left anterior insula
- Anterior mid-cingulate cortex
- Left supplementary motor area
- Left supramarginal gyrus

EARLY AFFECTED MEMORY DOMAINS
- Implicit memory
- Semantic memory

ASSOCIATED BEHAVIOURAL FUNCTIONS
*Social brain profile*
- Emotion/induction (especially anxiety)
- Reward
- Language semantics and speech
- Action imagination, execution, and inhibition
- Working and explicit memory
- Cognition and attention
- Audition and passive listening
- Pitch discrimination
- Shape vision
- Face monitoring

*Visual imagination profile*
- Aesthetic value evaluation
- Artwork brightness evaluation
- Creative thought evaluation
- Flexible thought generation
- Sad and beautiful evaluation of art
- Unusually coloured objects evaluation
- Verbal and visuospatial creative thought generation

Figure 25

# SOCIAL BRAIN ATLAS

## NONFLUENT PRIMARY PROGRESSIVE APHASIA PROFILE

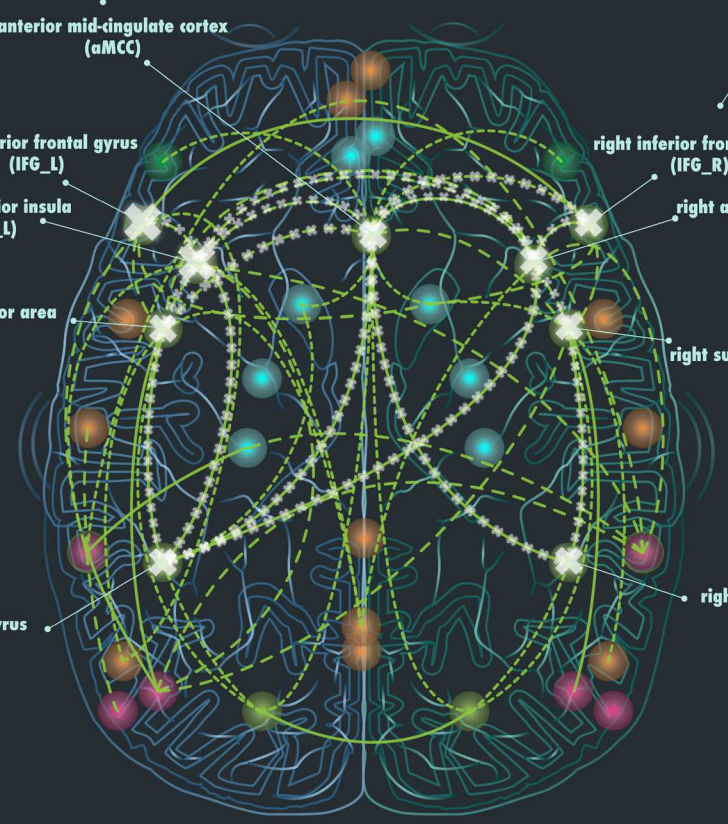
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




Creative Thought Evaluation*
Emotion Reward Cognition Sad & Beautiful Evaluation of Art*
Anxiety Attention Memory Working Unusually Coloured Objects Evaluation*
Language Semantics Language Speech

Emotion
Memory Explicit Language Semantics
Memory Working Language Speech Passive Listening
Face Monitoring Reward Attention Audition
Vision Shape Finger Tapping/Button Press
Verbal Creative Thought Generation*

Cognition Language Semantics
Emotion Induction Emotion Reward Action Execution
Action Inhibition Reasoning Audition Colour Vision
Finger Tapping/Button Press Artwork Brightness *
Flexible Thought Generation*
Aesthetic Value Evaluation *

Memory Working Action Execution
Memory Explicit Cognition Finger Tapping/Button Press
Vision Shape Face Monitoring Attention Reward Emotion
Audition Passive Listening Language Semantics Colour Vision
Artwork Brightness * Aesthetic Value Evaluation *
Sad & Beautiful Evaluation of Art*

Audition Language Semantics
Memory Explicit Memory Working Action Inhibition
Vision Emotion Reward Colour Vision

Emotion
Attention Face Monitoring Reward
Audition Language Speech Language Semantics
Visuospatial Creative Thought Generation* Cognition

Action Execution
Attention Reward Memory Working
Face Monitoring Emotion Memory Explicit
Audition Passive Listening Cognition
Artwork Brightness * Finger Tapping/Button Press
Aesthetic Value Evaluation *

Emotion
Attention Reward Cognition
Memory Explicit Memory Working
Passive Listening Face Monitoring Action Execution
Aesthetic Value Evaluation * Artwork Brightness *
Sad & Beautiful Evaluation of Art*

Language Semantics Memory Working Emotion
Word Generation (Covert) Language Speech Emotion Induction
Pitch Discrimination Attention Cognition Passive Viewing Reward
Action Imagination Action Execution Vision Shape
Finger Tapping/Button Press

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Figure 26

# SOCIAL BRAIN ATLAS

## NONFLUENT PRIMARY PROGRESSIVE APHASIA PROFILE

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

LEFT HEMISPERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy

Memory Working Action Execution
Vision Shape Face Monitoring Attention Reward Emotion
Memory Explicit Cognition Finger Tapping/Button Press Colour Vision
Audition Passive Listening Language Semantics
**Aesthetic Value Evaluation * Artwork Brightness ***
**Sad & Beautiful Evaluation of Art***

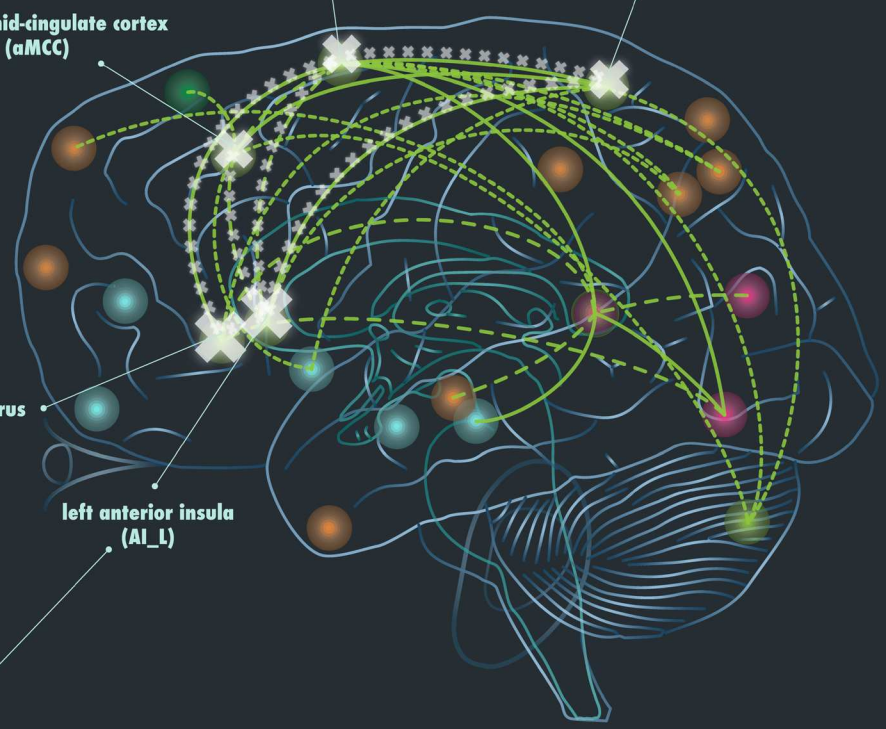
Audition Language Semantics
Vision Emotion Reward Action Inhibition
Colour Vision Memory Explicit Memory Working

Emotion Reward Cognition
Anxiety Attention Memory Working
Language Semantics Language Speech
**Creative Thought Evaluation***
**Sad & Beautiful Evaluation of Art***
**Unusually Coloured Objects Evaluation***

left supplementary motor area (SMA_L)

left supramarginal gyrus (SMG_L)

anterior mid-cingulate cortex (aMCC)



Emotion
Memory Explicit Language Semantics
Memory Working Language Speech Passive Listening
Face Monitoring Reward Attention Audition
Vision Shape Finger Tapping/Button Press
**Verbal Creative Thought Generation***

left inferior frontal gyrus (IFG_L)

left anterior insula (AI_L)

Cognition Language Semantics
Emotion Induction Emotion Reward Action Execution
Action Inhibition Reasoning Audition Colour Vision Finger Tapping/Button Press
**Artwork Brightness * Aesthetic Value Evaluation ***
**Flexible Thought Generation***

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Figure 27

# SOCIAL BRAIN ATLAS

## NONFLUENT PRIMARY PROGRESSIVE APHASIA PROFILE

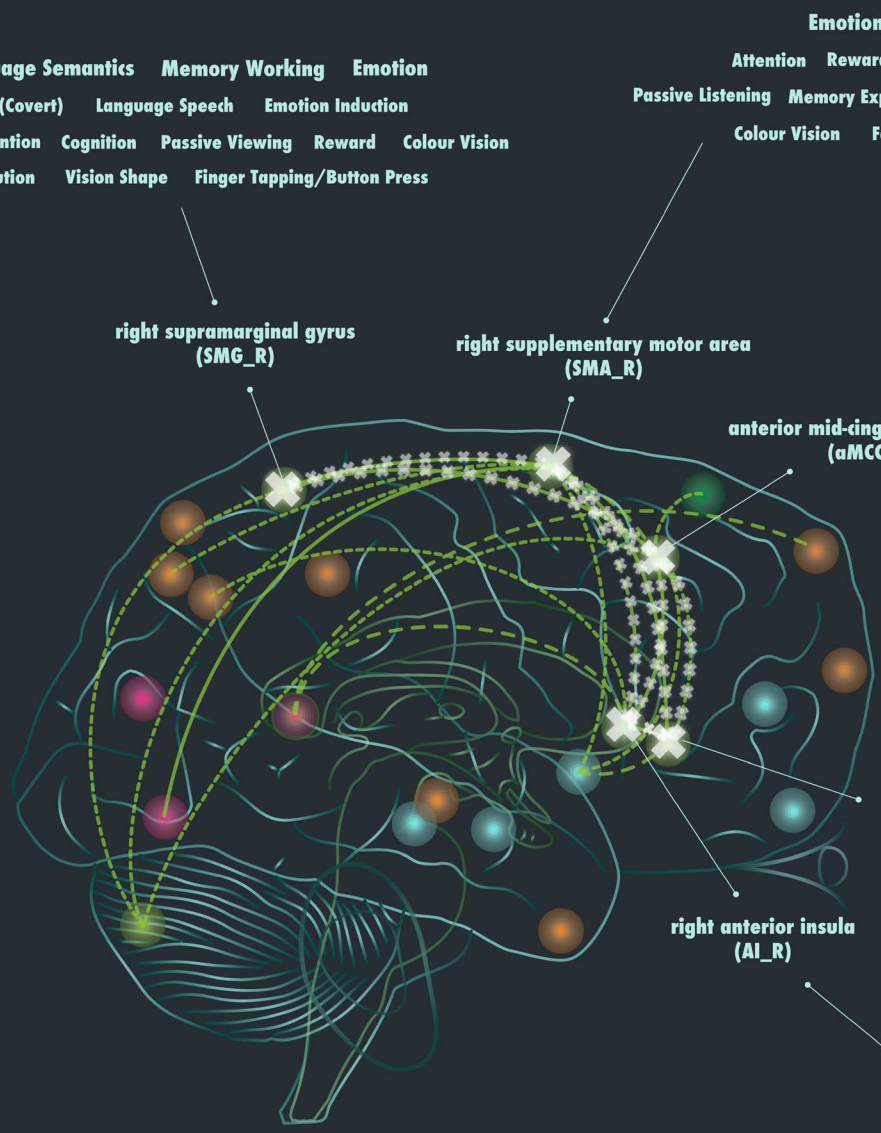
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent
Resting State
Task State

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

RIGHT HEMISPHERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




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### 2.3.4 LOGOPENIC PRIMARY PROGRESSIVE APHASIA

Logopenic Primary Progressive Aphasia is characterised by word finding difficulties that lead to intermittent loss of verbal fluency, with relatively preserved speech comprehension, production and grammar (Gorno-Tempini et al., Mesulam et al., 2014; Neary et al., 1998; Seeley et al., 2014).
Logopenic Primary Progressive Aphasia is most likely caused by Alzheimer's Disease pathology and associated with decreased functional connectivity in language areas in the posterior temporal, parietal and occipital brain areas (Mesulam et al., 2014; Ranasinghe et al., 2017; Zhou et al., 2017).

Mapped onto the Social Brain Atlas, Logopenic Primary Progressive Aphasia affects the bilateral posterior superior temporal sulcus, extending anteriorly to the middle temporal lobe and posteriorly to the temporoparietal junction with a left hemispheric dominance. These areas are predominantly part of the Construction Network, which is congruent with an underlying Alzheimer's Disease pathology and indicates a most likely disruption of higher order processing, but involvement of the posterior superior temporal sulcus means there could be a disruption of bottom-up processes as well.

Figure 28: Logopenic Primary Progressive Aphasia Axial
Figure 29: Logopenic Primary Progressive Aphasia Left
Figure 30: Logopenic Primary Progressive Aphasia Right

PRIMARY SOCIAL BRAIN NETWORKS
- Construction
- Interaction
- Perception

EARLY AFFECTED AREAS
- Left posterior superior temporal sulcus
- Left middle temporal gyrus
- Left temporoparietal junction

EARLY AFFECTED MEMORY DOMAINS
- Semantic memory
- Episodic memory

ASSOCIATED BEHAVIOURAL FUNCTIONS
*Social brain profile*
- Working memory
- Language semantics, orthography and speech
- Overt and covert word generation
- Emotion
- Reward
- Cognition and social cognition
- Visuospatial attention
- Visual object identification
- Motion vision
- Music comprehension/production
- Space representation

*Visual imagination profile*
- Creative production
- Creative thought generation

Figure 28

# SOCIAL BRAIN ATLAS

## LOGOPENIC PRIMARY PROGRESSIVE APHASIA PROFILE

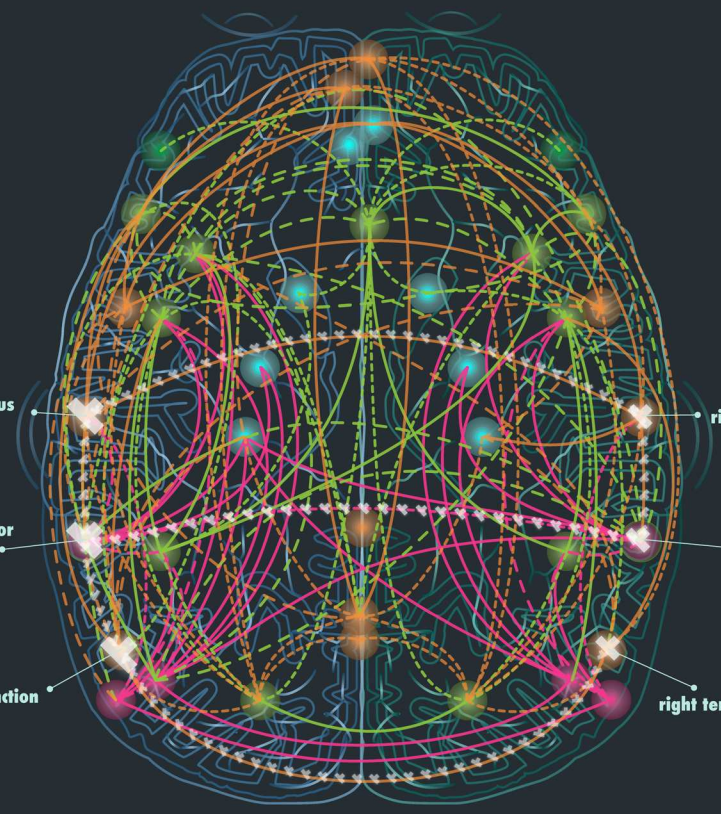
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



**left middle temporal gyrus (MTG_L)**

Emotion Language Semantics
Language Speech Language Orthography Word Generation (Covert)
Memory Working Social Cognition Cognition Action Execution
Music Comprehension/Production Mental Rotation Vision Shape
Creative Thought Generation* Creative Production*

**left posterior superior temporal sulcus (pSTS_L)**

Memory Working
Language Semantics
Passive Listening Language Speech Word Generation (Covert)
Emotion Reward Music Comprehension/Production

**left temporo-parietal junction (TPJ_L)**

Reward Emotion Cognition
Language Semantics Memory Working
Language Speech Memory Explicit Music Comprehension/Production
Visual Object Identification Vision Motion
Creative Thought Generation*
Creative Production*

**right middle temporal gyrus (MTG_R)**

Memory Working
Language Semantics Word Generation (Overt)
Emotion Music Comprehension/Production
Language Speech Word Generation (Covert) Language
Happiness Social Cognition Visuospatial Attention Vision
Reward Action Inhibition Cognition
Creative Thought Generation*
Creative Production*

**right posterior superior temporal sulcus (pSTS_R)**

Language Semantics Language Speech Memory Working Cognition
Word Generation (Covert) Reward Emotion Attention
Music Comprehension/Production

**right temporo-parietal junction (TPJ_R)**

Emotion
Reward Social Cognition Cognition
Action Observation Action Execution Memory Working
Space Passive Listening Language Semantics
Creative Thought Generation*
Creative Production*

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Figure 29

# SOCIAL BRAIN ATLAS

## LOGOPENIC PRIMARY PROGRESSIVE APHASIA PROFILE

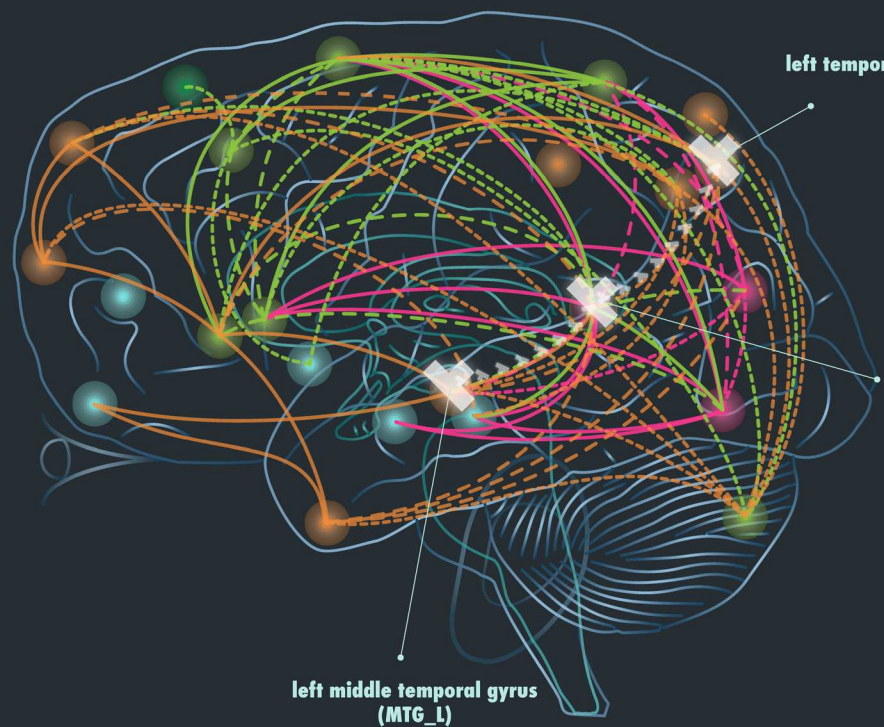
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

LEFT HEMISPERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



**left temporo-parietal junction (TPJ_L)**

Reward Emotion Cognition
Language Semantics Memory Working
Language Speech Memory Explicit
Music Comprehension/Production
Visual Object Identification
Vision Motion
Creative Production*
Creative Thought Generation*

**left posterior superior temporal sulcus (pSTS_L)**

Memory Working
Language Semantics
Passive Listening Language Speech
Emotion Reward Word Generation (Covert)
Music Comprehension/Production

**left middle temporal gyrus (MTG_L)**

Emotion Language Semantics
Language Speech Language Orthography
Memory Working Cognition Social Cognition
Action Execution Word Generation (Covert)
Music Comprehension/Production
Mental Rotation Vision Shape
Creative Thought Generation*
Creative Production*

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Figure 30

# SOCIAL BRAIN ATLAS

## LOGOPENIC PRIMARY PROGRESSIVE APHASIA PROFILE

RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

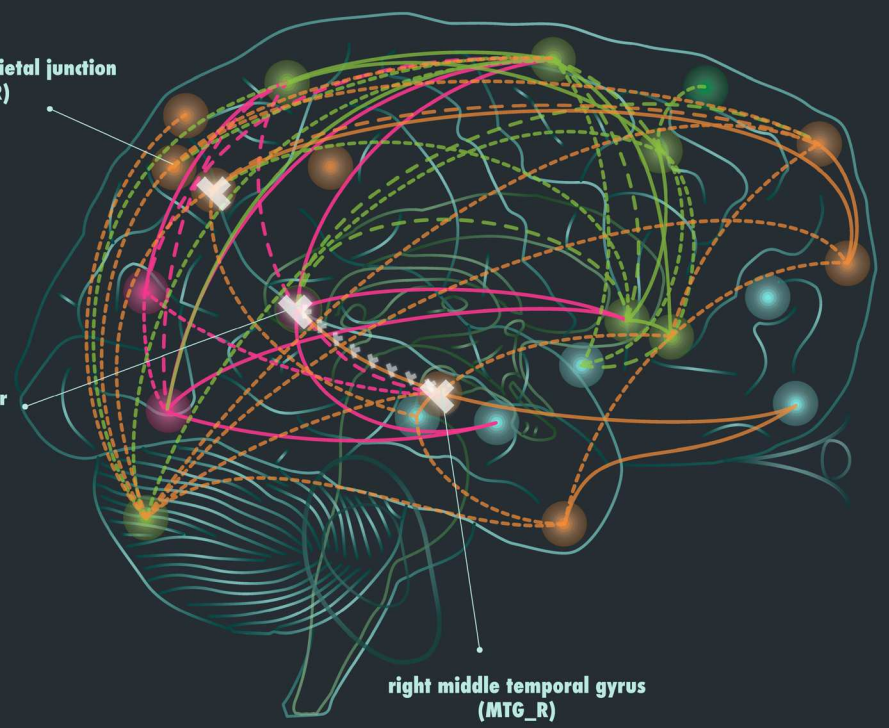
FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy

**Emotion**
**Reward** **Social Cognition**
**Action Observation** **Action Execution**
**Passive Listening** **Language Semantics**
**Memory Working** **Space** **Cognition**
**Creative Thought Generation***
**Creative Production***

**right temporo-parietal junction (TPJ_R)**



**Memory Working** **Cognition**
**Language Semantics** **Language Speech**
**Word Generation (Covert)** **Reward** **Emotion**
**Music Comprehension/Production** **Attention**

**right posterior superior temporal sulcus (pSTS_R)**

**right middle temporal gyrus (MTG_R)**

**Memory Working**
**Music Comprehension/Production**
**Word Generation (Overt)** **Emotion**
**Language Semantics** **Language** **Reward** **Happiness**
**Language Speech** **Word Generation (Covert)** **Cognition**
**Visuospatial Attention** **Vision** **Social Cognition** **Action Inhibition**
**Creative Thought Generation***
**Creative Production***

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### 2.3.5 BEHAVIOURAL FRONTOTEMPORAL DEMENTIA

Behavioural Frontotemporal Dementia is characterised by progressive changes in social behaviour and personality. Symptoms include disinhibition, apathy, loss of empathy, obsessive–compulsiveness and a change in appetite, often in the form of a sweet tooth. Some people with Behavioural Frontotemporal Dementia will also develop movement problems associated with motor neuron disease (Seeley et al., 2011; Rohrer, 2012). Behavioural Frontotemporal Dementia can be caused by various pathogenic proteins, including microtubule-associated protein tau (MAPT), progranulin (GRN) and C9ORF72. While different underlying pathogens can cause different atrophy patterns, anterior medial hubs that are part of the so-called Salience Network which corresponds with the Interaction Network in the Social Brain Atlas show a consistent pattern of deactivation in behavioural variants of Frontotemporal Dementia, with generally a right hemispheric dominance. Mapped onto the Social Brain Atlas, areas in the Interaction Network that are likely to be affected early on are the anterior insula, the dorsal anterior cingulate cortex (anterior mid-cingulate cortex in the Social Brain Atlas) and the (pre-) supplementary motor area, extending to the ventromedial prefrontal cortex and nucleus accumbens in the Animation Network as well as the medial frontal pole in the Construction Network (Moller et al., 2015; Rohrer et al., 2011; Schroeter et al., 2007; Seeley et al., 2007; 2009; Warren et al., 2012, 2013). Decreased functional connectivity in the anterior insula has also been demonstrated in pre-symptomatic carriers of familial forms of frontotemporal dementia (Dopper et al., 2014; Rohrer et al., 2015; Seeley et al., 2009). The early impairment of core hubs in the Interaction and Construction Networks points to changes in top-down processes, but the involvement of brain areas in the Animation Network indicates a disruption of bottom- up processes in social behaviour as well.

Figure 31: Behavioural Frontotemporal Dementia Axial
Figure 32: Behavioural Frontotemporal Dementia Left
Figure 33: Behavioural Frontotemporal Dementia Right

PRIMARY SOCIAL BRAIN NETWORKS

- Construction
- Interaction
- Animation

EARLY AFFECTED AREAS

- Bilateral anterior insula
- Anterior mid-cingulate cortex
- Bilateral supplementary motor area
- Ventromedial prefrontal cortex
- Bilateral nucleus accumbens
- Medial frontal pole

EARLY AFFECTED MEMORY DOMAINS

- Implicit memory
- Semantic memory

ASSOCIATED BEHAVIOURAL FUNCTIONS

*Social brain profile*

- Emotion/induction and reward
- Action execution and inhibition
- Working and explicit memory
- Attention, cognition and reasoning
- Social cognition and face monitoring
- Language semantics and covert word generation
- Imagined objects/scenes
- Music comprehension/production
- Shape vision

*Visual imagination profile*

- Artwork brightness and aesthetic value evaluation
- Creative thought evaluation
- Flexible thought generation
- Joyful and beautiful evaluation of art
- Personal reward value of art
- Sad and beautiful evaluation of art
- Unusually coloured objects evaluation

Figure 31

# SOCIAL BRAIN ATLAS

## BEHAVIOURAL FRONTOTEMPORAL DEMENTIA PROFILE

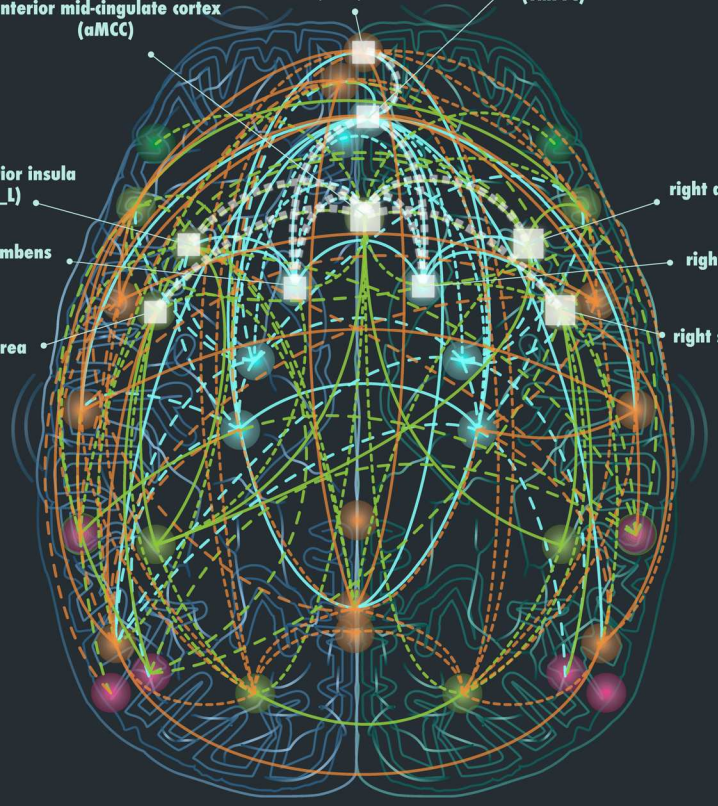
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



Emotion
Happiness Sadness Fear
Social Cognition Face Monitoring
Language Semantics Passive Listening
Word Generation (Covert) Memory Working
Music Comprehension/Production
Joyful & Beautiful Evaluation of Art*
Authenticity Evaluation of Art*

Creative Thought Evaluation*
Emotion Reward Cognition
Anxiety Attention Memory Working
Language Semantics Language Speech
Sad & Beautiful Evaluation of Art*
Unusually Coloured Objects Evaluation*

Emotion
Memory Working
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Action Execution Passive Listening Language Semantics
Personal Reward Value of Art*
Beautiful/Joyful Evaluation of Art*

Action Execution
Attention Reward Memory Working
Face Monitoring Emotion Memory Explicit
Audition Passive Listening Cognition
Artwork Brightness * Finger Tapping/Button Press
Aesthetic Value Evaluation *

Cognition Language Semantics
Emotion Induction Emotion Reward Action Execution
Action Inhibition Reasoning Audition Colour Vision
Finger Tapping/Button Press Artwork Brightness *
Flexible Thought Generation*
Aesthetic Value Evaluation *

Emotion Memory Working
Language Semantics

Memory Working Emotion
Cognition Emotion Induction Reward Language Syntax

Emotion
Attention Reward Cognition
Memory Explicit Memory Working
Passive Listening Face Monitoring Action Execution
Aesthetic Value Evaluation * Artwork Brightness *
Sad & Beautiful Evaluation of Art*

Memory Working Action Execution
Memory Explicit Cognition Finger Tapping/Button Press
Vision Shape Face Monitoring Attention Reward Emotion
Audition Passive Listening Language Semantics Colour Vision
Artwork Brightness * Aesthetic Value Evaluation *
Sad & Beautiful Evaluation of Art*

medial frontal pole (mFP)
ventromedial prefrontal cortex (vmPFC)
anterior mid-cingulate cortex (aMCC)
left anterior insula (AI_L)
right anterior insula (AI_R)
left nucleus accumbens (NAC_L)
right nucleus accumbens (NAC_R)
left supplementary motor area (SMA_L)
right supplementary motor area (SMA_R)

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Figure 32

# SOCIAL BRAIN ATLAS
## BEHAVIOURAL FRONTOTEMPORAL DEMENTIA PROFILE

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

LEFT HEMISPERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease ▲
Semantic Primary Progressive Aphasia ▌
Nonfluent Primary Progressive Aphasia ✖
Logopenic Promary Progressive Aphasia ✖
Behavioural Frontotemporal Dementia ■
Dementia with Lewy Bodies ★
Posterior Cortical Atrophy ⋀




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Figure 33

# SOCIAL BRAIN ATLAS

## BEHAVIOURAL FRONTOTEMPORAL DEMENTIA PROFILE

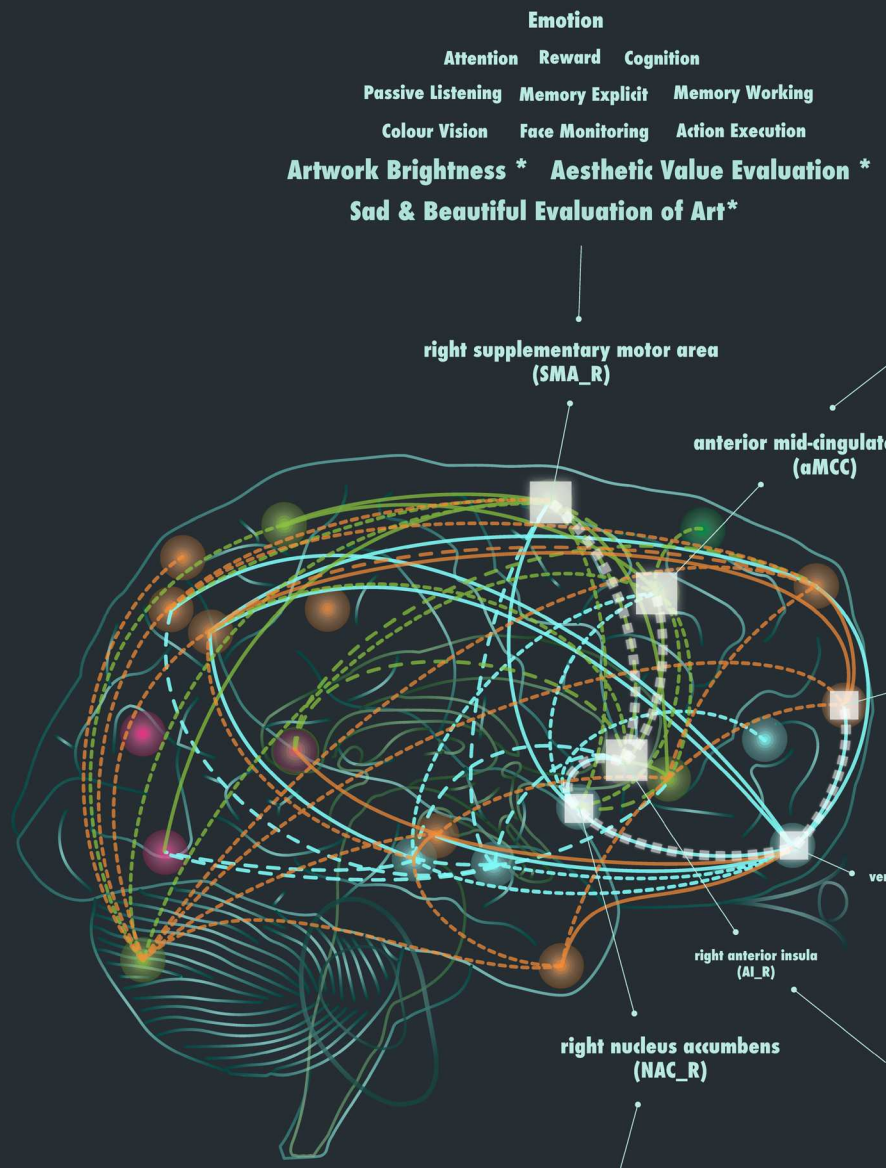
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

RIGHT HEMISPHERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



**Emotion**
**Attention Reward Cognition**
**Passive Listening Memory Explicit Memory Working**
**Colour Vision Face Monitoring Action Execution**
**Artwork Brightness * Aesthetic Value Evaluation ***
**Sad & Beautiful Evaluation of Art***

right supplementary motor area (SMA_R)

**Emotion Reward Cognition**
**Anxiety Attention Memory Working**
**Language Semantics Language Speech**
**Creative Thought Evaluation***
**Unusually Coloured Objects Evaluation***
**Sad & Beautiful Evaluation of Art***

anterior mid-cingulate cortex (aMCC)

**Emotion**
**Happiness Sadness Fear**
**Social Cognition Face Monitoring**
**Language Semantics Passive Listening**
**Word Generation (Covert) Memory Working**
**Music Comprehension/Production**

medial frontal pole (mFP)

**Joyful & Beautiful Evaluation of Art***
**Aesthetic Value Evaluation of Art***

**Emotion**
**Memory Working**
**Attention Reward Social Cognition**
**Imagined Objects/Scenes Reasoning Cognition**
**Action Execution Passive Listening Language Semantics**

ventromedial prefrontal cortex (vmPFC)

**Personal Reward Value of Art***
**Beautiful/Joyful Evaluation of Art***

right anterior insula (AI_R)

right nucleus accumbens (NAC_R)

**Action Execution**
**Attention Reward Memory Working**
**Face Monitoring Emotion Memory Explicit**
**Colour Vision Audition Passive Listening Cognition**
**Finger Tapping/Button Press**
**Artwork Brightness ***
**Aesthetic Value Evaluation ***

**Emotion Memory Working**
**Language Semantics**
**Aesthetic Value Evaluation ***
**Artwork Brightness ***

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### 2.3.6 DEMENTIA WITH LEWY BODIES

Dementia with Lewy Bodies presents with fluctuating changes in alertness and attention, movement problems, visual hallucinations, sleep disturbances, including vivid dreams, fainting, unsteadiness and falls as well as difficulties with detecting smells. This type of dementia is caused by an accumulation of Lewy body protein deposits in the brain. Using both resting-state and task-dependent functional imaging, hypo-connectivity of both the ventral and the dorsal attention stream have been found in Dementia with Lewy Bodies, including the bilateral occipital lobe, lingual gyrus, cuneus, precuneus, posterior cingulate cortex, inferior parietal lobe, left supramarginal gyrus, temporal lobes, striatum, and thalamus, with less hypometabolism in the posterior cingulate cortex compared to the precuneus, the so-called cingulate island sign (Walker et al., 2015; Whitwell et al., 2017). Involvement of the temporal pole and orbitofrontal areas, as well as a more asymmetrical atrophy patterns in Dementia with Lewy Bodies is thought to distinguish it from Posterior Cortical Atrophy (Whitwell et al., 2017).

Mapped onto the Social Brain Atlas, Dementia with Lewy Bodies affects core hubs within all four network levels, indicating a complex disease dynamic involving both bottom-up and top-down processes.

Figure 34: Dementia with Lewy Bodies Axial
Figure 35: Dementia with Lewy Bodies Left
Figure 36: Dementia with Lewy Bodies Right

PRIMARY SOCIAL BRAIN NETWORKS
- Construction
- Interaction
- Animation
- Perception

EARLY AFFECTED AREAS
- Posterior: Bilateral fusiform gyrus, bilateral MT/V5 area, bilateral posterior superior temporal sulcus, precuneus, posterior cingulate cortex, left supramarginal gyrus
- Anterior: bilateral temporal pole, bilateral amygdala, ventromedial prefrontal cortex

EARLY AFFECTED MEMORY DOMAINS
- Semantic memory

ASSOCIATED BEHAVIOURAL FUNCTIONS

*Social brain profile*
- Shape vision
- Language semantics, orthography and speech
- Emotion and reward
- Working and explicit memory
- Action observation and execution
- Social cognition and face monitoring
- Visuospatial attention and motion vision
- Visual object identification
- Space representation
- Music comprehension/production

*Visual imagination profile*
- Creative thought generation and production
- Emotional response to art
- Joyful and beautiful evaluation of art
- Naturally coloured objects evaluation
- Overt visual imagination and mental rotation
- Personal reward value of and resonance with art
- Pictorial objects, faces and landscapes viewing
- Pictorial visuospatial qualities and implied motion

Figure 34

# SOCIAL BRAIN ATLAS

## DEMENTIA WITH LEWY BODIES PROFILE

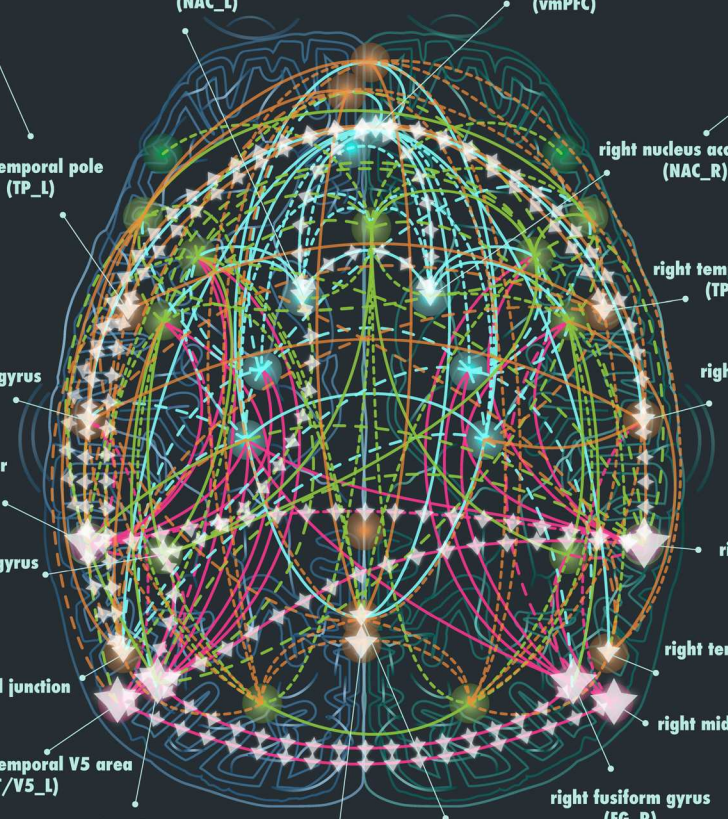
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



Memory Working Emotion
Cognition Emotion Induction Reward Language Syntax

Emotion
Reward Audition Cognition
Happiness Language Semantics Reasoning Attention
Action Execution Action Observation Mental Rotation
Music Comprehension/Production

Emotion
Memory Working
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Action Execution Passive Listening Language Semantics
Personal Reward Value of Art* Joyful & Beautiful Evaluation of Art*

left nucleus accumbens (NAC_L)

ventromedial prefrontal cortex (vmPFC)

Emotion Memory Working
Language Semantics

Reward
Reasoning Cognition Action Execution
Emotion Happiness Social Cognition
Emotion Induction Memory Working Face Monitoring
Attention Vision Motion Audition Language
Music Comprehension/Production

Emotion Language Semantics
Language Speech Language Orthography Word Generation (Covert)
Memory Working Social Cognition Cognition Action Execution
Music Comprehension/Production Mental Rotation Vision Shape
Creative Thought Generation* Creative Production*

left temporal pole (TP_L)

right nucleus accumbens (NAC_R)

right temporal pole (TP_R)

Creative Thought Generation* Memory Working
Language Semantics Word Generation (Covert)
Emotion Music Comprehension/Production
Language Speech Word Generation (Covert) Language
Happiness Social Cognition Visuospatial Attention Vision
Creative Production* Reward Action Inhibition Cognition

Memory Working
Language Semantics
Passive Listening Language Speech Word Generation (Covert)
Emotion Reward Music Comprehension/Production

left middle temporal gyrus (MTG_L)

right middle temporal gyrus (MTG_R)

Audition Language Semantics
Memory Explicit Memory Working Action Inhibition
Vision Emotion Reward Colour Vision

left posterior superior temporal sulcus (pSTS_L)

Language Semantics Language Speech Memory Working Cognition
Word Generation (Covert) Reward Emotion Attention
Music Comprehension/Production

left supramarginal gyrus (SMG_L)

right posterior superior temporal sulcus (pSTS_R)

Reward Emotion Cognition Creative Thought Generation*
Language Semantics Memory Working Creative Production*
Language Speech Memory Explicit Music Comprehension/Production
Visual Object Identification Vision Motion

left temporo-parietal junction (TPJ_L)

right temporo-parietal junction (TPJ_R)

Creative Thought Generation* Emotion
Creative Production* Reward Social Cognition Cognition
Action Observation Action Execution Memory Working
Space Passive Listening Language Semantics

Reward Language Speech Language Semantics
Emotion Emotion Induction Attention Passive Listening
Action Execution Memory Explicit Memory Working
Cognition Vision Shape Pictorial Implied Motion Perception*

left middle temporal V5 area (MT/V5_L)

right middle temporal V5 area (MT/V5_L)

Pictorial Implied Motion Perception* Language Semantics Emotion
Memory Working Language Speech Social Cognition Reward
Memory Explicit Face Monitoring Vision Motion
Music Comprehension/Production

left fusiform gyrus (FG_L)

right fusiform gyrus (FG_R)

Naturally Coloured Objects Evaluation*
Vision Shape Language Semantics Pictorial Objects and Faces Viewing*
Attention Passive Viewing Audition Passive Listening Cognition
Face Monitoring Emotion Reward Language Speech
Memory Explicit Memory Working
Finger Tapping/Button Press

precuneus (Prec)

posterior cingulate cortex (PCC)

Emotion
Vision Shape Visuospatial Attention
Memory Working Audition Language Semantics
Memory Explicit Reward Cognition Action Execution
Naturally Coloured Objects Evaluation*
Pictorial Objects and Faces Viewing*

Creative Thought Generation*
Emotion Reward Memory Working
Sadness Social Cognition Cognition Attention
Language Semantics Language Speech
Music Comprehension/Production
Action Execution Space

Memory Working
Emotion Reward
Face Monitoring Cognition
Language Semantics Language Speech
Music Comprehension/Production
Creative Thought Generation*
Personal Resonance with Art*
Creative Production*

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Figure 35

# SOCIAL BRAIN ATLAS
## DEMENTIA WITH LEWY BODIES PROFILE

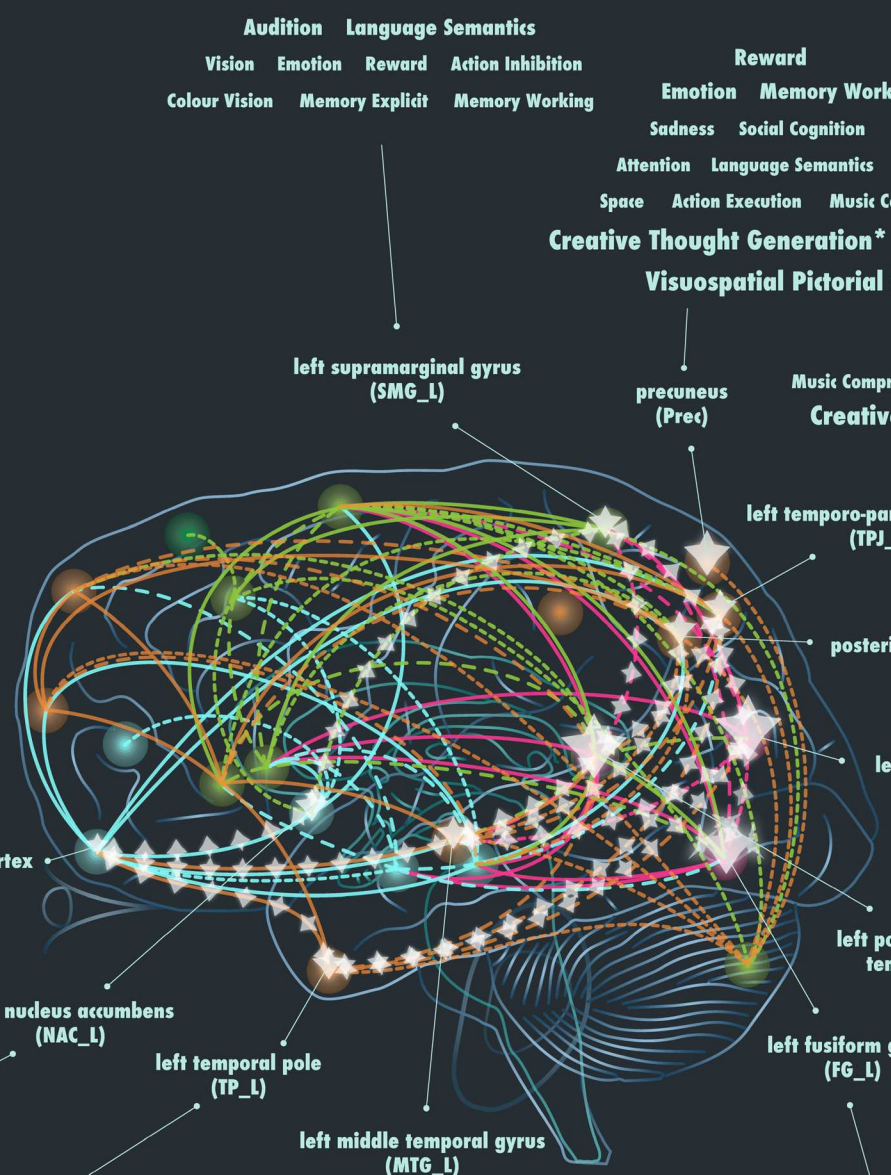
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

LEFT HEMISPERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



Audition Language Semantics
Vision Emotion Reward Action Inhibition
Colour Vision Memory Explicit Memory Working
left supramarginal gyrus (SMG_L)

Reward
Emotion Memory Working
Sadness Social Cognition Cognition
Attention Language Semantics Language Speech
Space Action Execution Music Comprehension/Production
Creative Thought Generation* Creative Production*
Visuospatial Pictorial Qualities*
precuneus (Prec)

Reward Emotion Cognition
Language Semantics Memory Working
Music Comprehension/Production Language Speech Memory Explicit
Creative Production* Vision Motion Visual Object Identification
Creative Thought Generation*
left temporo-parietal junction (TPJ_L)

Memory Working
Emotion Reward Face Monitoring Cognition
Language Semantics Language Speech
Music Comprehension/Production
Creative Thought Generation*
Personal Resonance with Art*
Creative Production*
posterior cingulate cortex (PCC)

left middle temporal V5 area (MT/V5_L)

Emotion
Memory Working
Attention Reward Social Cognition
Imagined Objects/Scenes Reasoning Cognition
Passive Listening Language Semantics Action Execution
Beautiful/Joyful Evaluation of Art*
Personal Reward Value of Art*
ventromedial prefrontal cortex (vmPFC)

Reward Language Speech Language Semantics
Emotion Emotion Induction Attention Passive Listening
Cognition Memory Explicit Memory Working
Action Execution Vision Shape
Pictorial Implied Motion Perception*
left posterior superior temporal sulcus (pSTS_L)

left nucleus accumbens (NAC_L)

left temporal pole (TP_L)

Memory Working Emotion
Cognition Emotion Induction
Language Syntax
Reward

Emotion
Reward Audition Cognition
Happiness Language Semantics
Action Execution Action Observation Reasoning
Music Comprehension/Production Attention
Mental Rotation

left middle temporal gyrus (MTG_L)

Emotion Language Semantics
Language Speech Language Orthography
Memory Working Cognition Social Cognition
Action Execution Word Generation (Covert)
Music Comprehension/Production
Mental Rotation Vision Shape
Creative Thought Generation*
Creative Production*

left fusiform gyrus (FG_L)

Vision Shape Language Semantics
Attention Passive Viewing Language Speech
Face Monitoring Passive Listening Audition
Memory Explicit Emotion Reward Cognition
Memory Working Finger Tapping/Button Press
Naturally Coloured Objects Evaluation*
Pictorial Objects and Faces Viewing*

Memory Working
Language Semantics
Passive Listening Language Speech
Reward Word Generation (Covert)
Music Comprehension/Production
Emotion

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Figure 36

# SOCIAL BRAIN ATLAS

## DEMENTIA WITH LEWY BODIES PROFILE

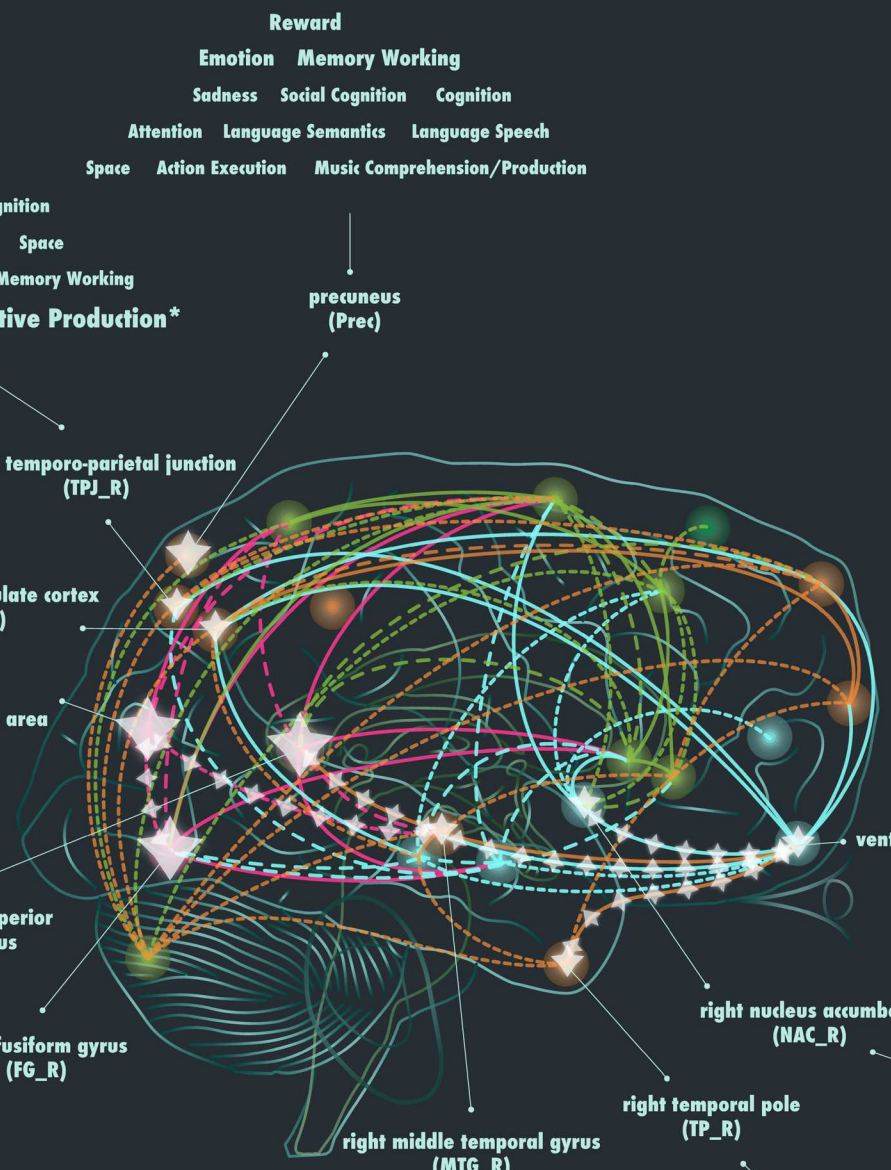
RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



**Reward**
**Emotion** **Memory Working**
**Sadness** **Social Cognition** **Cognition**
**Attention** **Language Semantics** **Language Speech**
**Space** **Action Execution** **Music Comprehension/Production**

**precuneus (Prec)**

**Emotion**
**Reward** **Social Cognition** **Cognition**
**Action Observation** **Action Execution** **Space**
**Passive Listening** **Language Semantics** **Memory Working**
**Creative Thought Generation*** **Creative Production***

**Memory Working**
**Emotion** **Reward** **Face Monitoring** **Cognition**
**Language Semantics** **Language Speech**
**Music Comprehension/Production**
**Creative Thought Generation***
**Personal Resonance with Art***
**Creative Production***

**right temporo-parietal junction (TPJ_R)**

**posterior cingulate cortex (PCC)**

**Language Semantics** **Emotion**
**Language Speech** **Social Cognition** **Reward**
**Memory Working** **Memory Explicit** **Vision Motion**
**Face Monitoring** **Music Comprehension/Production**
**Pictorial Implied Motion Perception***

**right middle temporal V5 area (MT/V5_R)**

**right posterior superior temporal sulcus (pSTS_R)**

**Memory Working** **Cognition**
**Language Semantics** **Language Speech**
**Word Generation (Covert)** **Reward** **Emotion**
**Music Comprehension/Production** **Attention**

**right fusiform gyrus (FG_R)**

**Emotion**
**Visuospatial Attention** **Vision Shape** **Action Execution**
**Audition** **Language Semantics** **Reward**
**Cognition** **Memory Working** **Memory Explicit**
**Naturally Coloured Objects Evaluation***
**Pictorial Objects and Faces Viewing***

**ventromedial prefrontal cortex (vmPFC)**

**Emotion**
**Memory Working**
**Attention** **Reward** **Social Cognition**
**Imagined Objects/Scenes** **Reasoning** **Cognition**
**Action Execution** **Passive Listening** **Language Semantics**
**Personal Reward Value of Art***
**Beautiful/Joyful Evaluation of Art***

**right nucleus accumbens (NAC_R)**

**Emotion** **Memory Working**
**Language Semantics**

**right temporal pole (TP_R)**

**Reward**
**Reasoning** **Action Execution** **Cognition**
**Emotion** **Happiness** **Social Cognition**
**Emotion Induction** **Memory Working**
**Attention** **Vision Motion** **Face Monitoring**
**Music Comprehension/Production**
**Audition** **Language**

**right middle temporal gyrus (MTG_R)**

**Memory Working**
**Music Comprehension/Production**
**Word Generation (Overt)** **Emotion**
**Language Semantics** **Language** **Reward** **Happiness**
**Language Speech** **Word Generation (Covert)** **Cognition**
**Visuospatial Attention** **Vision** **Social Cognition** **Action Inhibition**
**Creative Thought Generation***
**Creative Production***

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### 2.3.7 POSTERIOR CORTICAL ATROPHY

Posterior Cortical Atrophy (PCA) is a syndrome which presents with progressive difficulties in the perception of form and space, but mood changes and problems with language and practical skills are often also present. In the majority of the cases Posterior Cortical Atrophy is caused by Alzheimer's Disease pathology, but it can also be caused by different neurodegenerative diseases, such as Dementia with Lewy Bodies, corticobasal degeneration and prion disease (Crutch et al., 2012, Tang-Wai, 2004).

Posterior Cortical Atrophy has been associated with hypo-metabolism in the lateral occipital lobe, lingual gyrus, cuneus, precuneus, posterior cingulate cortex, inferior parietal lobe, left supramarginal gyrus, temporal lobes, striatum, and thalamus, with less hypo-metabolism in the posterior cingulate cortex compared to the precuneus, the so-called cingulate island sign (Crutch et al., 2012; Walker et al., 2015; Whitwell et al., 2017).

These areas are associated with both the cortical ventral attention stream – the 'What?' -, as well as the cortical dorsal attention stream – the 'Where?'- (Milner and Goodale, 1992; Ungerleider and Mishkin, 1982). A more asymmetric atrophy pattern and a lack of involvement of the temporal pole and orbitofrontal areas is thought to distinguish Posterior Cortical Atrophy from Dementia with Lewy Bodies (Whitwell et al., 2017).

Mapped onto the Social Brain Atlas, Posterior Cortical Atrophy shows a pattern of affected areas that spans both lower level sensory and higher level associative processing networks, indicating a complex interaction between bottom-up and top-down processes.

Figure 37: Posterior Cortical Atrophy Axial
Figure 38: Posterior Cortical Atrophy Left
Figure 39: Posterior Cortical Atrophy Right

PRIMARY SOCIAL BRAIN NETWORKS

- Construction
- Interaction
- Animation
- Perception

EARLY AFFECTED AREAS

- Posterior: Bilateral fusiform gyrus, bilateral MT/V5 area, bilateral posterior superior temporal sulcus, precuneus, posterior cingulate cortex, left supramarginal gyrus

EARLY AFFECTED MEMORY DOMAINS

- Semantic memory
- Implicit memory

BEHAVIOURAL FUNCTIONS

*Social brain profile*

- Shape vision
- Language semantics, orthography and speech
- Working and explicit memory
- Action observation and execution
- Social cognition and face monitoring
- Visuospatial attention and motion vision
- Visual object identification and space representation

*Visual imagination profile*

- Creative thought generation and production
- Joyful and beautiful evaluation of art
- Music comprehension/production
- Naturally coloured objects evaluation
- Overt visual imagination
- Personal reward value of and resonance with art
- Pictorial objects, faces and landscapes viewing
- Pictorial visuospatial qualities and implied motion

Figure 37

# SOCIAL BRAIN ATLAS

## POSTERIOR CORTICAL ATROPHY PROFILE

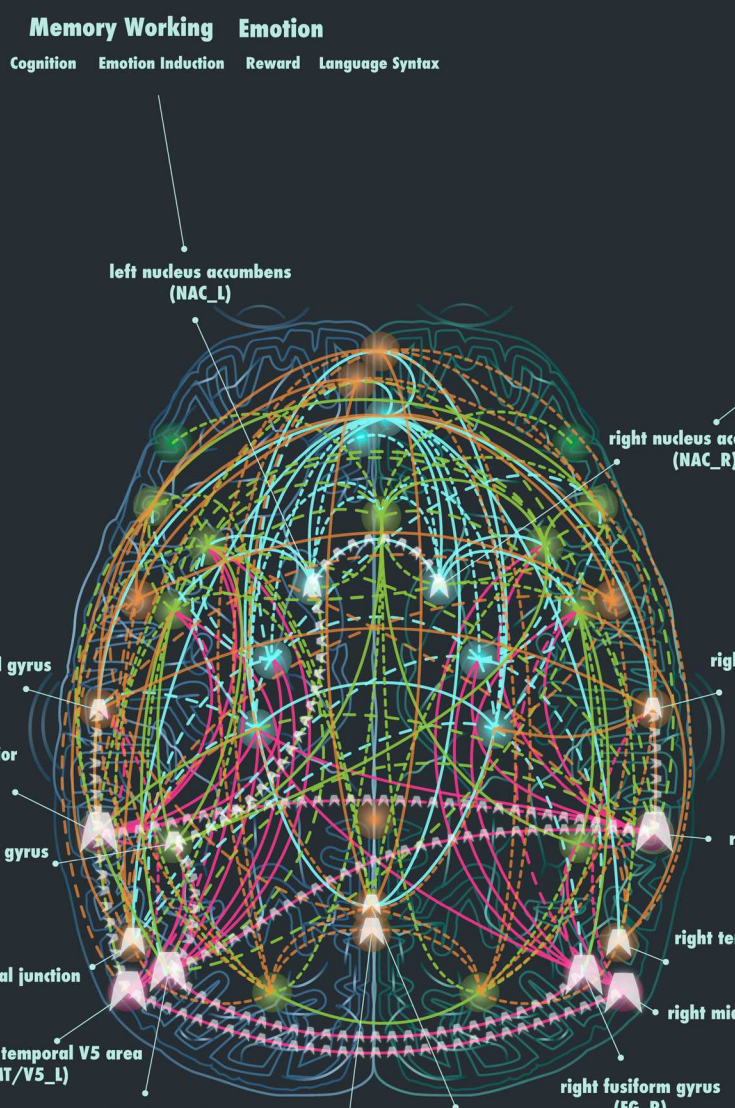
AXIAL PLANE
x-y axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




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Figure 38

# SOCIAL BRAIN ATLAS
## POSTERIOR CORTICAL ATROPHY PROFILE

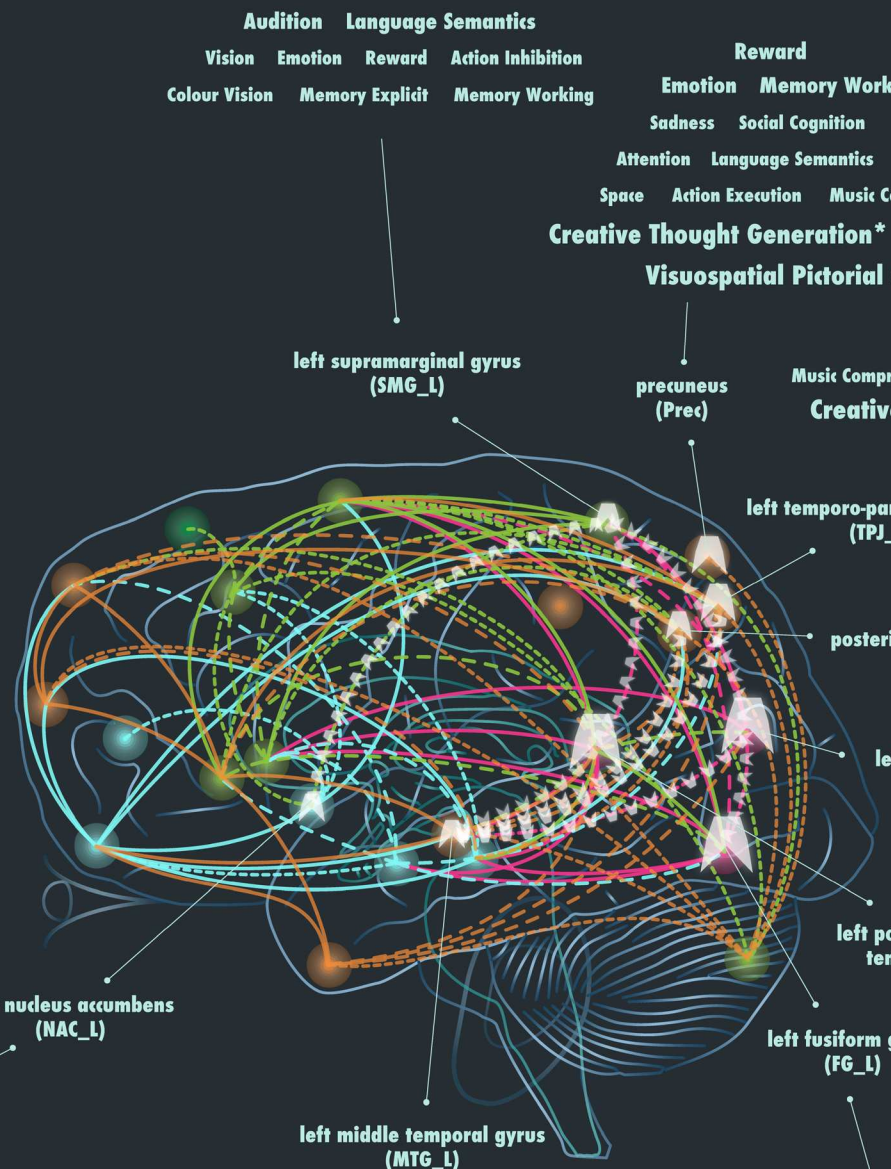
NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ——
Resting State --------
Task State – – – –

FUNCTIONAL PROFILES
Word Size ↑ Likelihood ↑
* Indeterminate Likelihood

LEFT HEMISPERE
y-z axis

DEMENTIA PROFILES
Typical Alzheimer's Disease
Semantic Primary Progressive Aphasia
Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy




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Figure 39

# SOCIAL BRAIN ATLAS

## POSTERIOR CORTICAL ATROPHY PROFILE

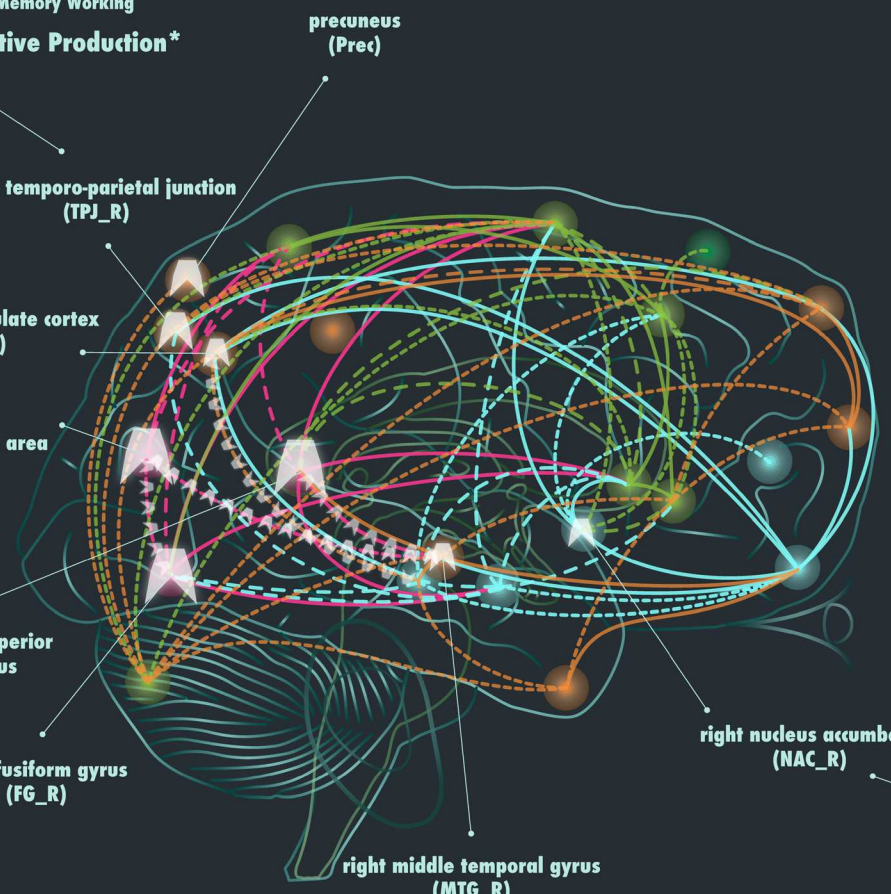
RIGHT HEMISPHERE
y-z axis

NETWORK LEVELS
4. Construction
3. Interaction
2. Animation
1. Perception

FUNCTIONAL CONNECTIVITY
State Independent ———
Resting State --------
Task State – – – –

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Nonfluent Primary Progressive Aphasia
Logopenic Promary Progressive Aphasia
Behavioural Frontotemporal Dementia
Dementia with Lewy Bodies
Posterior Cortical Atrophy



**Reward**
**Emotion** **Memory Working**
**Sadness** **Social Cognition** **Cognition**
**Attention** **Language Semantics** **Language Speech**
**Space** **Action Execution** **Music Comprehension/Production**

**precuneus (Prec)**

**Emotion**
**Reward** **Social Cognition** **Cognition**
**Action Observation** **Action Execution** **Space**
**Passive Listening** **Language Semantics** **Memory Working**
**Creative Thought Generation*** **Creative Production***

**Memory Working**
**Emotion** **Reward** **Face Monitoring** **Cognition**
**Language Semantics** **Language Speech**
**Music Comprehension/Production**
**Creative Thought Generation***
**Personal Resonance with Art***
**Creative Production***

**right temporo-parietal junction (TPJ_R)**

**posterior cingulate cortex (PCC)**

**Language Semantics** **Emotion**
**Language Speech** **Social Cognition** **Reward**
**Memory Working** **Memory Explicit** **Vision Motion**
**Face Monitoring** **Music Comprehension/Production**
**Pictorial Implied Motion Perception***

**right middle temporal V5 area (MT/V5_R)**

**right posterior superior temporal sulcus (pSTS_R)**

**Memory Working** **Cognition**
**Language Semantics** **Language Speech**
**Word Generation (Covert)** **Reward** **Emotion**
**Music Comprehension/Production** **Attention**

**right fusiform gyrus (FG_R)**

**Emotion**
**Visuospatial Attention** **Vision Shape** **Action Execution**
**Audition** **Language Semantics** **Reward**
**Cognition** **Memory Working** **Memory Explicit**
**Naturally Coloured Objects Evaluation***
**Pictorial Objects and Faces Viewing***

**right middle temporal gyrus (MTG_R)**

**Memory Working**
**Music Comprehension/Production**
**Word Generation (Overt)** **Emotion**
**Language Semantics** **Language** **Reward** **Happiness**
**Language Speech** **Word Generation (Covert)** **Cognition**
**Visuospatial Attention** **Vision** **Social Cognition** **Action Inhibition**
**Creative Thought Generation***
**Creative Production***

**right nucleus accumbens (NAC_R)**

**Emotion** **Memory Working**
**Language Semantics**

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## 2.4 RESEARCH QUESTIONS AND HYPOTHESES

As I will elaborate on more in depth in the experimental research chapters, the point of view I have taken in this study, is that visual art offers us a way to connect our inner worlds with the world around us. This idea of visual art aligns with the more mechanical neuroscientific concept of the human brain as a predictive coding organ, which constantly tries to anticipate what might happen next, based on previous experiences and learned knowledge of the outside world.

Neuroscientific research aims to describe how the brain works, through direct and indirect measures. The human brain is very difficult to study directly due to its physical inaccessibility, functional complexity and biological fragility and not even all neuroimaging techniques don't always measure direct neural activity. An example of this is functional MRI scanning, which measures blood flow in the cerebral cortex as a proxy for neural activity. In this study I developed experiments that focused on behavioural components of the social brain dynamics of visual imagination and related complex social behaviours.
The rationale behind this was that brain processes that are related to social behaviour will have a measurable impact on a person's internal experiences and outward behaviour.

Following from the theoretical framework of the Social Brain Atlas and my literature research into the functional neuroanatomy of visual imagination in the context of visual art and creativity, I formulated the following research questions:

**Research question 1 (Q1):**
How does visual perception relate to visual imagination and other social brain functions?

**Research question 2 (Q2):**
Does healthy ageing have an effect on visual imagination and other social brain functions?

**Research question 3 (Q3):**
Do different forms of dementia have general effects on visual imagination and other social brain functions?

**Research question 4 (Q4):**
Do different forms of dementia have specific effects on visual imagination and other social brain functions?

Based on an extensive qualitative review of the neuroimaging literature on changes in brain network architecture and cognitive functioning in healthy ageing, Spreng and Turner (2019) concluded that a shift takes place from a greater reliance on executive-control networks in younger adulthood to a greater reliance on semantic knowledge in senior adulthood, reflected in a less flexible coupling between the default mode and executive-control networks in senior adults. This proposed shift in neural dynamics in healthy ageing is relevant to consider in the context of this study, as it could indicate that young and senior adults might employ different strategies when they engage with visual artworks and complex images.

The neuroscientific experiments that I developed to investigate my research questions, explored the following hypotheses:

**Hypothesis 1 (H1):**
Neurologically healthy young adults are likely to show more sensitive perceptual (bottom-up) and flexible cognitive (top-down) behavioural responses to visual artworks and complex images than neurologically healthy senior adults.

**Hypothesis 2 (H2):**
Neurologically healthy senior adults are likely to rely more strongly on semantic knowledge in cognitive (top-down) responses to visual artworks and complex images than neurologically healthy young adults.

**Hypothesis  3 (H3):**
The functional profiles of the dementia syndromes that I have mapped onto the Social Brain Atlas will align with the behavioural measurements.

**Hypothesis  4 (H4):**
Given the prominence of semantic language in all dementia profiles in the Social Brain Atlas, it is likely that dementia is in general associated with decreased semantic language access in responses to visual artworks and complex images, compared to neurologically healthy senior adults.

In the context of this study, I defined 'perceptual sensitivity' as 'attentive and responsive to sensory information' and 'cognitive flexibility' as 'the ability to modify cognitive processing templates (so-called priors) in response to new information.'

In the Thinking Eyes project I addressed the research questions by investigating multi-modal responses to visual artworks and complex images in three successive eye tracking experiments that were modelled on the arts-based facilitated conversation method Visual Thinking Strategies (VTS).

In the Colour Spaces project I probed the research questions with two successive eye tracking experiments that investigated multi-modal responses to a selection of 26 colours that varied in hue, saturation and brightness and were presented to the research participants in different spatial and material contexts.

I have described the Thinking Eyes and Colour Spaces projects in detail under the Experimental Research chapter. In the next chapter, Experimental Framework, I have first detailed the general research methods and the contextual information of the neuroscientific research cohorts.

# 3. EXPERIMENTAL FRAMEWORK

## 3.1 GENERAL METHODS

This chapter describes the research cohorts of the two neuroscientific research projects, as well as the general aspects of my multi-modal neuroscientific research methods. Under the experimental research project chapters I have detailed the specific research materials and methods for the Thinking Eyes and Colour Spaces projects.

### Ethical approval

The study was approved by both the University College London Research Ethics Committee (8545/002: Created Out of Mind) and the UCL Queen Square Research Ethics Committee (17/LO/0099).

### Cohorts description

To investigate the effects of healthy ageing and different forms of dementia on visual imagination and other social brain functions, I defined the following three research cohorts:

- Neurologically healthy young adults, aged 20-30
- Neurologically healthy senior adults, aged 50+
- Senior adults living with various forms of dementia

Taking into account that each research session would take at least 3 hours to complete, I aimed to recruit 20 participants for each research cohort. I strived to compose gender-balanced and generally diverse research groups. I was motivated to include various dementia syndromes to get a better understanding of both general and specific effects of dementia might have on visual imagination aspects in relation to the social brain dynamics.

I recruited the neurologically healthy research participants via public social media, such as Twitter and Facebook, as well as via internal communication platforms at the Wellcome Collection and the UCL Dementia Research Centre in London, where my research jointly took place. The majority of the research participants living with a dementia had been referred to me by colleagues at the UCL Dementia Research Centre and some participants got in touch after learning more about my research at a Rare Dementia Support Group meeting, which were also hosted by the UCL Dementia Research Centre.
The inclusion criterion for adults living with a dementia was that they should be able to give informed consent in accord with the Declaration of Helsinki guideline. This also entailed that I, in my role as lead researcher, should be able to understand their communications sufficiently and that they were able to engage with the eye tracking experiments.

### Participant background methods

In order to collect demographic information about the research participants I created the Thinking Eyes Questionnaire (Appendix 1). This questionnaire used the first two sections on personal background and general health from the UCL Dementia Research Centre demographics questionnaire – which is used in clinical assessments – to which a third section was added to gather information on how much experience participants had regarding the practical and theoretical aspects of visual art. The questionnaire consisted of multiple choice questions and open follow-up questions, which participants were free to skip if they didn't wish to answer them.
The main purpose of collecting this data was to establish whether the three research cohorts had similar variance in personal background, general health and art experiences except for the cohort defining characteristics of age and neurological health.

### Neuropsychometry methods

To get an understanding of the general visuospatial cognitive abilities of the neurologically healthy research participants, I asked them to fill out an abbreviated version of the Wechsler Abbreviated Scale of Intelligence (WASI) Matrix Reasoning (Wechsler, 1999), a standardised test which aims to measure perceptual reasoning ability. The participants were given privacy to fill out the test which consisted of 18 multiple choice items that were presented on an iPad.

With respect to the research participants living with a dementia, I wanted to get a broader understanding of their baseline cognitive functioning, in order to create a frame of reference for my multi-modal arts-based methods to assess social brain functioning. For this purpose I selected the Addenbrooke's Cognitive Examination (ACE) III, which I administered myself using pen and paper. The ACE III is a standardised neuro-psychological test which has been designed to detect mild cognitive impairment and early signs of dementia. It consists of 24 open question items, which aim to assess various domains of cognitive functioning, including: attention, memory, fluency, language, as well as visuospatial perceptual and constructive abilities. The ACE III has been validated as an effective bedside test to diagnose Frontotemporal Dementia and typical Alzheimer's Disease (Hsieh et al., 2013; Mathuranath et al., 2000).

**Colour perception methods**

I designed the Matching Colours Scale, a digital 12-item colour hue matching task, as a tight low-level visual perceptual control which needed minimal verbal explanation. The rationale behind this brief test was that this instrument aimed to minimise the cognitive strain as well as the risk to be confounded by difficulties understanding verbal language in participants living with dementia. Creating a novel instrument, rather than choosing an existing colour perception test, also allowed me to align the colours exactly with the colour selection of the Colour Spaces research project. The 12 items were designed to assess the participants' ability to perceive variations of lightness and saturation within each colour category (purple, blue, green, yellow, red and greyscale), as well as between colours of similar saturation or lightness belonging to different colour categories.

Each item consisted of a colour block with a question mark placed underneath. In a row below three numbered colour blocks of identical size were shown, with one colour block being the exact same hue as the colour block with the question mark. Participants were requested to read out the matching colour block out loud. Each colour category was allocated two items that aimed to assess lightness differentiation in one item and saturation differentiation in the other. The items that aimed to assess lightness differentiation contained 1 colour block of a neighbouring colour on the light spectrum in the same lightness as one of the 3 colour block options to choose from. Greyscale perception was assessed in a single item with greyscale colour blocks that varied in lightness. The 12 items were shown one at the time on an Eizo ColorEdge CG2420 24-inch LCD monitor, which had been calibrated in the sRGB gamut to a white point of 6500K at a brightness level of 100 cd/m$^2$ in a blackout room. Figure 40 shows the 12 items of the Matching Colours Scale with alphabetical letters indicating the order in which the items were shown to the research participants.

**Visual exploration methods**

I measured the visual exploration of visual artworks and complex images with an Eyelink 1000 Plus eye tracking camera, which was directed at the research participants' eyes while they were looking at a display on a table in a blackout room. Figure 41 shows the experimental set-up of the neuroscientific research at the Wellcome Collection in London. The visual stimuli were displayed to participants either digitally on an Eizo ColorEdge CG2420 24-inch LCD monitor which had been calibrated in the sRGB gamut to a white point of 6500K at a brightness level of 100 cd/m$^2$ in a blackout room or as photographic prints on a table easel, which were placed at 75 cm distance from a table-mounted headrest. The eye tracking camera recorded binocular eye movement and pupil dilations and was placed in front of the display (below the line of vision), at 55 cm distance from the table-mounted headrest. I spatially calibrated the eye tracking camera software with a 9-point grid before the start of each experiment. The monitor was colour calibrated with an Eye-One Display 2 and ColorNavigator software in the sRGB colour space. The recorded eye tracking data was pre-processed in Data Viewer, a software programme made by SR-Research, the same company that makes the EyeLink eye tracking cameras.

I defined three interest periods to segment the eye tracking data, which aligned with the time windows described by Cela-Conde et al. (2013 in their MEG study into aesthetic evaluations.
The first time window (Perceptual Processing) contained fixations recorded during the first 250 ms of each image presentation.
The second time window (Gist Evaluation) contained fixations recorded between 250 – 750 ms of each image presentation.
The third time window (Construct Inference) contained fixations recorded after 750 ms of each image presentation.
I created fixation heat maps for the different time windows to allow for a visual analysis of the visual exploration patterns.
The recorded eye tracking data within each interest area reports were exported for further statistical analysis, for which only the recorded data from the right eye was used.

**Electrodermal activity methods**

Electrodermal activity is considered to be a sensitive indicator of sympathetic nervous system arousal (Critchley, 2002). It has been shown to increase during motor activity or increased cognitive load, as well as in response to emotional arousal (Poh et al., 2010). The neural pathways that regulate electrodermal activity are thought to have both ipsilateral and contralateral trajectories. Bouscein (2012) defined three central nervous system pathways that influence electrodermal activity:

1. An ipsilateral pathway originating in the limbic region, including the amygdala, cingulate gyrus, anterior thalamus, fornix, hippocampus, and hypothalamus. This pathway is thought to regulate electrodermal responses to emotional arousal.

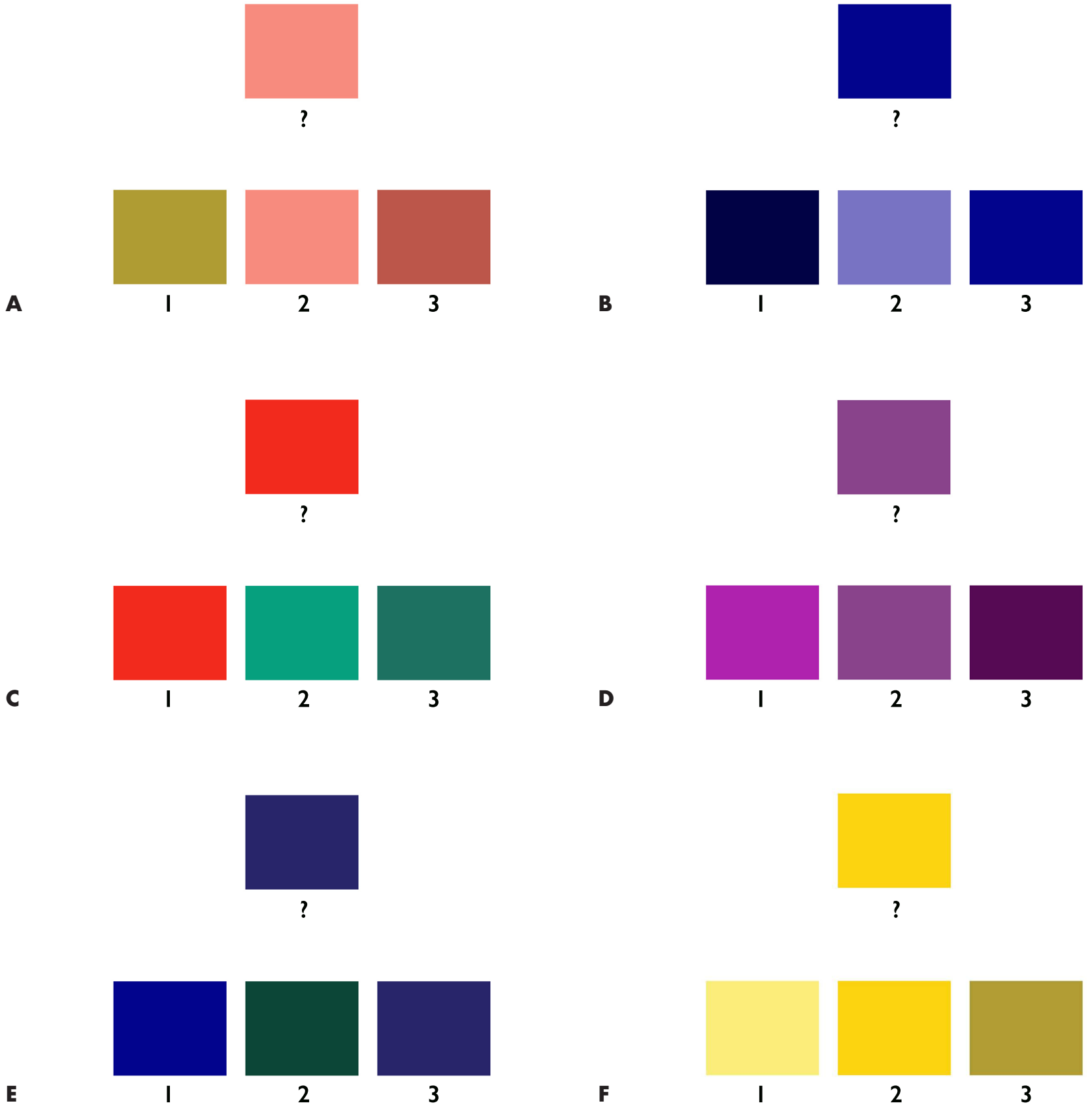
2. A contralateral pathway originating in the basal ganglia and pre-motor cortex that links electrodermal activity to motor activity.

3. A probably ipsilateral reticular pathway, which is thought to influence electrodermal activity through fluctuations in general arousal levels.

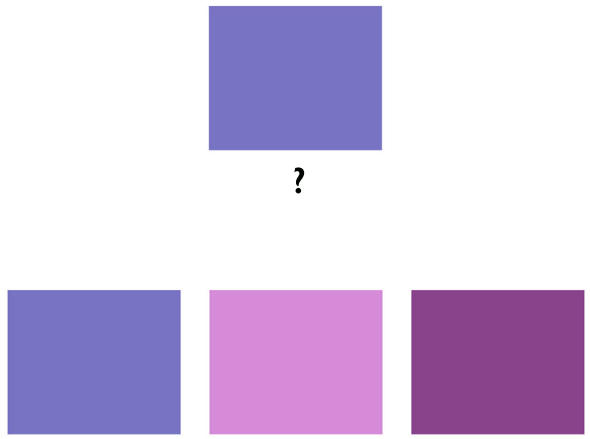
Direct stimulation research with epilepsy patients awaiting brain surgery found that electrical stimulation of limbic regions caused strong and asymmetric ipsilateral electrodermal responses. Electrodermal responses to electrical stimulation of cortical areas were small and symmetric (Mangina and Beuzeron-Mangina, 1996). Lanteaume et al (2007) investigated both electrodermal and affective responses to direct electrical stimulation of the amygdala. They found that stimulations of the right amygdala always induced negative emotions (fear, anxiety and sadness). Stimulations of the left amygdala evoked pleasant (happiness) emotions in 53% of the attempts, whereas 47% of the stimulations induced unpleasant emotions (fear, anxiety, sadness) emotions. When changes in emotional state were reported, these were always accompanied by increases in electrodermal activity measured from the distal phalanges of the second and third finger on the ipsilateral hand from the stimulation side (Lanteaume et al., 2007). Picard et al (2015) studied asymmetry patterns in electrodermal activity during daily life activities, measured with Empatica E4 wristbands from both wrists. They found that strong right-sided increases in electrodermal activity were consistently associated with feelings of threat.
A study by Holroyd et al (1978) studied electrodermal activity responses to test stress, measured from the non-dominant hand in undergraduate female students with high and low test anxiousness and reported strong increases in electrodermal activity regardless of the subjective level of test anxiousness. The authors of this study did not report the handedness of the research participants however, but in all likelihood the electrodermal activity was measured from the left hand in most cases.

To gain insight into the – possibly asymmetrical – emotional arousal levels during the research visit, I measured bilateral electrodermal activity during the standard neuropsychological tests as well as the arts-based methods that I had developed. The electrodermal activity, expressed in micro Siemens, was recorded via Empatica E4 wristbands that were worn on the left and right wrist. Recording started immediately after the consenting process at the beginning of the research session and

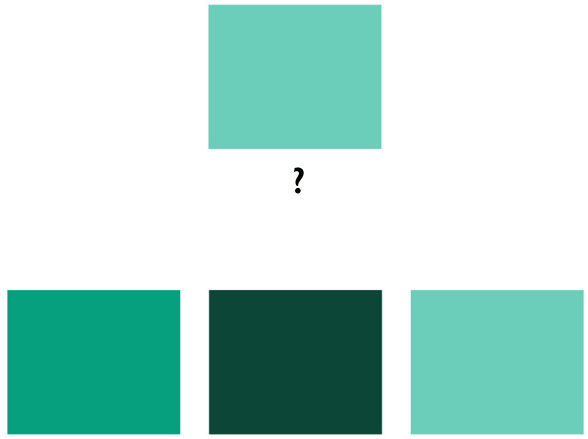
**Figure 40: Matching Colours Scale Items**



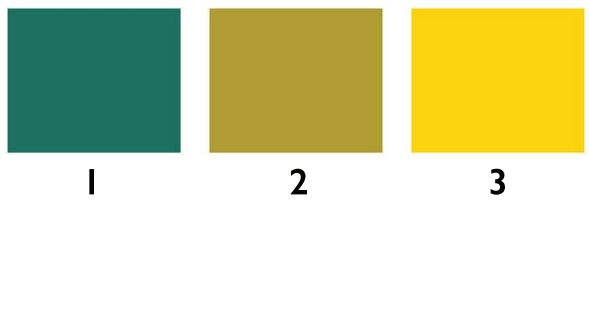
G



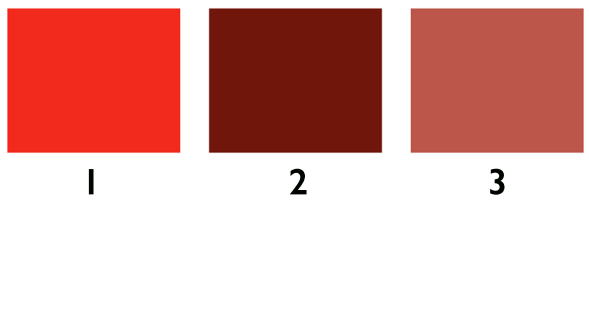

H



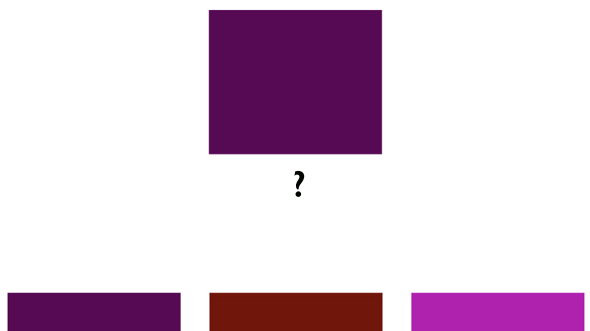

I




J




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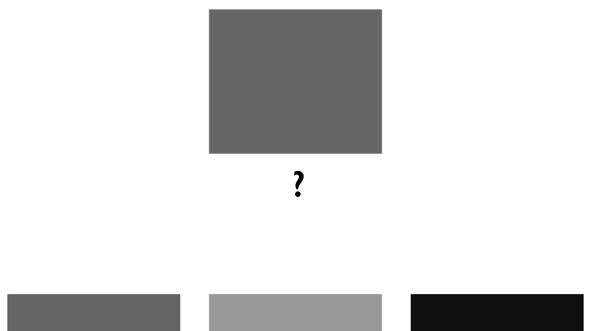


**Figure 41: Experimental set-up neuroscientific research, Wellcome Collection Londo**



continued till the last experiment has finished. The internal clock of the wristbands was synchronised with the MacBook Pro from which the eye-tracking experiments were run. For each individual research participant I time-locked the start and end times of each research section with the electrodermal activity recordings, so that I only included the measurements during the research activities in that analysis.
Because the baseline electrodermal activity varied greatly between people, I analysed the flux patterns of electrodermal activity instead of absolute values. I defined flux in this context as the percentile deviations from the personal average of electrodermal activity, measured from both wrists across the 6 research sections and only including active research time and micro Siemens values higher than 0. The 6 research sections consisted of: Baseline neuropsychology; Thinking Eyes 'Snap-shots' experiment; Thinking Eyes 'Perspectives' experiment; Thinking Eyes 'Panorama' experiment; Digital Colour Spaces experiment and Print Colour Spaces experiment.

I developed an Excel template to read out the relevant bilateral electrodermal activity recordings for each defined time window. The protocol I wrote to describe each step in this process can be found under Appendix 2 and the Excel template can be freely downloaded from my website The Thinking Eye (https://www.thinkingeye.org), under the research tab.

**Internal state evaluation methods**

In order to gain a better understanding of the subjective experiences of the participants during the various research tasks I collected both quantitative and qualitative information. Out of dissatisfaction with existing numerical and emoticon rating scales, I decided to develop novel visual rating scales to assess internal states in the context of this study. My aim was to create simple scales to capture the core dimensions of complex internal states with abstract visual symbolism that can be understood intuitively with minimal verbal explanation.
I designed the following three visual rating scales:

i) The Mood Shade Scale (Figure 42), aimed to measure subjective evaluation of the current mood on a scale of 1 (very bright/positive mood), to 5 (very dark/negative mood).

ii) The Resonance Radius Scale (Figure 43) aimed to measure subjective resonance with a stimulus on a scale of 1 (strongly resonates), to 5 (very little to no resonance).

iii) The Affect Amplitude Scale (Figure 44) aimed to measure subjective affective responses to a stimulus on a scale of 1 (strongly positive feeling), to 5 (strongly negative feeling), whereby a score of 3 indicated a neutral feeling.

I took inspiration for the abstract geometric forms from previous research that found a strong correspondence between the perception of sounds and shapes, with rounded shapes being associated with round sounds and angular shapes with sharper sounds (Köhler, 1929, Ramachandran and Hubbard, 2001). Another study found that this object-sound correspondence is already present in very young children (Maurer et al., 2006). Based on these findings, I argued that a similar correspondence between visual cues and internal representations of affective states could exist, which is also reflected in everyday language. Examples of an intrinsic connection between visual properties and emotional dimensions in the English language are: feeling down, a flat affect, a sinking feeling, light-hearted, lifting the spirit, a low/even/elevated/dark/mood.
In this study, I therefore associated upwards directing or bright shapes with a positive valence and downwards pointing or dark shapes with negative valence. I associated a stronger intensity of feeling with larger dimensions of the abstract shapes. To assess the face validity of these abstract visual rating scales, I asked each research participant whether or not they felt they were easy to use and whether the geometric shapes presented an accurate reflection of that internal state.
Under the Experimental Research chapter I have further elaborated on how I defined the concepts of resonance and affect in the context of this study.

**Figure 42: Mood Shade Scale**

What shade is your mood?

1.

2.

3.

4.

5.

**Figure 43: Resonance Radius Scale**

How much does this resonate with you?

1.

2.

3.

4.

5.

**Figure 44: Affect Amplitude Scale**

How does this make you feel?

1.

2.

3.

4.

5.

**Group level statistical analyses**

The multi-modal quantitative parameters were analysed on a cohort level with the statistical analysis software application JASP. Independent group comparisons were made between neurologically healthy young and senior adults and also between neurologically healthy senior adults and senior adults living with dementia. However, because the sample size of senior adults living with dementia was very small and consisted of research participants with various dementia diagnoses, individual level comparisons against the neurologically healthy senior adults cohort were made as well.

Assumption checks for normality of the means distribution in each cohort were performed with the Shapiro-Wilk test of Normality. Assumption checks for the equality of variances between the two groups being compared, were performed with Levene's Test of the Equality of Variances. For parameters with normally distributed means and an equal amount of variance between the two groups being compared, a Student's independent samples t test was performed. For parameters with means that were not normally distributed, but with an equal amount of variance between the two groups being compared, a Mann-Whitney U test was applied.
For parameters with normally distributed means, but with an unequal amount of variance between the two groups being compared, a Welch's t test was used. If the values of a parameter had neither normally distributed means nor an equal amount of variance between the two groups being compared, the mean differences were described but not statistically tested.
Group differences were presented as the mean difference/ location parameter, with a two-sided p-value. For all analyses, I considered a p value below 0.05 as statistically significant.
I also reported the odds that the alternative hypothesis $H_1$ was true, indicated by the Vovk-Sellke maximum p-ratio.

The Vovk-Sellke maximum p-ratio functions as a Bayes factor, which describes how the data have changed the likelihood of the alternative hypothesis compared to the null hypothesis.

Van Kesteren (2017), the developer of the statistical analysis software JASP, explains the Vovk-Sellke maximum p-ratio as follows: When no real difference exists between two groups ($H_0$ is true), every possible p-value is equally likely to occur. When the alternative hypothesis $H_1$ is true, small p-values are more likely to occur than large p-values.
When the true effect is modest however, small p-values are only a little more likely than large p-values. When the true effect is significant, small p-values are much more likely than large p-values. This difference in the likelihood of obtaining small p-values when the true effect is modest or significant, is addressed by the Vovk-Sellke maximum p-ratio (MPR), which gives an indication of the so-called diagnosticity of a two-sided p-value. The Vovk-Sellke MPR shows the maximum odds in favour of the alternative hypothesis ($H_1$) over the null hypothesis ($H_0$), defined as $1/(-e\ p \log(p))$ for $p \leq 0.37$ (Sellke et al., 2001).
I used the JASP platform to calculate the Vovk-Sellke MPR for group level comparisons.

Within-group comparisons on quantitative parameters were made with paired samples t tests. For parameters with normally distributed means, I used a Student's paired samples t test and for parameters with means that were not normally distributed, a Wilcoxon signed-rank paired samples test.
Results were presented as location parameters with a two-sided p-value and the odds that the alternative hypothesis $H_1$ was true (Vovk-Sellke MPR).

**Statistical analyses of case studies**

In order to analyse potential specific effects of different dementia syndromes on visual imagination and other social brain functions, I also analysed the multi-modal quantitative data on a case versus control cohort level with an adjusted independent samples Student's t test (Crawford & Howell, 1998). While the Student's t test assumes a normal distribution of the control cohort data, it has been demonstrated that this method is nonetheless very robust even in the case of severe skew and/or leptokurtosis (Crawford et al., 2006).

The case study data was by default compared to the control cohort of neurologically healthy senior adults. Results were presented as cohort means and standard deviation, the mean differences and a two-sided p-value, accompanied by the odds that the alternative hypothesis $H_1$ was true (Vovk-Sellke MPR). For the case study statistical analyses I calculated the Vovk-Sellke MPR with the following Excel formula:

=IF($A_n$<1/EXP(1),1/(-1*EXP(1)*$A_n$*LN($A_n$)),1)

In this formula, '$A_n$' referenced a cell in column A which contained the two-sided p-value of the modified Student's t test (Crawford et al., 2006).

**Interpretation of multiple comparisons**

While my research hypotheses contained predictions of directional differences between the different research cohorts, I wanted to remain open to the possibility of performance differences associated with compensation strategies or altered functional connectivity patterns in the research participants living with dementias. My statistical approach in this study was therefore exploratory, which is why findings were assessed with bidirectional t tests. Since my experiments focused on visual imagination and other complex social behaviour, I also assumed a high level of correlation between the measurements in the multiple comparisons. It is generally accepted that when a large number of comparisons are made and the tests are not independent, correcting for multiple comparisons – such as Bonferroni or Šidàk – tends to give too conservative results (Abdi, 2006). For this reason I did not perform any corrections for the multiple comparisons I made in this study. However, an indication of the strength of each individual reported significant effect among multiple comparisons can be gleaned from the Vovk-Sellke maximum p-ratio, indicated as the odds of a true effect in each data table. The higher the odds, the more likely it is that the effect would still be significant in the case a correction for multiple corrections would have been made.

## 3.2 CONTEXTUAL INFORMATION RESEARCH COHORTS

**Demographic profiles**

Recruiting participants for my neuroscientific experiments was a challenge as it required a time commitment of 3 hours, and I was initially not allowed to offer any financial compensation by the UCL Dementia Research Centre out of ethical concerns. This turned out to be especially a barrier for the recruitment of young adults. Towards the deadline of my data collection phase, I was given permission by the UCL Dementia Research Centre to offer young participants an Amazon voucher as a compensation for their donated time to the research. This helped to recruit an extra 10 participants to the young adults cohort. Below I have detailed the demographic profiles of the 3 research cohorts.

*Neurologically healthy adults*

I managed to recruit in total 17 neurologically healthy young adults (F=10, M=7) and 20 neurologically healthy senior adults (F=10, M=10). All neurologically healthy adults took part in both neuroscientific research projects (Thinking Eyes and Colour Spaces). Figure 45 shows that the demographic background of these two cohorts was comparable on all factors except age, meaning that any significant differences between them on the research measurements would most likely be associated with the age difference.

*Senior adults living with dementia*

Of the senior adults living with various forms of dementia who took part in my research, 11 participants (F=4, M=7) were able to take part in both the Thinking Eyes and Colour Spaces project, of whom 9 came for two research visits to minimise fatigue. Figure 46 shows the background data of these participants. I did not include information on clinical duration, as people generally receive a dementia diagnosis in different stages of the illness and in addition, the gradation and pace of functional decline also varies widely. As Figure 47 shows, the demographic backgrounds of the senior adults living with

dementia were similar to the neurologically healthy senior adults. This means that any significant differences between them on the research measurements would most likely be associated with the effects of dementia.
Three additional participants living with a dementia were able to contribute to some parts of the Thinking Eyes questionnaire, the neuropsychometry test and various elements of the colour research. These participants were diagnosed with Semantic Primary Progressive Aphasia (N=2, M) and Logopenic Primary Progressive Aphasia (N=1, M). Their colour perception ability was included in the cohort level descriptions, but all other findings on the research sections they took part in has only been outlined under the case study sections.

**Matching Colours Scale results**

All the neurologically healthy young and senior adults accurately colour-matched the 11 colour hue items and the grey-scale hue item. Of the senior adults living with a dementia, 36% made one or more colour hue matching mistakes and 15% inaccurately matched the grey-scale hue item. The senior adults who made mistakes with matching the colour hue items were diagnosed with Posterior Cortical Atrophy (N=2, F, M), or Nonfluent Primary Progressive Aphasia (N=2, F, M). Purple, blue and red colour nuances were most often mismatched. The senior adults diagnosed with Typical Alzheimer's Disease, Behavioural Frontotemporal Dementia, Semantic Dementia and Unspecified Dementia accurately matched all the colour items as well as the grey-scale item.

Two research participants living with dementia matched a saturated red with a muted green colour block: 1 male senior adult who was diagnosed with Posterior Cortical Atrophy and 1 senior female who was diagnosed with Nonfluent Primary Aphasia. Neither participant had indicated that they were colour blind in the Thinking Eyes questionnaire, which seems to suggest they might have developed a perceptual difficulty to distinguish green from red as a results of their dementia. The male senior adult with Posterior Cortical Atrophy had mentioned in the questionnaire that his father had been green/red colour blind, which could point to a possible genetic vulnerability for colour perception difficulties. Both the senior male adult with Posterior Cortical Atrophy and the senior female with Nonfluent Primary Progressive Aphasia who had mismatched the red with a green colour block also made a mistake on the grey-scale item, matching the dark grey hue with a lighter hue of grey. This raises the question whether their difficulties with colour hue perception might be related to a strongly altered brightness perception.

The colour blocks that were mismatched by participants living with dementia varied between the left, middle and right position in the row of three colour blocks they were presented in, which is a sign that spatial neglect and/or choice bias are an unlikely explanation for the findings. I also asked if they were perhaps experiencing colour after-images, as this could have been a confounding factor, but all of them indicated this was not the case.

The research participants who made mistakes in matching the colour and grey-scale hues had all been diagnosed with a form of dementia that affects the parietal cortex, which could provide a possible clue to the underlying neural mechanisms of cortical in colour hue perception. Posterior Cortical Atrophy and Nonfluent Primary Progressive Aphasia both have affected brain areas that are part of the posterior Interaction Network of the Social Brain Atlas. This network is also – weakly – associated with colour vision in the functional profiles of the Social Brain Atlas (Alcalá-López et al., 2017). In Semantic Primary Progressive Aphasia and Typical Alzheimer's Disease the Interaction Network is relatively spared and in Behavioural Frontotemporal Dementia predominantly frontal and medial areas of the Interaction Network are affected. This could explain why the research participants with these dementia syndromes did not have difficulties with matching colour and grey-scale hues, if this function is indeed to an extend regulated by posterior hubs in the Interaction Network.
In the Colour Spaces project (described in section 4.3) I further investigated the social brain dynamics of colour experiences.

**Mood Shade Scale results**

To assess the baseline mood of the research participants on the day of the research visit, I asked them to fill out the Mood Shade Scale I had created. The Mood Shade Scale consists of 5 vertically ordered spheres, varying from deep black at the bottom (very dark mood) to very light at the top (very bright mood). At the start of the research visit I showed the research participants the Mood Shade Scale and I explained that the darker shades represented darker moods and that the lighter spheres represented brighter moods. I then asked them to select the sphere that most closely represented their current mood that day. The neurologically healthy adults filled out a digital version of the Mood Shade Scale on an iPad and the senior adults living with dementia were given the option to fill out a pen and paper version of the scale. Some participants indicated that they had never thought of their mood in terms of shades of brightness, but the vast majority reported they found the scale intuitive and easy to use.

The mean score on the Mood Shade Scale of the neurologically healthy young adults was 2.0 (SD=0.6), indicating that their average mood that day was bright, ranging from neutral/bright to bright/very bright). The mean score on the Mood Shade Scale of the neurologically healthy senior adults was 1.8 (SD=0.9), indicating that their average mood that day was bright/very bright, ranging from neutral/bright to very bright.

A little more than half of the participants living with a dementia took part in the research spread over two visits (57%). At the start of each visit I asked the participants to rate their mood on the Mood Shade Scale. The mean score on the Mood Shade Scale of the senior adults living with dementia on the 1st research visit was 2.2 (SD=1.0), indicating that their average mood was bright/neutral that day, ranging from neutral/dark to very bright/bright. The mean score on the Mood Shade Scale of those who came for a 2nd research visit (N=8) was 2.5 (SD=1.1) that day, indicating that their average mood was neutral/bright that day, ranging from dark/neutral to bright/very bright.

The distributions of the mood shade scores of the healthy young and senior adult research cohorts were found to be both not normally distributed and to have unequal variances as well. It was therefore not appropriate to perform an independent samples t test to evaluate the group mean difference, but the small mean difference suggests that the average mood of neurologically healthy young and senior adults on the day of the research visit was likely similar (bright). The distributions of the mood shade scores of the neurologically healthy senior adults and the senior adults living with dementia did have equal variances, which allowed me to performed a Mann-Whitney U test to evaluate the mean differences. The results showed that on the first research visit it was 2.48 times more likely that the participants living with a dementia (N=14) had a darker average mood that day than the neurologically healthy senior adults (N=20), with a mean difference of 0.4 and a p-value of 0.049. It was 2.25 times more likely that the senior adults living with a dementia (N=8) who came for a 2nd research had a darker average mood that day than the neurologically healthy senior adults during their research visit, with a mean difference of 0.7 and a p-value of 0.057.

A Wilcoxon signed-rank test also showed that it was most likely that the average mood shade of the participants living with a dementia who came for two research visits (N=8) was the same during the 1st and the 2nd visit, with a mean difference of 0 and a p-value of 1. The time between the two research visits was on average 2 weeks, ranging from a day to 3 months. These findings suggests that the average mood of people living with dementia is relatively stable over a time period of several weeks. The consistency in the mood shade scores of the people living with a dementia are also an indication that the Mood Shade Scale is an intuitive visual rating scale which can accurately measure the valence of mood in people living with dementia.

**Face validity novel visual rating scales**

I introduced each novel visual rating scale to the research participants as follows:

i) The Mood Shade Scale (Figure 42): "This scale aims to measure what your current mood is. The brightest sphere, number 1, means your mood is very bright (positive).
The darkest sphere, number 5, means your mood is very dark (negative). Could you select which circle best represents your mood at the moment?"

ii) The Resonance Radius Scale (Figure 43): "You will be shown visual artworks and other images. After each viewing you will be asked "How much does this resonate with you?".
1. The widest circle means it resonates very strongly with you.
5. The smallest circle means it resonates very little with you.
To make your selection, you can say out loud the number next to the circle of your choice."

iii) The Affect Amplitude Scale (Figure 44): "You will be shown a series of colours on a computer screen. After each viewing you will be asked "How does this make you feel?".
1. The largest upwards pointing shape means it makes you feel strongly positive.
5. The smallest downwards pointing shape means it makes you feel strongly negative.
The flat lines, number 3, means you feel neutral about it.
To make your selection, you can say out loud the number next to the shape of your choice."

After each introduction, I asked the participants whether they felt the visual rating scale accurately represented the concept I was trying measure (mood, resonance and affect). The results are shown in Table 1 as percentiles of affirmative responses within each research cohort.

**Table 2: Face validity novel visual rating scales**

| Cohort | Mood Shade Scale | Resonance Radius Scale | Affect Amplitude Scale |
|---|---|---|---|
| Young adults | 87% | 100% | 100% |
| Senior adults | 90% | 95% | 100% |
| Senior adults living with dementia | 93% | 77% | 85% |

These percentile ratings of face validity of the novel visual rating scales were based on 15 neurologically healthy young adults (F=10, M=7), 19 neurologically healthy senior adults and 11 (Resonance Radius Scale; F=4, M=7) and 14 (Mood Shade Scale and Affect Amplitude Scale; F=4, M=10) senior adults living with dementia. The neurologically healthy participants who said that the Mood Shade Scale didn't accurately measure what it intended to gave the following reasons:

- Couldn't relate to the concept of mood assessment (N=1)
- A colour gradient would be more intuitive (N=1)
- Their mood is more a binary state: good or bad (N=2)

Four neurologically healthy adults indicated that they could relate to the Mood Shade Scale as it was intended after instructions, but that they would have instinctively chosen the darkest sphere as the most positive mood (having the most solid/intense presence). One neurologically healthy adult indicated that they could relate to the Mood Shade Scale as it was intended, but that they would have preferred only 3 gradients (positive/neutral/negative). Another participant would have preferred more gradients than the 5 that were presented.
One senior adult living with dementia (P10M_bvFTD) doubted whether the Mood Shade Scale accurately measured what it intended to and he gave the following reason:

- Perhaps people just like black or white

The neurologically healthy participants who said that the Resonance Radius Scale didn't accurately measure what it intended gave the following reasons:

- Interpreted it as how it made them feel emotionally (N=1)

Some senior adults living with dementia struggled with the Resonance Radius Scale for the following reasons:

- Resonance concept was not understood (P5M_svPPA)
- The scale was only responded to when the options were read out to them (P11M_bvFTD, P12M_PCA)

All neurologically healthy participants said that the shapes of the Affect Amplitude Scale accurately measured what it intended. Two neurologically healthy participants indicated however that it would have been more intuitive for them if the most positive shape was numbered '5' and the most negative shape was numbered '1', instead of the other way around.

Some senior adults living with dementia struggled with the Affect Amplitude Scale for the following reason:

- The scale was only responded to when the options were read out to them (P11M_bvFTD, P12M_PCA)

**Neuropsychometric test results**

*Neurologically healthy adults*

To create a frame of reference for my novel multi-modal arts-based methods to assess visual imagination and other social brain functions, I asked the neurologically healthy research participants to fill out an abbreviated version of the Wechsler Abbreviated Scale of Intelligence (WASI) Matrix Reasoning (Wechsler, 1999), a standardised test which aims to measure perceptual reasoning ability.

The maximum score that could be obtained was 18, the average score of the neurologically healthy young adults was 15.45 (SD=1.82) and the average score of the neurologically healthy senior adults was 16.29 (SD=1.05).

Both data distributions were not normal and also had unequal variances so it was not appropriate to statistically assess the mean difference of 0.84 with an independent samples t test, but given the close average scores and standard deviations of each cohort, it is likely that the average perceptual reasoning ability of both the young and the senior adult cohort was similar and clustered around the upper 20th percentile.

*Senior adults living with dementia*

For the research participants living with dementia I aimed to create a broader frame of reference of their cognitive abilities and difficulties. For this reason I administered the Addenbrooke's Cognitive Examination (ACE) III (see also under the Neuroscientific Research Methods section).
The average total score on the ACE III was 58.38 (SD=16.14). The maximum total score is 100 and a total score below 88 is generally considered to be indicative of a dementia diagnosis. It has been suggested that a score below 61 could separate mild from moderate dementia (Giebel and Challis, 2017). Based on these criteria, the research participants living with a dementia had on average a moderate degree of the disease, varying from mild to more severe. The individual scores on the subcategories of the ACE III have been detailed under the individual case studies in this chapter.

**Neuropsychometric test electrodermal activity flux**

*Neurologically healthy adults*

To assess the emotional arousal of the research participants during each research section, I measured electrodermal activity from both wrists.

The electrodermal activity flux of the neurologically healthy young adults during the neuro/psychometry research section, which lasted between 20-30 minutes, was on average -30% (SD=21%) in their left wrist and on average -3% (SD=47%) in their right wrist, compared to each participant's personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account.

These findings suggest that the autonomous arousal of the young adults was on average slightly lower during the neuro-psychometric tasks, compared to the other research sections. There was comparatively more electrodermal activity in the right wrist however, with more variance as well. This could be partly explained by the fact that except for one, all young adult participants were right-handed and used their right hand to type on the IPad during this research section.

The distribution of the right wrist data was not normal so I performed a Wilcoxon signed-rank paired samples t test which showed that the odds that there was an unequal amount of electrodermal activity in both wrists were low; 1.5, with a location parameter of 14% difference in electrodermal flux between the left and right wrist and a two-sided p-value of 0.107. I took this 14% higher electrodermal activity flux in the right wrist, which I ascribed to motor activity, as a benchmark to gage the possible contribution of emotional arousal to the electrodermal activity flux patterns in the research participants across the different research sections.

The electrodermal activity flux of the neurologically healthy senior adults during the neuro/psychometry research section was on average +28% (SD=72%) in their left wrist and on average +79% (SD=87%) in their right wrist, compared to each participant's personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. When comparing these findings to the young adult cohort, a Welch's independent samples t test showed that it was 22 times more likely that the neurologically healthy senior adults had a significantly different flux pattern of electrodermal activity in their left wrist than the young adults during the neuropsychometric test, with a location parameter of +58% in electrodermal flux and a two-sided p-value of 0.003. A partial explanation might be that there were 4 times more left-handed people among the senior adult participants. However, increased motor activity is a less likely explanation for the large difference in electrodermal flux in the right wrist between the young and senior adults during the neuropsychometric test, which was +82%. It's implausible that the senior adults made more vigorous hand movements as all the neuropsychometric test items were presented as multiple choice questions on an IPad and participants simply had to tap the answer of their choice.

It was not possible to statistically test the mean difference in electrodermal activity flux in the right wrist between the young and senior adults because the data distribution of the young adults was not normal and the two groups had unequal variances. However, when comparing the electrodermal activity flux in the left wrist with the right wrist in the neurologically healthy senior adults, it was 7.7 times more likely that there was a true unequal level of electrodermal activity between both wrists during the neuropsychometric test, with a location parameter of +63% in electrodermal flux and a two-sided p-value of 0.01.

Neurologically healthy young and senior adults had similar scores on the abbreviated WASI Matrices test, but it could be possible that the cognitive load of performing the task was higher for senior adults, which could explain their higher level of electrodermal activity during the neuropsychometric research section. Another explanation for this finding could be that the senior adults experienced considerably more emotional arousal during the neuropsychometric test, compared to the other research sections. Since the increase in electrodermal activity was strongly asymmetrical and highest in the right wrist, this could signify that the valence of the emotional arousal was more likely to be negative (Lanteaume et al., 2007; Picard et al., 2015) and could possibly be a sign that the neurologically healthy senior adults were experiencing stress during the neuropsychometric test. The electrodermal flux patterns of the young adults suggest that they were relatively at ease during the neuropsychometric testing, in comparison to the other research sections.

*Senior adults living with dementia*
The electrodermal activity flux of the senior adults living with dementia during the neuropsychometric test was on average +15% (SD=82%) in their left wrist and on average +69% (SD=136%) in their right wrist, compared to each participant's personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. The electrodermal activity flux patterns of both wrists looked quite similar to the neurologically healthy senior adults, with a location parameter of -17% and a two-sided p-value of 0.751 for the left wrist and a location parameter of 27% and a two-sided p-value of 0.848 for the right wrist.
However, the large variances in both wrists, especially the right wrist, suggest significant differences in individual electrodermal activity flux patterns among the senior adults living with a dementia, which I have further detailed under the case study profiles.

The neuropsychometric results of the neurologically healthy adults are shown in Figure 47. Figures 48 and 49 visualise the neuropsychometric results of the senior adults living with dementia.

## 3.3 CONTEXTUAL INFORMATION CASE STUDIES

### Case studies descriptions

14 senior adults living with various forms of dementia took part in my research. In this section I have summarised their demographic information, the neuropsychometric task results and their autonomous arousal levels during the ACE III; a standard neuropsychometric test. Each participant was given a code P for person, followed by a participant number, their gender (F/M) and their dementia diagnosis code.

### Case study P1M_tAD

A 70 years old, right-handed man who was diagnosed with Typical Alzheimer's Disease outside the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had lived in Nigeria for 5 years. His highest obtained level of education was a BA degree and he used to be a judge by profession. He reported no visual or hearing impairment. He indicated that he looked at visual art monthly and appreciated both figurative and abstract art. He engaged visual art making activities weekly and had done one or more visual art making courses. His knowledge of visual art history/theory was self-taught. He was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale. He reached a total of 50 points on the ACE III test, suggestive of a moderate degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 3: P1M_tAD ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 50 | 50% |
| ACE III Attention | 10 | 56% |
| ACE III Memory | 5 | 19% |
| ACE III Fluency | 3 | 21% |
| ACE III Language | 21 | 81% |
| ACE III Visuospatial | 9 | 56% |

During the neuropsychometric test, the electrodermal activity flux in his left wrist was on average +10% and on average +16% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. This seems to suggest a modest elevation of autonomous arousal during this research section, which was statistically within the same range as the average electrodermal flux in both wrists of the neurologically healthy senior adults. He came for 1 research visit and indicated at the start of the research that his mood was very bright on the Mood Shade Scale.

**Case study P2F_tAD**

An 86 years old, right-handed woman who was diagnosed with Typical Alzheimer's Disease at the National Hospital for Neurology and Neurosurgery, London She had been born in the UK and had lived  in South Africa for 5 years. Her highest obtained level of education was a MA degree and she had been a jazz singer by profession. She reported no visual or hearing impairment. She indicated that she looked at visual art weekly and appreciated both figurative and abstract art. She engaged in visual art making activities monthly and had done one or more courses in visual art making. She had received a formal education in visual art history/theory (she had gone to art school). She was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale. She reached a total of 85 points on the ACE III test, suggestive of a mild degree of dementia. Her outcomes on the subcategories of the ACE III were as follows:

**Table 4: P2F_tAD ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 85 | 85% |
| ACE III Attention | 14 | 78% |
| ACE III Memory | 18 | 69% |
| ACE III Fluency | 12 | 86% |
| ACE III Language | 26 | 100% |
| ACE III Visuospatial | 15 | 94% |

During the neuropsychometric test, the electrodermal activity flux was on average +387% in her left wrist and on average +249% in her right wrist, compared to her personal average electrodermal activity in both wrists across all research sections, taking only the active research time into account. This seems to suggest an extreme elevation of autonomous arousal during this research section, which was much higher than the average electrodermal flux in the left wrists of the neurologically healthy senior adults during the neuropsychometric test with an two-sided p-value of 0.0001 and a likelihood ratio of 375 (Vovk-Sellke MPR).

The electrodermal activity in the right wrist of the neurologically healthy senior adult cohort was already elevated at +79%, but in comparison hers was still significantly higher at +249%. This was close to the upper boundary within the range of variance with a two-sided p-value of 0.06 and a likelihood ratio of 2.1. Her electrodermal activity was strongly asymmetrically elevated in both wrists, which seems most likely indicative of a starkly negative emotional arousal during the neuropsychometric test, which is congruent with behavioural signs of distress she displayed such as nervous twitches and verbal expressions of performance anxiousness.

She came for 2 research visits, with two weeks in between.

At the start of the first research visit she marked her mood as dark on the Mood Shade Scale and at the start of the second visit as very dark. These ratings were congruent with her expressed state of depression due to her dementia diagnosis.

**Case study  P3F_tAD**

A 70 years old, right-handed woman who was diagnosed with Typical Alzheimer's Disease at the National Hospital for Neurology and Neurosurgery, London. She had been born in the UK and had lived in Malta for 1 year. Her highest obtained level of education was a BA degree and she used to run community theatre programmes by profession. She reported no visual impairment, but mentioned that she was having her hearing tested that week because her adult son who lived in with her complained that she often didn't seem to notice that he was talking to her. She indicated that she looked at visual art a few times a year and appreciated both figurative and abstract art. She made visual art expressions weekly and had done one or more courses in visual art making, as well as in visual art history/theory. She was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale.  She obtained a total of 74 points on the ACE III test, suggestive of a mild degree of dementia. On the subcategories of the ACE III her outcomes were as follows:

**Table 5: P3F_tAD ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 74 | 74% |
| ACE III Attention | 13 | 72% |
| ACE III Memory | 7 | 27% |
| ACE III Fluency | 13 | 93% |
| ACE III Language | 25 | 96% |
| ACE III Visuospatial | 16 | 100% |

During the neuropsychometric test, the electrodermal activity flux was on average -23% in her left wrist and on average -15% in her right wrist, compared to her personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. These findings seem to suggest that she experienced a relatively low level of emotional arousal during this research section.
She came for 2 research visits, spread over two consecutive days. At the start of both research visits she indicated that her mood was bright on the Mood Shade Scale.

**Case study P4M_svPPA**

A 67 years old, right-handed man who was diagnosed with Semantic Primary Progressive Aphasia at the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had lived abroad in Tanzania for 4 years, in Cyprus for 3 years and in Australia for 6 months.
His highest obtained level of education was a BA degree and he used to be an international project developer. He reported no visual or hearing impairment. He was unable to answer the questions on his experience with visual art, as he told me he did not understand what art meant, an indication that his semantic knowledge about art had been affected by his dementia.
He also didn't know what the word 'colour' meant anymore, but he understood the Matching Colour Scale without any verbal instruction and was able to accurately match all 11 colour hue items as well as the grey-scale item. He reached a total of 39 points on the ACE III test, suggestive of a severe degree of dementia.

On the subcategories of the ACE III his outcomes were as follows:

**Table 6: P4M_svPPA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 39 | 39% |
| ACE III Attention | 16 | 89% |
| ACE III Memory | 3 | 12% |
| ACE III Fluency | 2 | 14% |
| ACE III Language | 7 | 27% |
| ACE III Visuospatial | 11 | 69% |

His electrodermal activity flux during the neuropsychometric test was not statistically evaluated as he was only able to participate in this research section and the Digital Colour Spaces experiment, which would give skewed results when compared to the other data which had been based on all 6 research sections.
He came for 1 research visits and the start of the research visits he indicated that his mood was dark on the Mood Shade Scale. This score was in line with his own verbal account of his state of mind, which he said was troubled as he found he was understanding less and less of what people were saying to him.

**Case study P5M_svPPA**

A 71 years old, right-handed man who was diagnosed with Semantic Primary Progressive Aphasia at the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had never lived abroad. His highest obtained level of education was a BA and he used to an osteopractor.
He reported no visual impairments, but he had been wearing hearing aids since the age of 25. He indicated that he looked a few times a year at visual art, but that appreciated neither figurative nor abstract art these days. He hardly engaged in visual making activities, but had received a formal training in visual art making (as a sculptor), as well as visual history/ theory. He was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale.
He reached a total of 61 points on the ACE III test, suggesting

he had a moderate degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 7: P5M_svPPA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 61 | 61% |
| ACE III Attention | 17 | 94% |
| ACE III Memory | 10 | 38% |
| ACE III Fluency | 7 | 50% |
| ACE III Language | 11 | 42% |
| ACE III Visuospatial | 16 | 100% |

His electrodermal activity flux during the neuropsychometric test was not statistically evaluated as his average electrodermal activity over the entire research visit could only be calculated over the time period of the neuropsychometric testing and the Digital and Print Colour Spaces experiments – the 3 research sections he was able to contribute to –, which would give skewed results when compared to the other data which had been based on all 6 research sections.
He came for 1 research visit and the start of the research visits he indicated that his mood was very dark on the Mood Shade Scale. This rating was in line with his verbal account of his state of mind, which he described as very depressed and throughout our communications he often spoke of wanting to commit suicide.

**Case study P6M_nfPPA**

A 73 years old, right-handed man who was diagnosed with Nonfluent Primary Progressive Aphasia at the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had never lived abroad. His highest obtained level of education was GCSE/O and he used to be an importer of overseas goods by profession. He reported no visual or hearing impairment. He indicated that he looked at visual art weekly and appreciated both figurative and abstract art.
He engaged in visual art making activities weekly – he was an avid hobby painter – and was self-taught in visual art making.
He had also received a formal education in visual art history/ theory. He initially mismatched 6 out of 11 colour hues on the Matching Colours Scale, but on a second attempt he only made 1 mistake; mismatching a light red to a muted red. In a previous clinical interview at the UCL Dementia Research Centre it had been observed that he appeared to struggle with naming primary colours. His wife who also took part in my research mentioned that he had started using more unnatural colours in his paintings and increasingly preferred grey-scale hues. He reached a total of 66 points on the ACE III test, suggestive of a mild towards moderate degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 8: P6M_nfPPA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 66 | 66% |
| ACE III Attention | 13 | 72% |
| ACE III Memory | 21 | 81% |
| ACE III Fluency | 0 | 0% |
| ACE III Language | 22 | 85% |
| ACE III Visuospatial | 10 | 63% |

During the neuropsychometric test, the electrodermal activity flux was on average -42% in his left wrist and on average +23% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. This seems to suggest he experienced a lower level of autonomous arousal during this research section in his left wrist, but a moderately elevated level in his right wrist, both of which were within the range of variance compared to the average electrodermal flux in both wrists of the neurologically healthy senior adults during the neuropsychometric test.
He came for 2 research visits, with a week in between.
At the start of the first research visits he indicated that his mood was very bright and at the start of the second research visits he indicated that his mood was bright on the Mood Shade Scale.

**Case study P7M_nfPPA**
A 57 years old, right-handed man who was diagnosed with Nonfluent Primary Progressive Aphasia at the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had never lived abroad. His highest obtained level of education was GCSE/O and used to be an account by profession. He reported no visual impairment but he did have a 10% level hearing impairment. He indicated that he looked at visual art a few times a year and appreciated both figurative and abstract art. He engaged in visual art making activities a few times a year and had little to no training in visual art making and visual art history/theory.

He was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale.
He reached a total of 57 points on the ACE III test, suggestive of a moderate degree of dementia. His outcomes on the subcategories of the ACE III his outcomes were as follows:

**Table 9: P7M_nfPPA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 57 | 57% |
| ACE III Attention | 17 | 94% |
| ACE III Memory | 10 | 38% |
| ACE III Fluency | 7 | 50% |
| ACE III Language | 13 | 50% |
| ACE III Visuospatial | 14 | 88% |

During the neuropsychometric test, the electrodermal activity flux was on average +47% in his left wrist and on average +121% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account.
This seems to suggest a significant elevation of autonomous arousal during this research section, which was within the range of variance compared to the average electrodermal flux in both wrists of the neurologically healthy senior adults during the neuropsychometric test.
As his electrodermal activity was asymmetrically strongly elevated in both wrists, with a higher increase in the right wrist, these findings seem most likely indicative of a negative emotional arousal during the neuropsychometric test.
He came for 1 research visit and the start of the research visits he indicated that his mood was bright on the Mood Shade Scale.

**Case study P8F_nfPPA**
A 70 years old, right-handed woman who was diagnosed with Nonfluent Primary Progressive Aphasia outside the National Hospital for Neurology and Neurosurgery, London. At the time of the research visit was nearly completely mute, but could still effectively communicate by gestures and with the aid of paper and digital notebooks.
She had been born in the UK and had lived 3 years in Sierra Leone and 3 years in Kenya. Her highest obtained level of education was a BA and she used to be a secretary by profession. She reported no visual impairment, but she had been wears hearing aids since 1995. She indicated that she looked at visual art daily and appreciated both figurative and abstract art. She added that what she enjoyed about looking at visual art was that she didn't needed verbal language to engage with it and allowed her to just experience it. She engaged in visual art making activities weekly, but had little to no training in visual art making. She had done one or more courses in art history/theory.

She mismatched 8 out of the 11 colour hues on the Matching Colours Scale. On the item that I designed to assess green/red colour blindness, she matched the saturated red block with a muted green colour block. She had not reported being colour blind on the Thinking Eyes Questionnaire, which asked this after this specifically. This suggests that she might have acquired a green/red colour blindness as a consequence of her Nonfluent Primary Progressive Aphasia.
It seems very unlikely that she would have been colour blind her whole life without realising. She made most of the other colour hue mismatches by consistently choosing a saturated colour

block in items where a non-saturated colour hue had to be matched. In items where a light colour block had to be matched, and there was no saturated colour as a choice option, she selected the exact matching hue 2 out of 3 times. She gave the impression that she had clearly understood the purpose of the task, but it is difficult to tell whether she persistently selected saturated colour blocks because she might have (sub-consciously) preferred these colours, or whether she perceived them as the right colour hue she had to match. She also mismatched the grey-scale item, matching a dark grey hue with a lighter hue of grey. She reached a total of 30 points on the ACE III test, suggestive of a severe degree of dementia. Her outcomes on the subcategories of the ACE III were as follows:

**Table 10: P8F_nfPPA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 30 | 30% |
| ACE III Attention | 11 | 61 |
| ACE III Memory | 2 | 8% |
| ACE III Fluency | 0 | 0% |
| ACE III Language | 3 | 12% |
| ACE III Visuospatial | 14 | 88% |

During the neuropsychometric test, the electrodermal activity flux was on average -24% in her left wrist and on average +385% in her right wrist, compared to her personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. This findings seems to suggest an extreme level of – most likely negative – emotional arousal during this research section, given the sustained asymmetrical increase of electrodermal in the right wrist, which was considerably higher than the average electrodermal flux in the right wrist of the neurologically healthy senior adults during the neuropsychometric test with an two-sided p-value of 0.002 and a likelihood ratio of 25.8. In stark contrast, her left wrist showed a lower electrodermal activity flux than her personal average across all research sections, and fell within the range of variance of the neurologically healthy senior adults.

She came for 2 research visits, with 2 weeks in between.
At the start of the first research visit she indicated that her mood was neutral and at the start of the second visit she indicated that her mood was bright on the Mood Shade Scale.

**Case study P9M_lpPPA**

A 69 years old, left-handed man who was diagnosed with Logopenic Primary Progressive Aphasia at the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had lived in Canada for unknown amount of time. His highest obtained level of education was a BA and he used to be a pastor by profession. He reported no visual or hearing impairment. He indicated that he looked at visual art monthly. His appreciation for figurative and abstract art was unknown. He hardly ever engaged in visual art making activities and had little to no training in visual art making and visual art history/theory. He was unfortunately unable to do any of the research sections due to his severe difficulties with semantic language comprehension and I decided it was in his best interest to stop the research visit soon after we started.

He came for 1 research visit and indicated that his mood was neutral on the Mood Shade Scale at the start of the visit.

**Case study P10M_bvFTD**

A 63 years old, right-handed man who was diagnosed with Behavioural Frontotemporal Dementia outside the National Hospital for Neurology and Neurosurgery, London. He had been born in the UK and had never lived abroad. His highest obtained level of education was a BA, he used to be a journalist by profession before his dementia diagnosis.
He reported no visual or hearing impairment. He indicated that he hardly ever looked at visual art, appreciated both figurative and abstract art. He hardly ever engaged in visual art making activities and had little to no training in visual art making and visual art history/theory. He was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale.

He reached a total of 46 points on the ACE III test, suggestive of a moderate degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 11: P10M_bvFTD ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 46 | 46% |
| ACE III Attention | 7 | 39% |
| ACE III Memory | 10 | 38% |
| ACE III Fluency | 3 | 21% |
| ACE III Language | 16 | 62% |
| ACE III Visuospatial | 10 | 63% |

During the neuropsychometric test, the electrodermal activity flux was on average -13% in his left wrist and on average -8% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account.
These values seem to suggest a relatively average/low personal level of autonomous arousal during this research section, in comparison to the other research sections.
While lower than the average electrodermal activity flux of the neurologically health senior adults during the neuropsychometric test, these values were still within the range of variance.
He came for 2 research visits, with 3 months in between.
At the start of the first research visits he indicated that his mood was neutral and at the start of his second research visit he indicated that his mood was bright on the Mood Shade Scale.

**Case study P11M_bvFTD**

A 61 years old, right-handed man who was diagnosed with Behavioural Frontotemporal Dementia at the National Hospital for Neurology and Neurosurgery, London.
He had been born in the UK and had lived never lived abroad.
His highest obtained level of education was a BA degree.
He reported no visual or hearing impairment. He used to be a Fine Art valuer by profession and he indicated that he looked at visual art daily and appreciated both figurative and abstract art.
He hardly ever engaged in visual art making activities himself and had little to no training in visual art making.
He had done one or more courses in visual art history/theory.
He was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale.
He reached a total of 74 points on the ACE III test, suggestive of a mild degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 12: P11M_bvFTD ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 74 | 74% |
| ACE III Attention | 15 | 83% |
| ACE III Memory | 11 | 42% |
| ACE III Fluency | 7 | 50% |
| ACE III Language | 25 | 96% |
| ACE III Visuospatial | 16 | 100% |

During the neuropsychometric test, the electrodermal activity flux was on average +5% in his left wrist and on average -49% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. This seems to suggest an average to low level of autonomous arousal during this research section, especially his right wrist electrodermal activity flux appeared to be considerably lower compared to the average electrodermal flux in the right wrist of the neurologically healthy senior adults during the neuropsychometric test, but both wrists were within the range of variance.
He came for 2 research visits with 3 weeks in between. At the start of both research visits he indicated that his mood was bright on the Mood Shade Scale.

**Case study P12M_PCA**

An 80 years old, right-handed man who was diagnosed with Posterior Cortical Atrophy. He had been born in the UK and lived 3 months each year in South Africa. His highest obtained level of education was a PHD and he used to be a Professor of

psychiatry by profession. He reported having visual impairments due to his dementia diagnosis and while he himself said he had no hearing impairment, his wife who was also present argued differently. He indicated that he looked at visual art daily and appreciated both figurative and abstract art. He engaged in visual art making activities weekly and had done one or more courses in visual art making and visual art history/theory.
He mismatched 6 out of the 11 colour hues on the Matching Colours Scale. I asked if he might be experiencing colour after-images, but he said that this was not the case.
On the item that I designed to assess green/red colour blindness, he matched the saturated red block with a muted green colour block. He had not reported being colour blind on the Thinking Eyes Questionnaire, which asked after this specifically. This suggests that he might have acquired a green/red colour blindness as a consequence of his Posterior Cortical Atrophy, as it seems very unlikely that he would have been colour blind his whole life without realising. He had reported earlier however that his father had a congenital green/red colour blindness, which might point to a genetic vulnerability.
He made further colour hue matching mistakes in every colour hue category across different brightness variations and he also mismatched the grey-scale item, matching a dark grey hue with a lighter hue of grey.

He reached a total of 42 points on the ACE III test, suggestive of a moderate degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 13: P12M_PCA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 42 | 42% |
| ACE III Attention | 5 | 28% |
| ACE III Memory | 11 | 42% |
| ACE III Fluency | 5 | 36% |
| ACE III Language | 19 | 73% |
| ACE III Visuospatial | 2 | 13% |

During the neuropsychometric test, the electrodermal activity flux was on average -20% in his left wrist and on average +40% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. The strongly asymmetrical elevation of electrodermal activity flux in his right wrist is suggestive of modest negative emotional arousal during this research section, which was within the range of variance of the average electrodermal flux in the right wrist of the neurologically healthy senior adults during the neuropsychometric test.
He came for 2 research visits with 4 weeks in between. At the start of both research visits he indicated that his mood was neutral on the Mood Shade Scale.

**Case study P13F_PCA**

A 64 years old, right-handed woman who was diagnosed with Posterior Cortical Atrophy. She had been born in Poland where she had lived for 28 years before moving to the UK where she had been living for the past 36 years. Her highest obtained level of education was a MA degree and she had been employed by a large supermarket chain. She reported having visual impairments due to her dementia diagnosis and she remarked that she was slow with processing sounds as well. She indicated that she looked at visual art monthly and appreciated both figurative and abstract art. She hardly ever engaged in visual art making activities and had little to no training in visual art making. Her knowledge of visual art history/theory was self-taught.
She made 1 mistake on the Matching Colours Scale, matching a muted blue with a saturated blue. She accurately matched the other 10 colour hue items, as well as the grey-scale item.

She reached a total of 64 points on the ACE III test, suggestive of a mild to towards moderate degree of dementia. Her outcomes on the subcategories of the ACE III were as follows:

**Table 14: P13F_PCA ACE III Outcomes**

| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 64 | 64% |
| ACE III Attention | 14 | 78% |
| ACE III Memory | 17 | 56% |
| ACE III Fluency | 4 | 29% |
| ACE III Language | 19 | 73% |
| ACE III Visuospatial | 10 | 63% |

During the neuropsychometric test, the electrodermal activity flux was on average -18% in her left wrist and on average +472% in her right wrist, compared to her personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. The extreme and strongly asymmetrical elevation of electrodermal activity flux in her right wrist is suggestive of a significant negative emotional arousal during this research section, which was far above the range of variance of the average electrodermal activity flux in the right wrist of the neurologically healthy senior adults during the neuropsychometric test with a two-sided p-value of 0.0003 and a likelihood ratio of 174,2. The electrodermal activity flux in her left wrist was slightly lower than her average electrodermal activity across all research sections, and fell within the range of variance of the neurologically healthy senior adults.
She came for 1 research visit and the start of the research visits she indicated that her mood was very bright on the Mood Shade Scale.

**Case study P14M_UD**

An 64 years old, right-handed man who was diagnosed with an unspecified dementia with possible subcortical involvement. He had been born in the UK and had lived abroad for 2 years in Sudan, Kenya and Saudi Arabia. His highest obtained level of education was A levels and he used to be a contracts manager for high voltage infrastructure business. He reported having no visual or hearing impairment. He indicated that he looked at visual art weekly and appreciated both figurative and abstract art. He hardly ever engaged in visual art making activities and had little to no training in visual art making. His knowledge of visual art history/theory was self-taught. He was able to accurately match all 11 colour hue items as well as the grey-scale item on the Matching Colours Scale.

He reached a total of 71 points on the ACE III test, suggestive of a mild degree of dementia. On the subcategories of the ACE III his outcomes were as follows:

**Table 15: P14M_UD ACE III Outcomes**

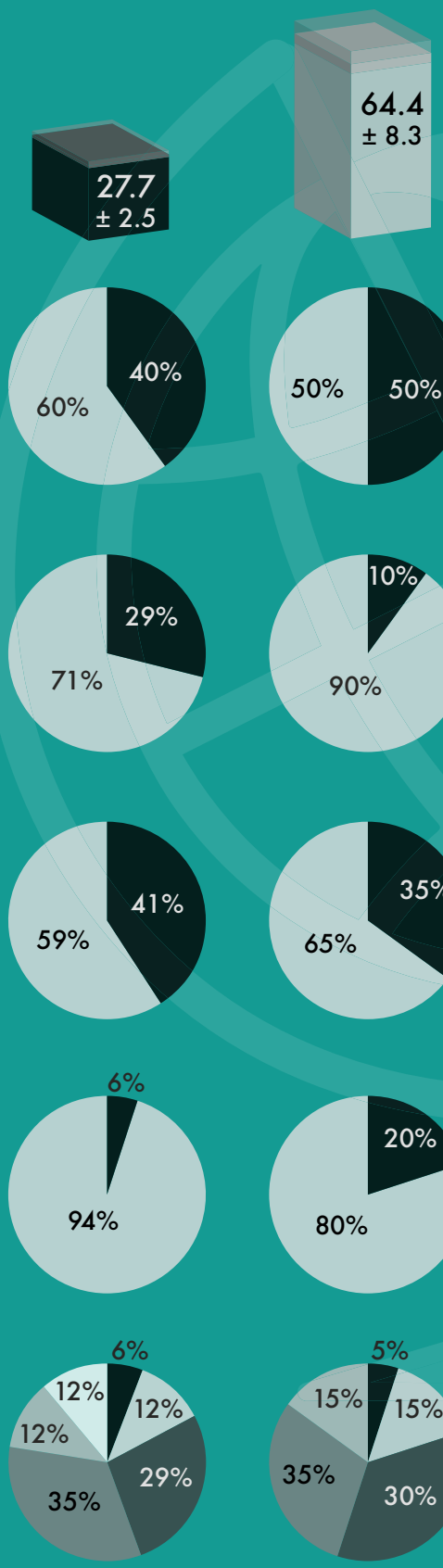
| Section | Score | % of Norm Score |
|---|---|---|
| Total ACE III | 71 | 71% |
| ACE III Attention | 13 | 72% |
| ACE III Memory | 14 | 54% |
| ACE III Fluency | 4 | 29% |
| ACE III Language | 24 | 92% |
| ACE III Visuospatial | 16 | 100% |

During the neuropsychometric test, the electrodermal activity flux was on average +199% in his left wrist and on average +70% in his right wrist, compared to his personal average electrodermal activity in both wrists across the entire research visit, taking only the active research time into account. His left wrist flux was just above the range of variance in the neurologically healthy adults with a two-sided p-value of 0.03 and a likelihood ratio of 3.4, whereas his right wrist electrodermal activity was elevated to a similar level as in the neurologically healthy adults during the neuropsychometric test (+79%). The strong and asymmetrical elevation of electrodermal activity flux in both wrists is suggestive of an increased negative emotional arousal during this research section.
He came for 2 research visits with a week in between.
At the start of both research visits he indicated that his mood was bright on the Mood Shade Scale.

**Figure 45**

# DEMOGRAPHIC BACKGROUND

**YOUNG ADULTS SENIOR ADULTS**




**AVERAGE AGE**
- Senior adults (N=20)
- Young adults (N=17)
- Standard deviation

**GENDER**
- Female
- Male

**PLACE OF BIRTH**
- UK
- Elsewhere

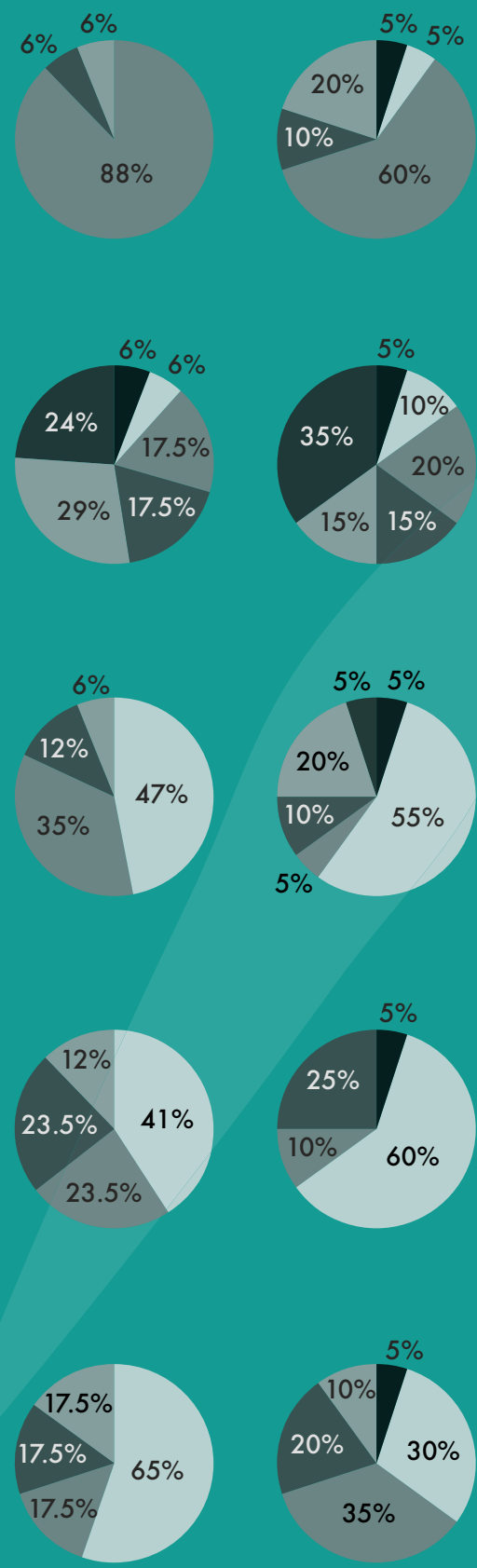
**LIVED ABROAD**
- Yes
- No

**HANDEDNESS**
- Right-handed
- Left-handed

**EDUCATION LEVEL**
- GCSE/O
- A levels
- BA/BSc
- MA/MSc
- PhD
- Unknown

# VISUAL ART EXPERIENCE

**YOUNG ADULTS SENIOR ADULTS**




**PREFERENCE**
- Figurative art
- Abstract art
- Prefers both
- Prefers neither
- Unknown

**VIEWING FREQENCY**
- Daily
- Weekly
- Monthly
- A few times a year
- Hardly ever
- Unknown

**MAKING FREQUENCY**
- Daily
- Weekly
- Monthly
- A few times a year
- Hardly ever
- Unknown

**PRACTICAL TRAINING**
- Formal education
- Course(s)
- Self-taught
- Little to no training
- Unknown

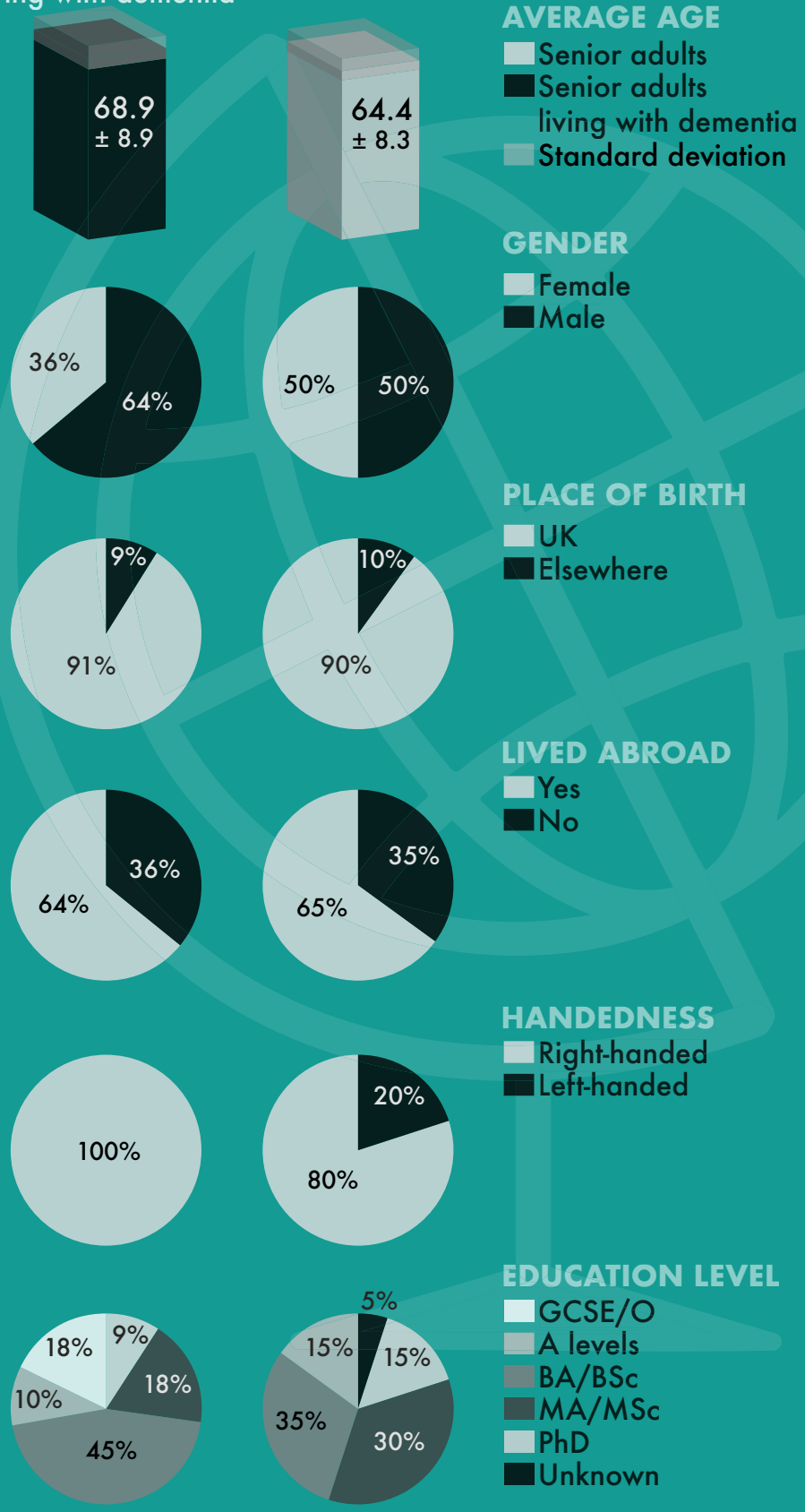
**THEORY TRAINING**
- Formal education
- Course(s)
- Self-taught
- Little to no training
- Unknown

Figure 46

# DEMOGRAPHIC BACKGROUND

**SENIOR ADULTS** living with dementia

**SENIOR ADULTS**




# VISUAL ART EXPERIENCE

**SENIOR ADULTS** living with dementia

**SENIOR ADULTS**

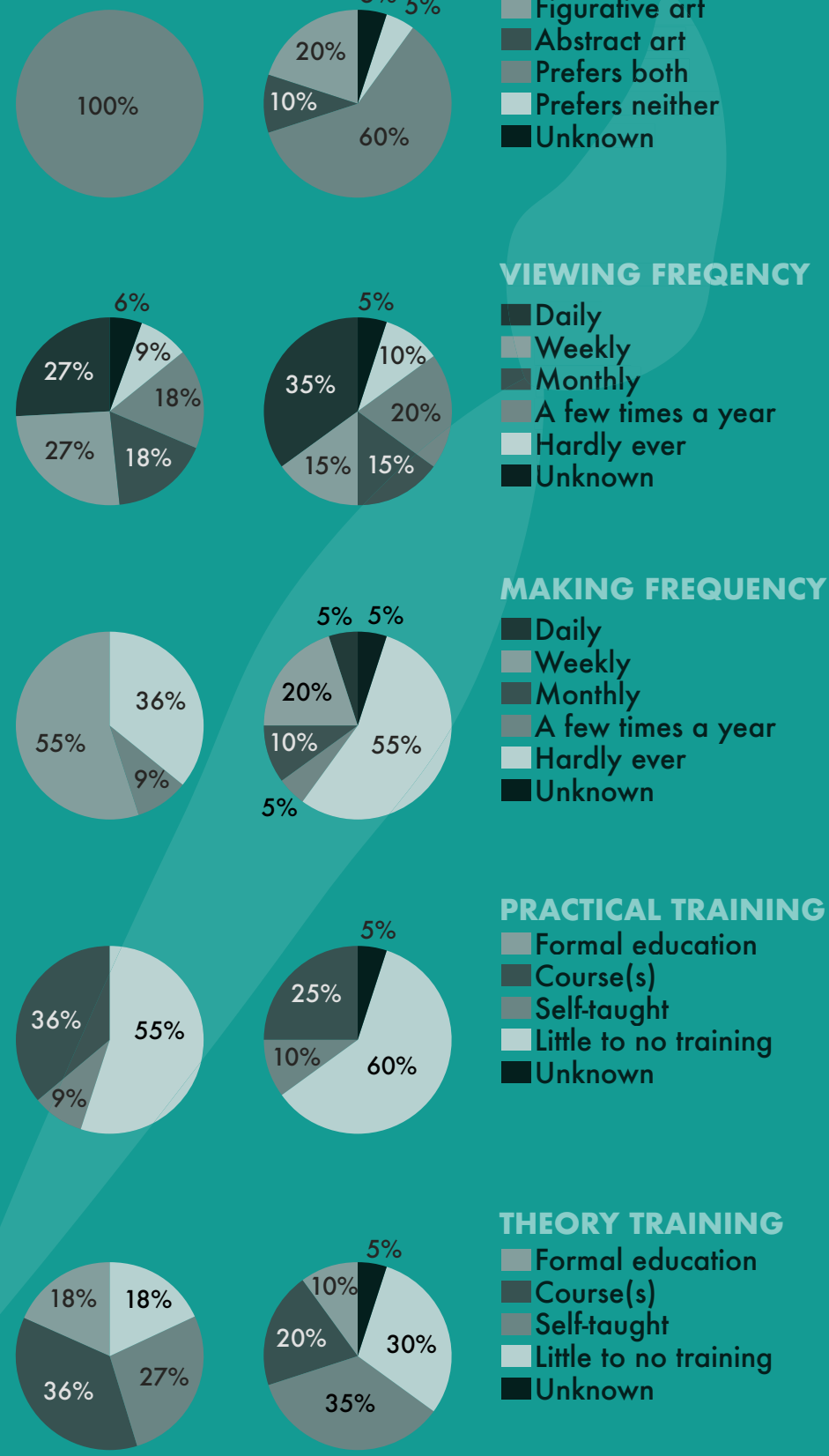
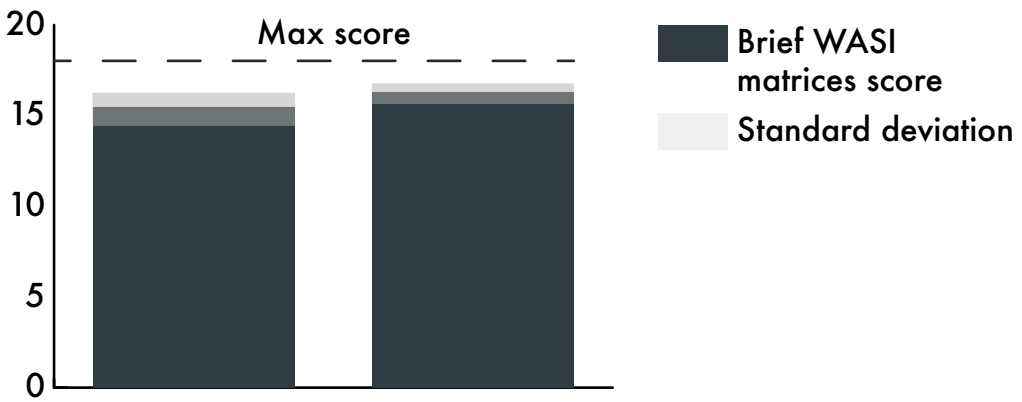


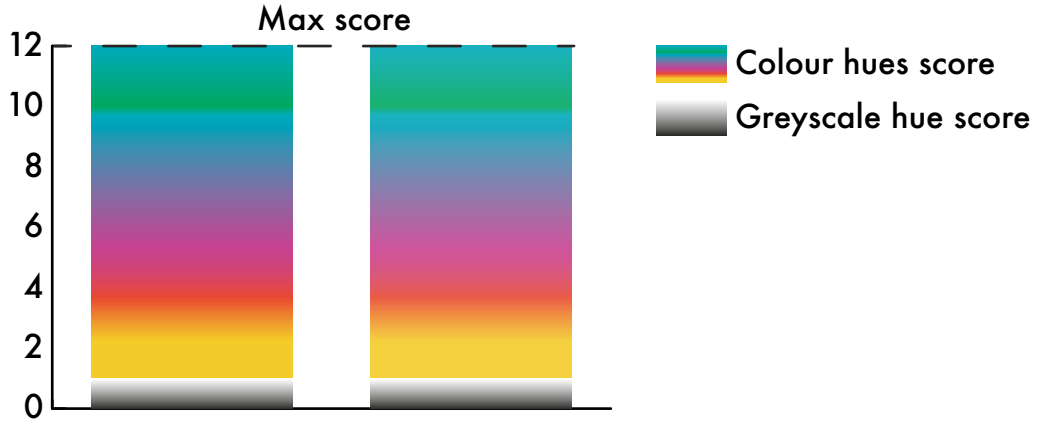
Figure 47

# CONTEXTUAL PSYCHOMETRY
## NEUROLOGICALLY HEALTHY ADULTS

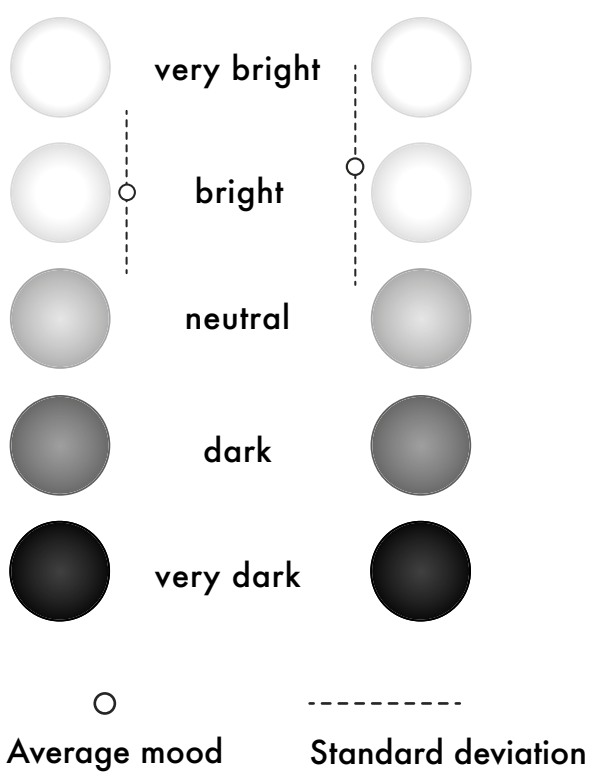
### PERCEPTUAL REASONING TEST
YOUNG ADULTS SENIOR ADULTS




### MATCHING COLOURS SCALE
YOUNG ADULTS SENIOR ADULTS




### MOOD SHADE SCALE
YOUNG ADULTS SENIOR ADULTS




### NEUROPSYCHOMETRY ELECTRODERMAL ACTIVITY (EDA)
YOUNG ADULTS SENIOR ADULTS

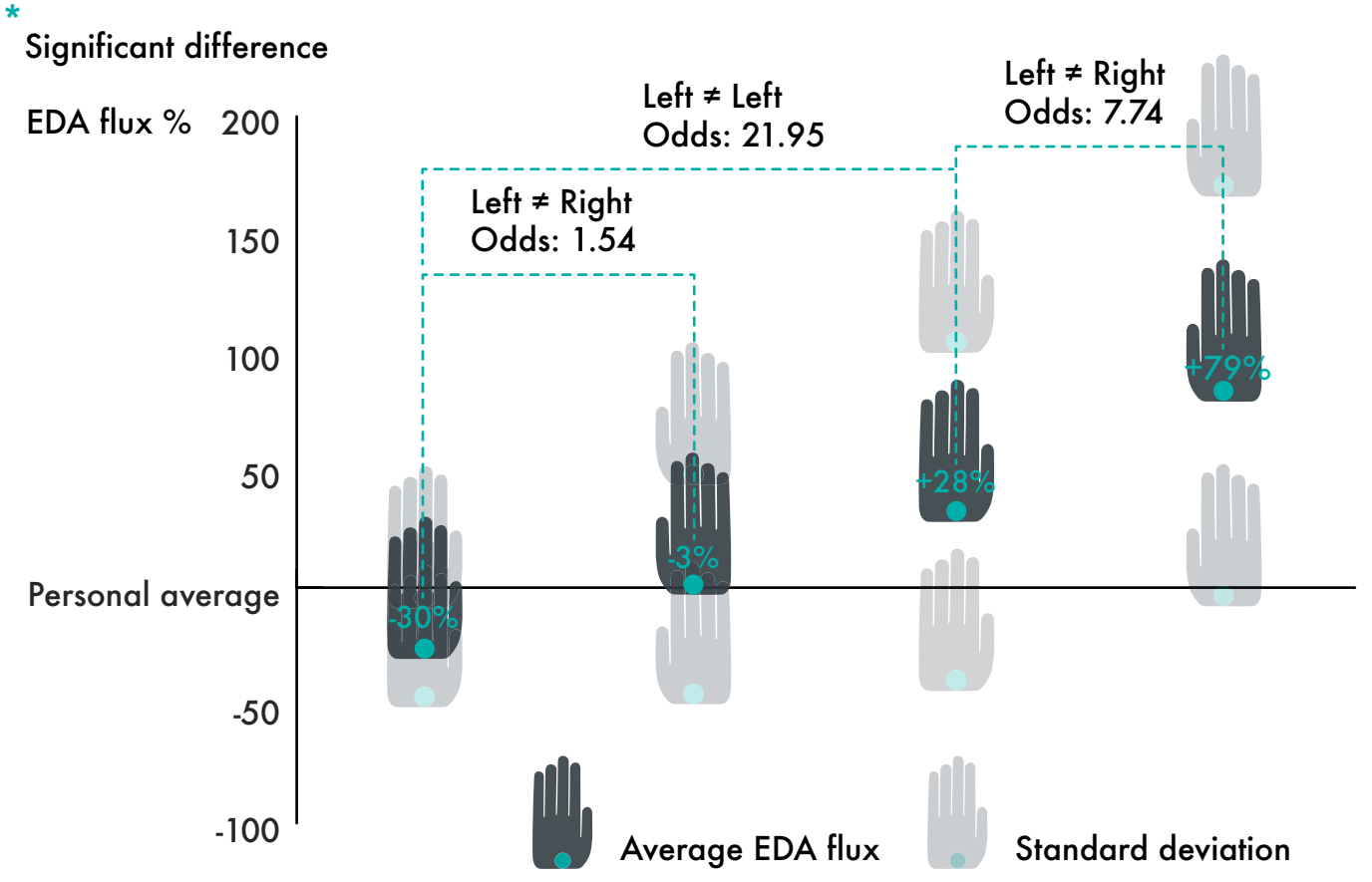
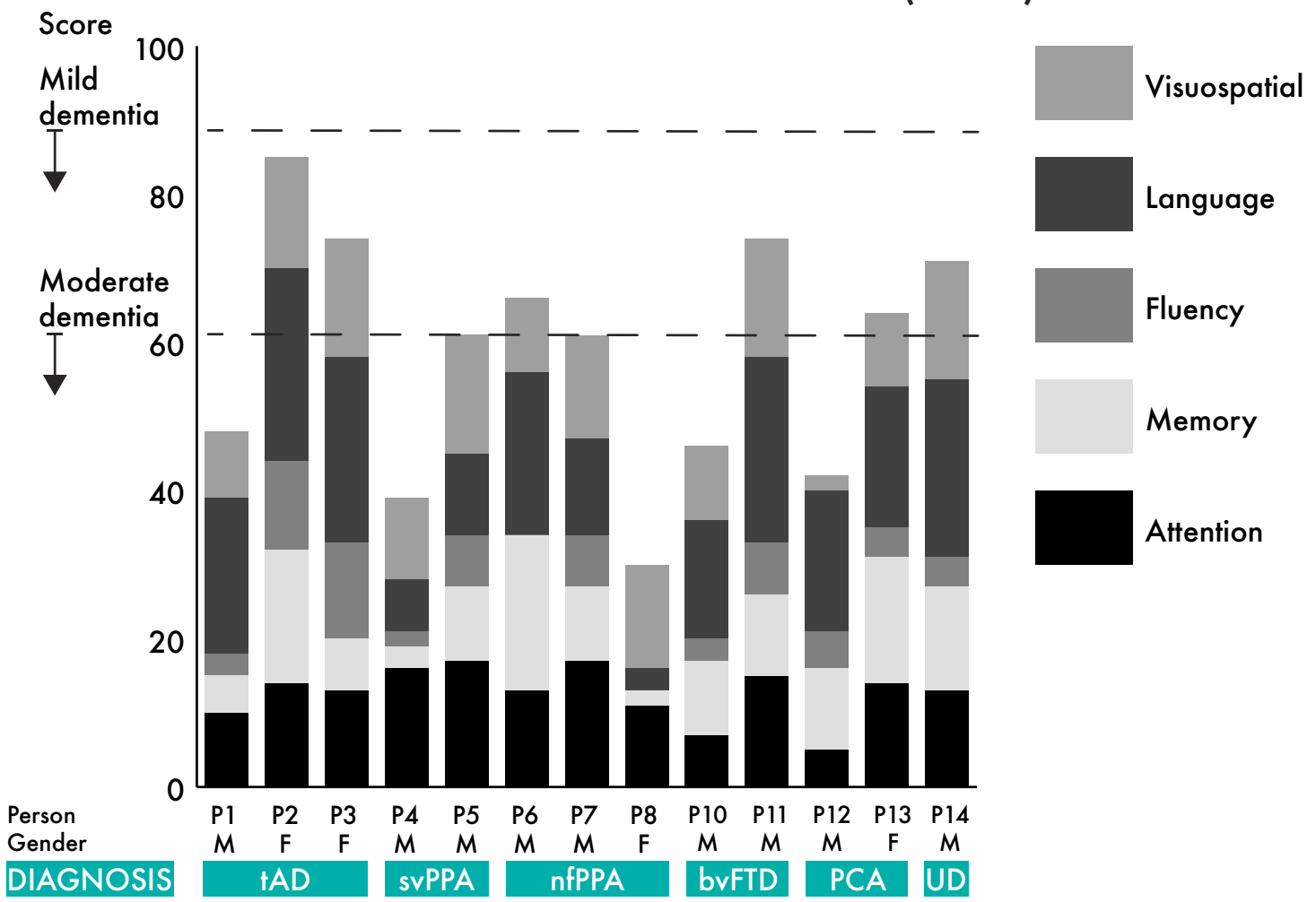


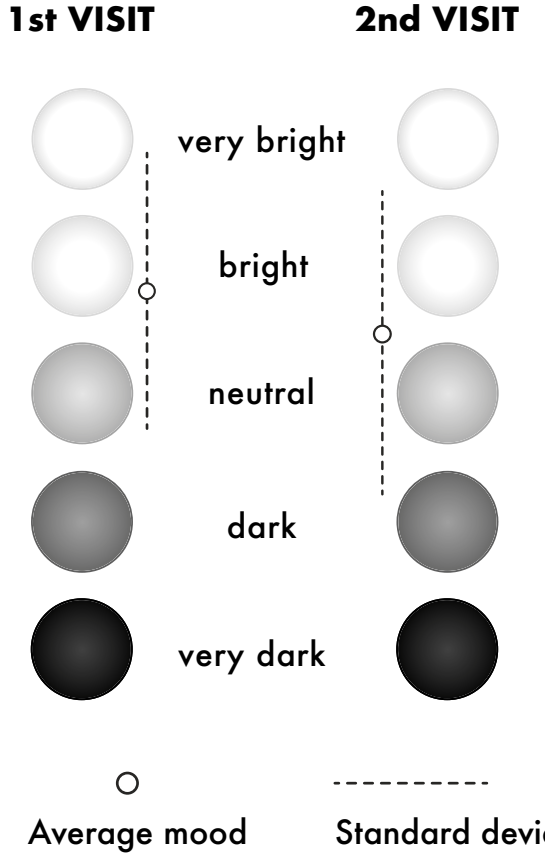
**Figure 48**

# CONTEXTUAL PSYCHOMETRY
## SENIOR ADULTS LIVING WITH DEMENTIA

### ADDENBROOKE'S COGNITIVE EVALUATION (ACE III)




### MOOD SHADE SCALE




### MATCHING COLOURS SCALE

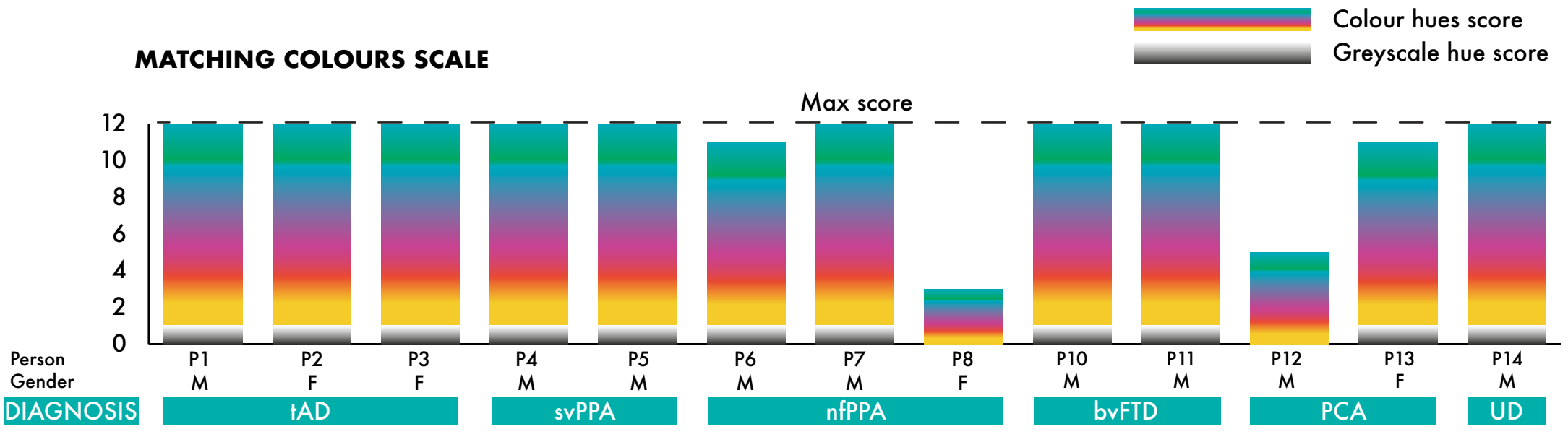
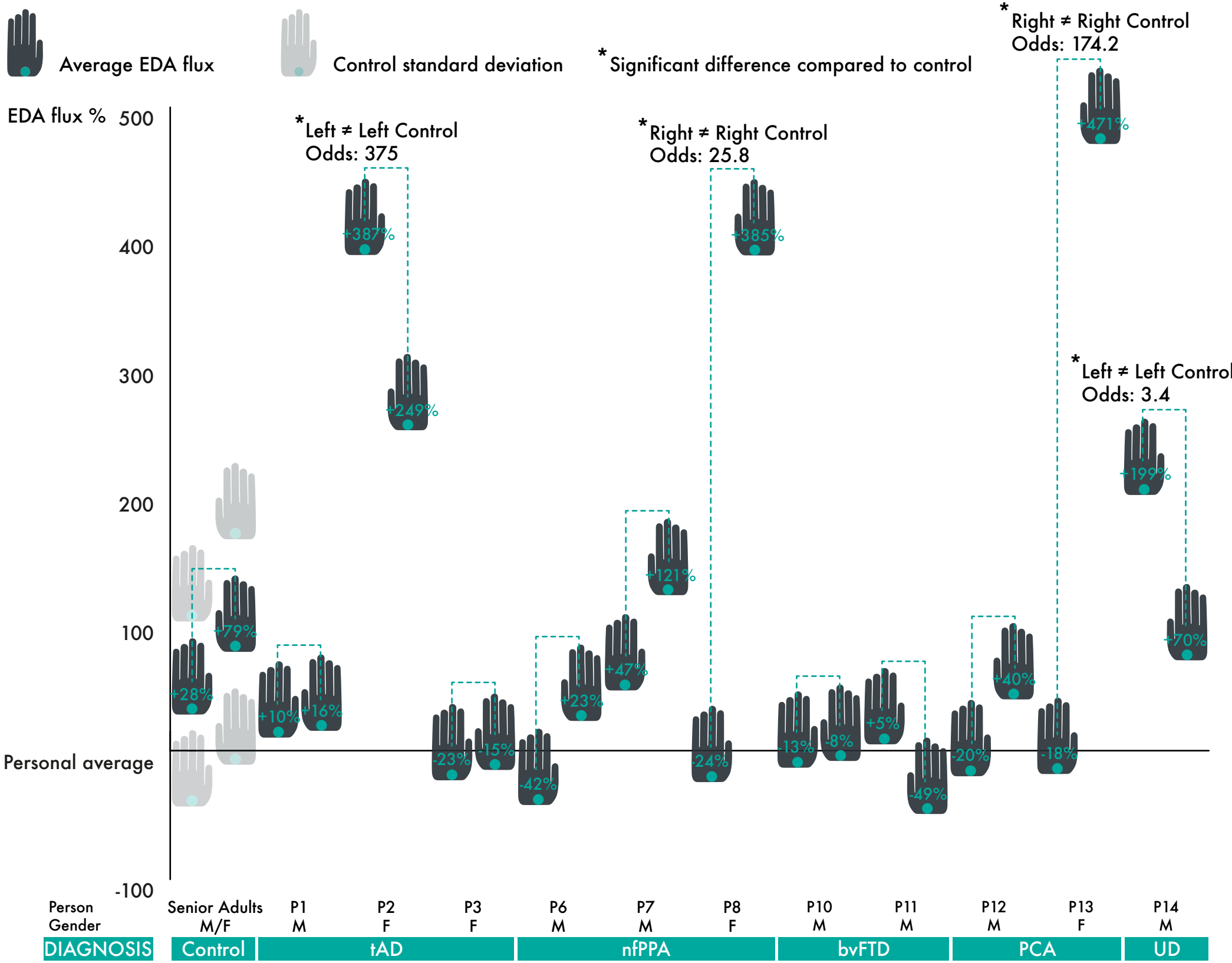


**Figure 49**

# NEUROPSYCHOMETRIC TEST ELECTRODERMAL ACTIVITY (EDA)

## SENIOR ADULTS LIVING WITH DEMENTIA





# 4. EXPERIMENTAL RESEARCH

## 4.1 OVERVIEW EXPERIMENTAL DESIGNS

In this chapter I have described the two neuroscientific research projects: Thinking Eyes and Colour Spaces. All neurologically healthy research participants took part in both projects and 11 of the 14 participants living with dementia as well (see also under the Experimental Framework chapter). The Thinking Eyes project consisted of 3 experiments and the Colour Spaces of 2 experiments. Figure 50 gives a visual overview of the experimental designs of the two neuroscientific research projects. I introduced the overlapping research methods between the two projects in the previous chapter and I have further detailed the specific experimental design for each project in the next sections.

## 4.2 THINKING EYES PROJECT

### 4.2.1 INTRODUCTION

The Swiss painter Paul Klee, whose collected notebooks 'The Thinking Eye' (1961) inspired the title of this study, once famously said:

'Art does not represent the visible; rather, it makes visible'

The astute insights of Paul Klee and many other great artists informed my own firm belief that art offers us a window to reflect on the complex interactions between the outside world and the worlds inside our heads.

Most of us operate on the assumption that the physical world is made up of elements which are consistent and objectively real. What is arguably far less present -at least in the Western individual's mind, with its focus on rational thought and individualism-, is an awareness of how much our perceptions, thoughts and communications are intertwined with our social environments. Our senses are neither passive nor neutral perceivers of the material world, but proactive interpreters; research has found for instance that the primary visual cortex (V1) creates templates of expected incoming information, even in absence of an actual visual stimulus (Kok et al., 2014). All human cognitive faculties, including logical reasoning, are limited by the boundaries of our imagination and are developed by interaction with the social environment (including cultural, economical, as well as political context).

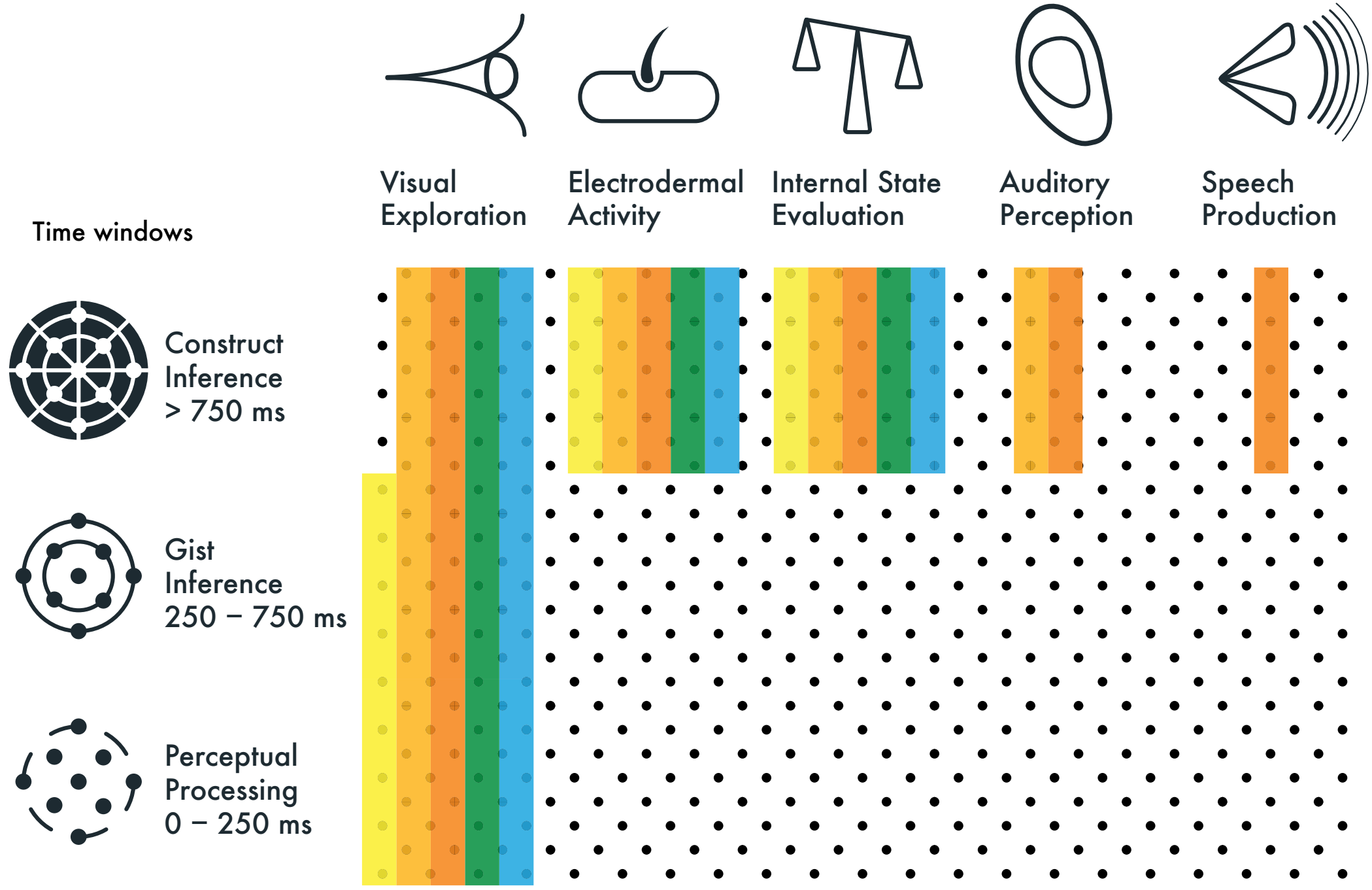
Neuroscience has been relatively slow to pick up on the concept of the social brain, which was introduced to the field in the 1990s (Lieberman, 2012). Well before that time, influential psychologists such as Rudolph Arnheim, Jerome Bruner, Abigail Housen, James Gibson and Lev Vygotsky had already written extensively on how visual perception, complex thought processes and the social environment are deeply interconnected.
The arts-based facilitated conversation method Visual Thinking Strategies (Housen, 1999), consolidated these insights by placing social context at the heart of perceptual interpretation, conceptual understanding and verbal communication. Before I will describe my experimental research, I will first give a further introduction to the Visual Thinking Strategies (VTS) method.

**How do people perceive visual art?**
In the early 1990's Philip Yenawine, at the time Director of Education of the Museum of Modern Art (MoMA) in New York, USA, was asked by the Board of Directors to study how effective the MoMa's educational programme was. What they knew, was that there was a great need among visitors for information and guidance and the feedback on the MoMA's guided gallery tours was consistently very positive. What was unknown up till that point however, was what visitors actually took in from the information that was given to them by the MoMA staff, who were all engaging and highly trained. In other words, what did people learn? Did the gallery talks help visitors to get a better understanding of the art?

To answer this question, Yenawine set up a study in collaboration with Cognitive Psychologist Abigail Housen, who had developed a theory of Aesthetic Development based on doing decades of

Figure 50

# NEUROSCIENTIFIC RESEARCH PROJECTS
## OVERVIEW EXPERIMENTAL DESIGNS




**THINKING EYES**

1. SNAPSHOTS 64 Trials
2. PERSPECTIVES 30 Trials
3. PANORAMAS 2 Trials

**COLOUR SPACES**

4. DIGITAL 52 Trials
5. PRINT 52 Trials

research on how people perceive visual art. The method behind this research was to record people while they talked about a visual artwork in a stream-of-consciousness way, the so-called Aesthetic Development Interview (ADI), which was then transcribed and analysed. Based on her research findings, Housen proposed that viewers understand works of art in predictable patterns, which she defined as 5 stages of Aesthetic Development as follows (Housen, 1999):

**Stage 1: Accountive** viewers are storytellers. Using their senses,memories, and personal associations, they make concrete observations about a work of art that are woven into a narrative. Here, judgments are based on what is known and what is liked. Emotions colour viewers' comments, as they seem to enter the work of art and become part of its unfolding narrative.

**Stage 2: Constructive** viewers set about building a framework for looking at works of art, using the most logical and accessible tools: their own perceptions, their knowledge of the natural world, and the values of their social, moral and conventional world. If the work does not look the way it is supposed to, if craft, skill, technique, hard work, utility, and function are not evident, or if the subject seems inappropriate, then these viewers judge the work to be weird, lacking, or of no value. Their sense of what is realistic is the standard often applied to determine value. As emotions begin to go underground, these viewers begin to distance themselves from the work of art.

**Stage 3: Classifying** viewers adopt the analytical and critical stance of the art historian. They want to identify the work as to place, school, style, time and provenance. They decode the work using their library of facts and Figures which they are ready and eager to expand. This viewer believes that properly categorized, the work of art's meaning and message can be explained and rationalized.

**Stage 4: Interpretive** viewers seek a personal encounter with a work of art. Exploring the work, letting its meaning slowly unfold, they appreciate subtleties of line and shape and colour. Now critical skills are put in the service of feelings and intuitions as these viewers let underlying meanings of the work what it symbolizes emerge. Each new encounter with a work of art presents a chance for new comparisons, insights, and experiences. Knowing that the work of art's identity and value are subject to reinterpretation, these viewers see their own processes subject to chance and change.

**Stage 5: Re-creative** viewers, having a long history of viewing and reflecting about works of art, now willingly suspend disbelief. A familiar painting is like an old friend who is known intimately, yet full of surprise, deserving attention on a daily level but also existing on an elevated plane. As in all important friendships, time is a key ingredient, allowing Stage 5 viewers to know the ecology of a work – its time, its history, its questions, its travels, its intricacies. Drawing on their own history with one work in particular, and with viewing in general, these viewers combine personal contemplation with views that broadly encompass universal concerns. Here, memory infuses the landscape of the painting, intricately combining the personal and the universal.

### The MoMA gallery talks study

In 1989, Yenawine and Housen set out to explore whether gallery talks led to a greater understanding of art of visitors at the Museum of Modern Art in New York and how this might be related to the visitors' Stage of Aesthetic Development (Yenawine, 2013). To this purpose, Yenawine and Housen recruited a group of 22 adults and first conducted an Aesthetic Development Interview (Housen, 1999) with them to determine their stage of aesthetic development. The participants then took part in a gallery talk on abstract and expressionist art, delivered by an experienced and engaging MoMA guide. Afterwards, participants were asked to recall what they remembered from the gallery talk.

What Housen and Yenawine found was that what people recalled from the gallery talk was coloured and filtered by their Stage of Aesthetic Development.

Beginner viewers (stage I & II) would frame the galley talk in their personal world view, norms & values and everything that fell outside this construct would be dismissed. The conclusion that Housen and Yenawine came to was that beginner viewers couldn't accommodate factual information yet in the analytical way stage III viewers and upwards could. Gallery talks with early stage viewers did not lead to a greater understanding of art that was not familiar or liked. An earlier study by Housen at the Institute of Contemporary Art (ICA) in Boston had found that most visitors were beginner viewers (Housen, 1987), which made Housen and Yenawine realise that the museum's much appreciated gallery talks were actually not the most helpful educational tool to the bulk of visitors. What these visitors needed more was a guiding framework that would assist them with looking at and making sense of art, which led Yenawine and Housen to develop the Visual Thinking Strategies (VTS) method.

**VTS in practice**

VTS is a facilitated group discussion on which guides participants in the perceptual meaning making process and verbal communication of their thoughts in a social context. VTS conversations were originally developed for art museums, but are very suitable for any kind of setting in which people explore an image together. The VTS facilitator structures the conversation with by the following 3 questions:

1. What's going on in this picture? (sculpture/installation/situation/etc)

2. What do you see that makes you say that?

3. What more can we find?

The role of the facilitator is not to provide information that satisfies these questions, but to guide people through a process of curious exploration, critical reflection and collective meaning making. By asking the participants to identify visible references for their thoughts and pointing these out, neutrally paraphrasing every comment and linking this to perspectives offered by other participants, the facilitator is scaffolding a visual thinking strategy which people can internalise over time. Housen and her research associate Karen DeSantis conducted their visual literacy research mostly in the context of fine art museums and primary education across America and the outcomes were published in reports and practical guidelines. Recent publications have provided supporting evidence for the effectiveness of VTS, showing that VTS develops social, visual observation and imagination skills, as well as critical thinking and verbal communication abilities (Hailey et al., 2015; Miller et al., 2013; Naghshineh et al., 2008). Beyond museums, VTS has been of great value in a broad spectrum of public education contexts over the past two decades, because of its ability to adapt to the developmental level and personal interest of the specific audience. An added benefit is that a formal art education is not a prerequisite to master the VTS facilitating techniques. In addition to leading fine art museums, the VTS method is now internationally used in primary and higher education. VTS co-founder Yenawine has published two books which provide practical guidelines how VTS can be incorporated into educational programmes and daily activities for children (Yenawine, 2013, 2018).

The VTS method is also applied to medical training, such as the Training The Eye programme at Harvard Medical School for instance, which was developed by Dr. Joel Katz in collaboration with Dr. Shahram Khoshbin and Alexa Miller (Miller et al., 2013). In Amsterdam, the Netherlands, the clinical neuropsychologist René ter Horst has pioneered VTS rehabilitation for people with acquired brain trauma (Kruiper-Doesborgh et al., 2014).

In the Thinking Eyes project I investigated the multi-modal social brain dynamics that are involved when people engage with visual art and complex images. In three successive eye tracking experiments, I studied the specific mechanisms of the VTS method. In this process, I explored whether there might be differences between young and senior adults in how they experience visual art and complex images. I also studied how people living various forms of dementia engage with visual art and complex images.

In the next chapter I have first described the experimental design, followed by the novel quantitative analyses methods that I developed, before presenting and discussing the results.

### 4.2.2 MATERIALS AND METHODS

Building on the core principles of the VTS method, I designed three experiments to investigate multi-modal aspects of visual imagination in the context of the social brain in healthy ageing and dementia. My aim was to create behavioural experiments that aligned with distinct temporal processes and network dynamics relevant to visual imagination and other complex social behaviour as described by the social brain connectome (Alcala-Lopez et al., 2017) and other studies I reviewed under the Theoretical Framework chapter. The 3 research cohorts have been described under the General Methods section of the Experimental Framework chapter.

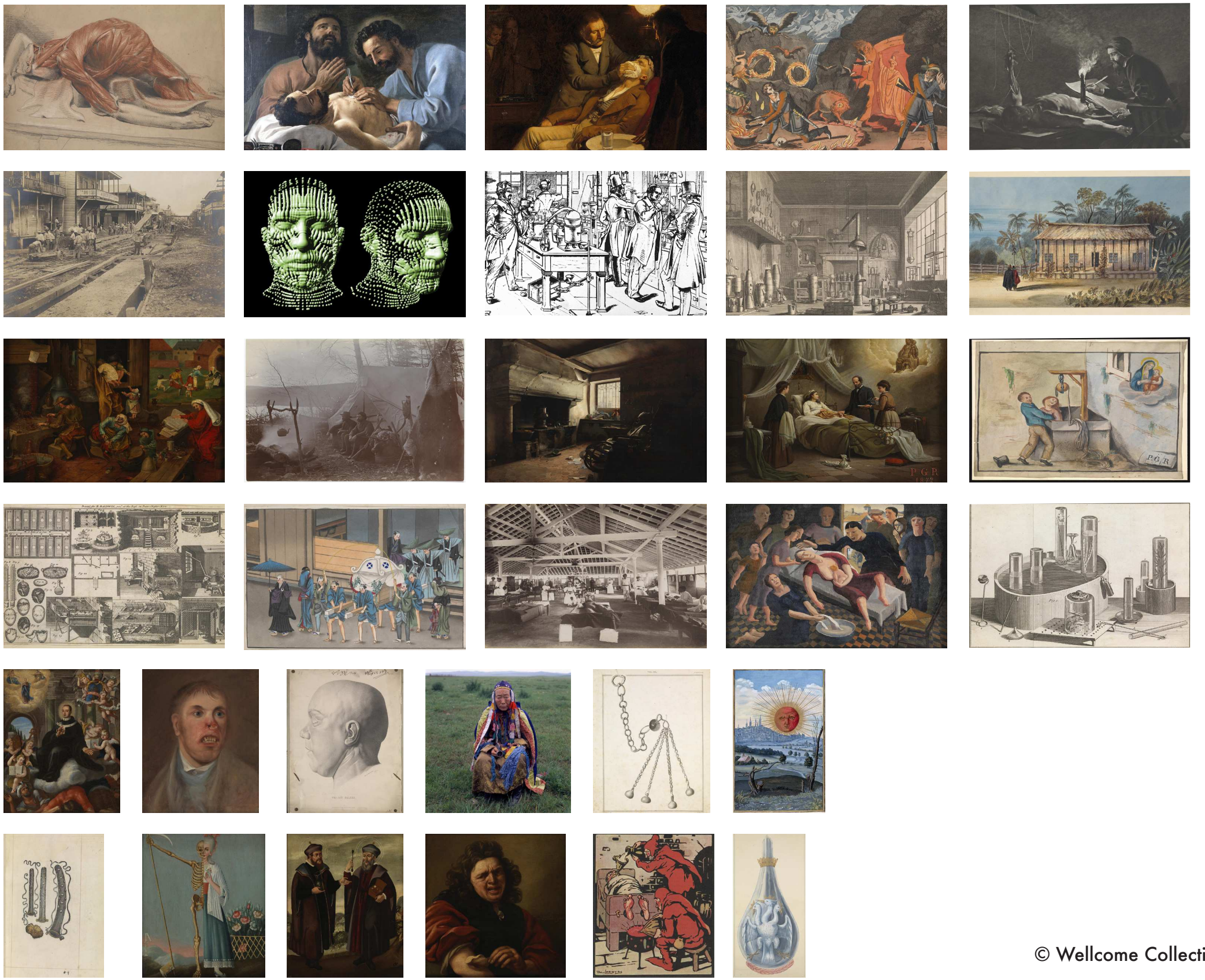
#### Experimental design

In the first  experiment 'Snapshots', I investigated participants' multi-modal responses to visual artworks and complex images after an initial perceptual processing and a gist evaluation phase (0 – 750 ms). The rationale behind this specific time window was to create an eye tracking experiment that aligned with the Initial Aesthetic Network as described by Cela-Conde et al. (2013), corresponding to the Perception and Animation Network in the Social Brain Atlas. Participants were shown a selection of 32 images from the Wellcome Collection in London on a high-quality LCD monitor in a black-out room. The image selection included only figurative depictions of mostly of public health and medical science related subject matters, which is the core focus of the Wellcome Collection. The images varied in medium (drawing, painting, photography and print) and chromaticity (colour and greyscale). I resized all images to a vertical dimension of 1000 pixels and placed them on a middle grey background. I created a distorted version of every image by applying in 50% of the images a wave and in the other 50%  a triangle wave distortion filter in Adobe Photoshop CS8, which fragmented the figurative cohesion but left the colour and light distributions largely intact. This allowed me to study to which extend bottom-up perceptual processing relate to top-down conceptual interpretation in the early cortical processing phases of visual artworks and complex images. The images were shown to participants for 750 ms in randomised order, while an eye tracking camera recorded their eye movements. In between each trial a middle grey screen with a small black central fixation cross was shown for 3 seconds to reorientate the gaze to centre of the screen. After each image presentation, participants were asked to say out loud how much it resonated with them on the Resonance Radius Scale; a 5-point visual rating instrument which I had specifically designed for this study (Figure 43).

Figure 51 shows an overview of the 32 coherent versions of the Wellcome image selection. Figure 52 shows the distorted versions of the Wellcome image selection.

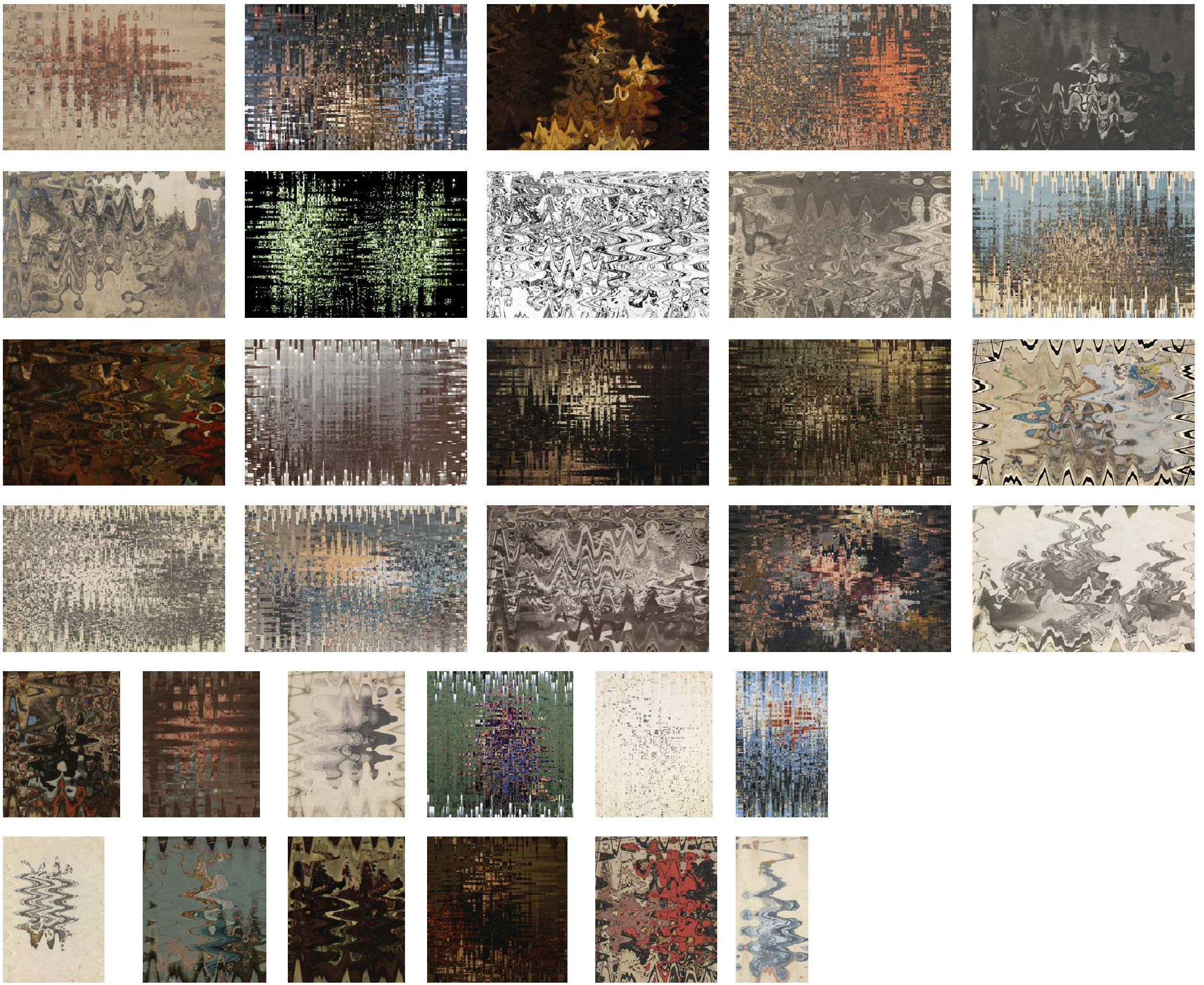
In the second experiment 'Perspectives', participants were shown 30 of the 32 figurative images from the 'first experiment again, but this time for 20 seconds while the eye tracking camera recorded their eye movements. The rationale behind this time window was that the longer viewing period would engage the Delayed Aesthetic Network as described by Cela-Conde et al. (2013), aligning with the Interaction and Construction Networks of the Social Brain Atlas. In this experiment it was also my aim to study the interaction between auditory perception and visual exploration and to investigate whether different viewing

**Figure 51: Coherent versions of the Wellcome selection of visual artworks and complex images**



© Wellcome Collection

**Figure 52: Distorted versions of the Wellcome selection of visual artworks and complex images**



conditions might have an effect on people's visual exploration patterns and their personal resonance responses.

As people were looking at the visual artworks and complex images, they were played an audio recording, all spoken by the same native British female voice, which talked about the image. After each image presentation, participants were asked to say out loud how much it resonated with them on Resonance Radius Scale. In between each trial a middle grey screen with a small black central fixation cross was shown for 3 seconds to reorientate the gaze to centre of the screen.

There were 3 different audio conditions, which each consisted of 10 different images from the selection of 32 figurative visual artworks and complex images presented in the first 'Snapshots' experiment In the first audio condition 'External context', participants were read out the contextual information the Wellcome Collection had provided about that image in their online catalogue. This was typically the kind of information that is usually written on the wall label next to an artwork in a museum, such as a clarification of what was depicted, the name of the artist and the year of production.

In the second audio condition 'External perspective', participants listened to a personal reflection on the image. This personal perspective was given in response to the first VTS question; 'What is going on in this picture?', which I asked the narrator just before the start of the audio recording. All the recorded responses were authentic and unscripted, but edited down to fit within the time frame of the trials. This condition was modelled on the social scaffolding aspect of the VTS method, whereby participants are exposed to other people's perspectives on the image they are viewing collectively.

In the third audio condition 'Internal perspective', the narrator asked the participants the first VTS question; 'What is going on in this picture?'. In the audio instructions that were played at the beginning of the experiment, participants had been requested to reply to this question inside their heads. The purpose of this was to create 3 comparable experimental conditions to study the relation between auditory perception and visual exploration. The 'External context' and 'External perspective' conditions alternated each other in pseudo randomised manner across two blocks of 10 image trials, with a block of 10 trials on the 'Internal perspective' in between.

In the third experiment 'Panoramas', I aimed to resemble the dynamics of a VTS group conversation as closely as possible under the restrictions of a carefully controlled experimental research setting.
In this experiment participants were shown the remaining 2 images from the selection of 32 figurative visual artworks and complex images presented in the first 'Snapshots' experiment. In this experiment I also recorded eye movements, but I specifically focused on the dynamics of speech production in response to visual exploration.

As soon as the first image was presented, participants were played an audio file in which a native British female voice asked the first VTS question: "What is going on this image?". Verbal responses were recorded over the duration of 1 minute, after which an audio recording with the second VTS question was played, asking: "What do you say that makes you say that?". Verbal responses were again recorded over a period of 1 minute. Participants were then played 2 consecutive audio recordings of 2 different people; 1 male and 1 female, who were talking about the image the participants were viewing. Each audio fragment was played during a 45 second presentation window. In the first trial, both audio recordings gave a personal perspective. In the second trial, the first recording offered a personal perspective and the second audio file read out the contextual information from the Wellcome Collection's online catalogue. After this, participants were played an audio recording with the third VTS question: "What more can you find?", and their verbal responses were once more recorded during a 1-minute time window.

After each image presentation, participants were asked to say out loud how much it resonated with them on Resonance Radius Scale. In between each trial a middle grey screen with a small black central fixation cross was shown for 3 seconds to reorientate the gaze to centre of the screen.

In the next sections I have set out the quantitative analysis methods that I developed in order to assess the complex social brain dynamics at play across the three experiments of the Thinking Eyes research project.

**Visual exploration analysis**

In this study I took the point of view that human visual exploration is tuned towards optimising interaction with the social world. Following from this premise, I created a novel quantitative method to predict and analyse visual exploration patterns that aligns closely with the physiology of human vision and the functional likelihood ratios of behavioural functions in the Social Brain Atlas (Alcalá-López et al., 2017).

The visual information that reaches the primary visual cortex arises from a complementary dynamic between peripheral and central vision. Peripheral vision consist of contrasts between light and dark, and is regulated by the rod receptors in the retina that are only sensitive to variations in brightness. The part of the human visual field that is perceived in colour and in high acuity is defined by the fovea, a small pit in the macula of the retina. The fovea is approximately 1.5 mm in diameter and densely populated by cone receptors that are selectively sensitive to different light wavelengths that broadly align with the colours blue (short wavelengths), green (medium wavelengths) and red (long wavelengths).

Foveal vision only makes up the central 5 degrees of the total human visual field, but it is responsible for a large amount of the visual information that reaches the visual cortex. This means that the eyes will constantly have to move around to perceive a visual scene sharply and in full colour.

According to the British theoretical neuroscientist Karl Friston, perception is a form of hypothesis testing and visual searches involve the optimisation of information gathering (Friston, 2012). Given the critical role of the fovea in colour and high acuity vision, foveal vision arguably leads to the most effective information gain. I reasoned that if the fixation patterns of foveal vision during the exploration of a visual scene correspond with the perceived salience of elements in that scene, these principles should also apply to visual artworks and complex images.

To test this hypothesis, I created 'foveal interest areas' that equalled the diameter of the foveal visual field and placed these on specific image features in each image to analyse which features would attract the highest proportion of dwell time during the visual exploration of the visual artworks and complex images. I defined a foveal interest area as a circular area of 5 degrees, which is an approximation of the foveal visual field as it is not perfectly circular in shape. I calculated the diameter of the foveal interest area with the use of the Pythagorean theorem by multiplying the tangent function of 2.5 degrees with 75, the distance in cm between the participant's eyes and the image display. I converted the resulting circle radius of 3.3 cm to pixel dimensions, using a cm to pixel ratio of 1: 37.795 (https://www.unitconverters.net), which corresponded to a digital circle diameter of 250 pixels.

If human visual exploration is indeed strongly directed by social relevance (top-down processing), I argued that the Perception Network in the Social Brain Atlas would offer clues as to which social factors are most salient in the early stages of visual processing. Previous research has found that a categorical distinction between animate and inanimate objects is made very early in the human cortical visual processing system (Carlson et al., 2013; Naselaris et al., 2012). I therefore allocated each perceptual category that I created to either the animate or the inanimate domain. What belongs to the animate and inanimate world is not universally agreed on. For instance, some people consider trees to be living creatures. In the context of this study

however, I defined the animate domain as containing (elements of) bodies with a heart beat. I grouped everything else under the inanimate domain. Within these two main domains, I set out to make predictions of the social saliency of distinct perceptual categories, based on the Social Brain Atlas (Alcalá-López et al., 2017) which I called the Social salience model of visual exploration.

I went about this by analysing the functional likelihood ratios of the 6 core hubs of the Perception Network (pSTS_R, FG_R, FG_L, MTV5_R, MTV5_L) in the Social Brain Atlas. Alcalá-López et al. (2017) had computed these likelihood ratios by means of reverse inference. This meant these likelihood ratios gave an indication of how likely it was that a particular mental operation was taking place, given an observed increase of activity in that particular brain area. I reasoned that higher likelihood ratios might also be a reflection of the significance of that particular psychological process in the early stages of visual processing. Following this line of thought, I calculated which functional profiles had the highest average likelihood ratio, across all six core nodes of the Perception Network.

I found that face monitoring engages 5 out of the 6 core nodes in the Perception Network (pSTS_R, FG_R, FG_L, MTV5_R, MTV5_L), with an average recruitment likelihood of 4.2, the highest ratio given for a specific task amongst the functional profiles within the animate domain. Based on this, I hypothesised that if any given visual scene contained facial features, the foveal vision would be directed at these for the longest amount of time during the visual exploration of that scene. I also hypothesised that human faces would be prioritised over animal faces, for other people are for human beings more socially relevant than animals. This prediction is also supported by the findings of a magnetoencephalography (MEG) study by Carlson et al. (2013), which found that in the human cortical processing system of visual information, human faces formed a separate perceptual cluster after 120 ms, whereas monkey faces did not form into a distinct cluster until 180 ms after presentation.

In addition to making a distinction between human and animal faces, I also made separate perceptual categories for frontal and sideways faces. The pioneering neuropsychologist Elizabeth Warrington was among the first to demonstrate that objects are better recognisable when they are observed from a standard (canonical) viewpoint (Warrington & Taylor, 1973). Based on this principle, I hypothesised that frontal faces would be favoured over sideways faces, reflected by longer dwell times.

In their functional profiling, the authors of the social brain connectome labelled action execution as a non-social behaviour (Alcalá-López et al., 2017), which I did not agree with. All social interactions involve action and observing actions performed by other humans and animals provides highly salient social cues. I therefore considered action observation to be a social behaviour. Action observation recruits 5 out of the 6 core nodes in the Perception Network of the Social Brain Atlas (pSTS_R, pSTS_L, FG_R, FG_L, MTV5_R), with an average likelihood of recruitment of 2.3 (Alcalá-López et al., 2017). Hands are perhaps the most versatile tools that human beings have at their disposal for action execution. So I created a 'hand actions' perceptual category within the animate domain, which I ranked directly below the face categories. I speculated that human hand actions would be more salient than animal hand actions during the visual exploration of a scene.

The last perceptual category I created within the animate domain was for body parts other than faces and hands engaged in action (including passive hands). Again, I reasoned that human body parts would be more salient that animal body parts.

The authors of the social brain connectome also categorised verbal language as a non-social behaviour (Alcalá-López et al., 2017), which I disagreed with as well. Language – in all its forms and expressions – only exists in a social context, what the philosopher Ludwig Wittgenstein demonstrated with the concept of language games in his seminal work Philosophical Investigations (1953).

Semantic language engages all 6 core nodes in the Perception Network of the Social Brain Atlas (pSTS_R, pSTS_L, FG_R, FG_L, MTV5_R, MTV5_L), with an average likelihood of recruitment of 12.4, the highest ratio given for a specific task in the inanimate domain amongst the functional profiles in the Social Brain Atlas (Alcalá-López et al., 2017).
The social connectome authors warned of a possible semantic bias in their model due to the strong reliance on semantic processing in the functional neuroimaging research paradigms to date. Based on the dominance of semantic language in the Social Brain Atlas however, the most logical prediction was that written text in visual scenes would attract the largest amount of dwell time in the inanimate domain of visual features. I therefore created a perceptual category 'text elements', which I ranked first in the inanimate domain. If there is indeed a semantic bias in the Social Brain Atlas, I expected that the predicted rank for text elements in visual scenes would turn out to be an over-estimation of the actual proportional dwell time on text elements during the visual exploration of the visual artworks and complex images.

Shape vision, also grouped under non-social behaviour by Alcalá-López et al (2017), can neither be understood outside a social context I argued. Perceptual elements are not processed in isolation by the brain, but understood as part of an entity that takes on a meaning of its own.
Kurt Koffka, co-founder of the Gestalt Psychology school of thought, emphasised this with his famous (often misquoted) proposition: 'The whole is other than the sum of its parts.'
For this reason, I argued that shape vision represents a crucial part of object recognition, a highly socially relevant psychological function. Shape vision engages all 6 core nodes in the Perception Network of the Social Brain Atlas (pSTS_R, pSTS_L, FG_R, FG_L, MTV5_R, MTV5_L), with an average likelihood of recruitment of 5.6, the second highest average after semantic language. Based on this, I created a perceptual category 'human made objects', which I ranked directly under 'text elements' in the inanimate domain.

Space perception, also grouped under non-social behaviour by Alcalá-López et al (2017), is arguably highly social in nature as well, especially in the context of the built environment. Space perception recruits 4 core nodes in the first processing level of the Social Brain Atlas (pSTS_R, pSTS_L, FG_R, FG_L, MTV5_R, MTV5_L), with an average likelihood of recruitment of 1.4 (Alcalá-López et al., 2017). Based on the lower ratio compared to shape vision, I reasoned that objects might possibly be prioritised over space during the earliest perceptual processing stages in the social brain networks. I therefore ranked the perceptual category 'built environment elements', under 'human made objects' in the inanimate domain. Directly below built environment elements, I ranked the perceptual category 'natural elements'.

The final perceptual category in the inanimate domain that I created was 'number elements'. In the human brain number processing is dissociated from lexical processing. Lexical processing is regulated by language networks, with core areas situated around the perisylvian fissure (Friederici & Gierhan, 2013, Xu et al., 2005), whereas number processing takes place across various predominantly parietal networks (Dehaene et al., 2003; Sokolowski et al., 2017). Park et al. demonstrated that already in the visual cortex distinct processing patterns can be observed from the age of 15 on, whereby written letters engage the left visual cortex more and numbers the engage the right visual cortex more (Park et al., 2018). The authors of the social brain connectome did not compute a functional profile for the visual processing of numbers however, which is why I ranked number processing at the bottom of the inanimate domain.

Table 16 on the next page shows the predicted ranking of the 14 perceptual categories of the Social salience model of visual exploration.

**Table 16:**
**The social salience model of visual exploration**

| | |
|---|---|
| **1** | **ANIMATE DOMAIN** |
| 1.1 | Frontal human faces |
| 1.2 | Frontal animal faces |
| 1.3 | Sideways human faces |
| 1.4 | Sideways animal faces |
| 1.5 | Human hand actions |
| 1.6 | Animal hand actions |
| 1.7 | Human body elements |
| 1.8 | Animal body elements |
| **2** | **INANIMATE DOMAIN** |
| 2.1 | Text elements |
| 2.2 | Human made objects |
| 2.3 | Built environment elements |
| 2.4 | Natural elements |
| 2.5 | Number elements |

I used this model to guide the placement of foveal interest areas on different image features within each of the 32 visual artworks and complex images that I had selected from the Wellcome Collection.

I considered the centre coordinates of each foveal interest area to be the most effective gaze orientation. I therefore aligned the centre of each foveal interest area with the centre of a rectangular outline I had drawn around an image feature. Taking into account that the foveal visual field covers a surface of 5 degrees, I reasoned that all fixations within a 2.5 degrees visual angle around the centre coordinates of a particular image feature (corresponding with the surface of the foveal interest area), would lead to effective visual information gain.
Image features that were too large to be captured by a single foveal interest area placement were only divided up in separate foveal interest areas if there was variance in the perceptual surface, whereby lighter or brighter coloured and nearer features were prioritised. If two or more separate image features belonging to the same perceptual category could be fixated with a single foveal interest area, the rectangular outline was drawn around the grouped feature surface.

Facial features were categorised under either the frontal or the sideways facial class, depending on the orientation of the face. Faces that were turned only slightly sideways were assigned to the frontal face category if the gaze was directed towards the viewer and assigned to the sideways face category if the eyes were averted. Objects that were touching a face were included in the rectangular outline that determined where the centre coordinates of the foveal interest area would be placed, as were objects that were held in hands. Human or animal body elements that did not contain visible heads, or hands and were largely or entirely covered by clothing or other covering material, were assigned to the human made objects category. Different image features that were placed in close proximity of each other were only designated separate foveal interest areas if their centre coordinates were more than 125 pixels (the radius of the foveal visual field) apart from each other. If the distance was equal or less than 125 pixels, a single foveal interest area was placed on the centre of the feature highest up in the proposed social salience model of visual exploration.

Since the participants were prompted to orientate their gaze to the centre of the screen before each image presentation, I predicted that they would spend the highest amount of dwell time looking at the centre of the image. Given the strong division in the visual processing of animate and inanimate elements, I expected that participants would spend more time looking at the centre of the image if an animate element was placed there, than if an inanimate element was placed there.

Figure 53 shows a visual overview of the perceptual categories in the animate and the inanimate domains of the Social salience model of visual exploration.
Figure 54 shows the placement of foveal interest areas on image #12 of the Wellcome selection as a demonstration of the method.

Figure 53

# SOCIAL SALIENCE MODEL OF VISUAL EXPLORATION

## ANIMATE DOMAIN



1. Animate image centre



1.1 Frontal human faces



1.2 Frontal animal faces



1.3 Sideways human faces



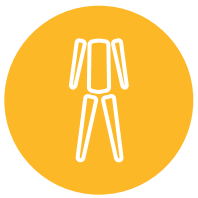
1.4 Sideways animal faces



1.5 Human hand actions



1.6 Animal hand actions

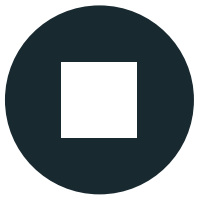


1.7 Human body elements

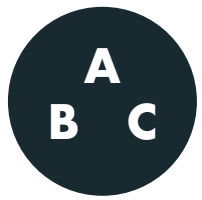


1.8 Animal body elements

## INANIMATE DOMAIN



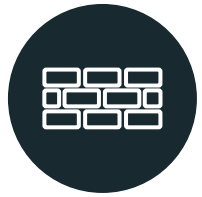
2. Inanimate image centre




2.1 Text elements



2.2 Human made objects



2.3 Built environment elements

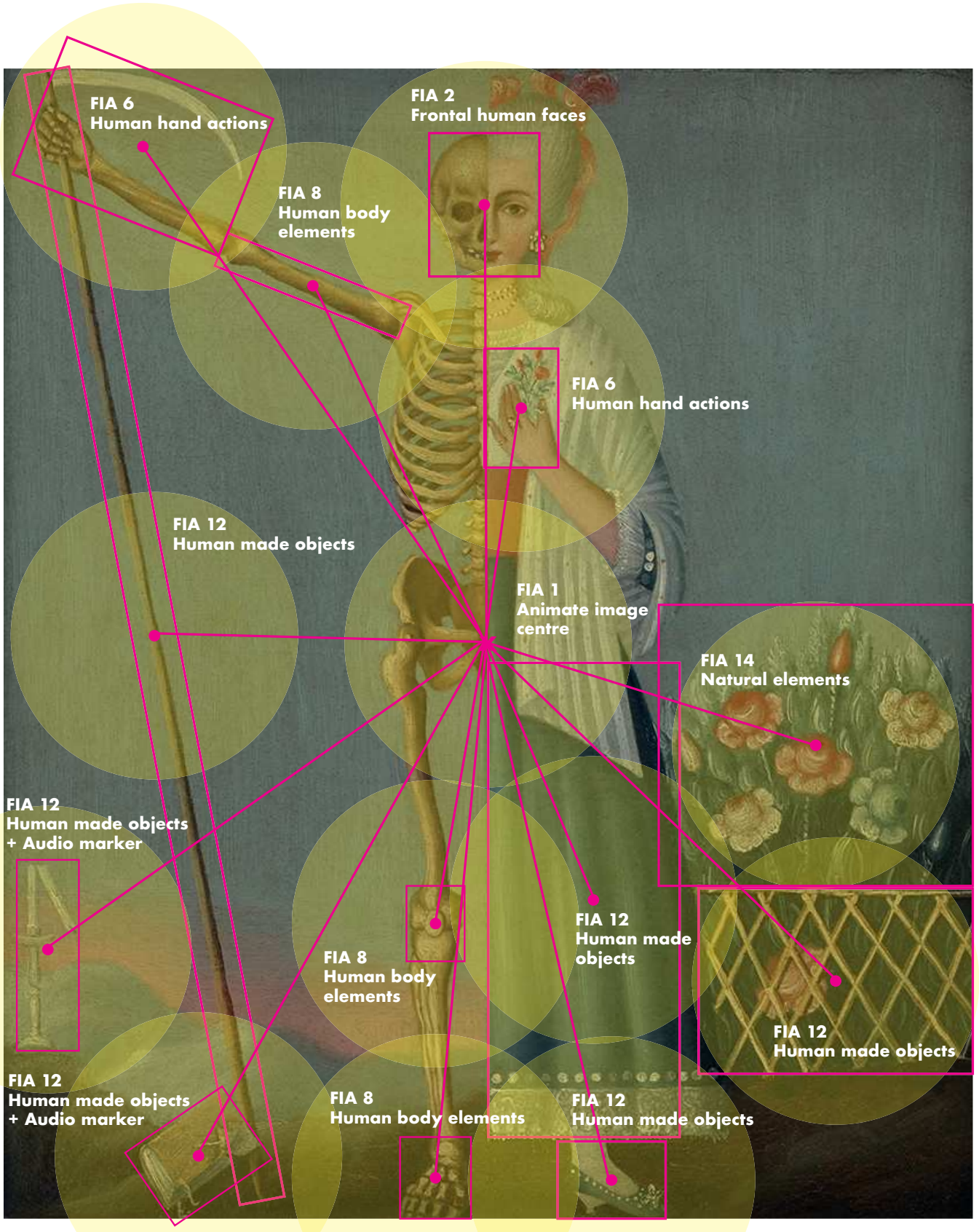


2.4 Natural elements




2.5 Number elements

**Figure 54: Foveal interest areas placement within image #12 from the Wellcome selection**



I created a total 444 foveal interest areas, including an animate and an inanimate central fixation area, which were divided unevenly across the 32 images in strongly varying combinations of the 15 different perceptual categories.
I balanced out the distribution differences, by aggregating the measured absolute and proportional dwell times within each perceptual category over all trials in each experiment.

To analyse the temporal dynamics of the visual exploration of the presented visual artworks and complex images, I segmented the measured average dwell times in each perceptual category into time windows that aligned with hierarchical processing stages in the social brain networks.
I reasoned that the temporal dynamics of aesthetic evaluations that were described by Cela-Conde et al (2013) were likely to be more broadly social in nature than purely art-specific.
Cela-Conde et al (2013) already alluded to this possibility, by remarking on a similarity between their research findings and a study into moral judgements making that had found a similar two-staged dynamic of a quick unconscious gist inference, followed by a delayed conscious reasoning process during which justifications are sought for the made decision (Haidt, 2001).
I therefore modelled my time windows to analyse the visual exploration data on the temporal processing stages that were proposed by Cela-Conde et al (2013), but renamed them into more general terms that broadly aligned with the processing levels of the Social Brain Atlas.

The first time window covered the first 250 ms of each image presentation, which corresponded with the perceptual processing phase that takes place in mostly occipital and parietal cortical areas.

The second time window covered the period between 250 – 750 ms, during which a first gist inference is made of the scene between core hubs of the Animation and Interaction Networks in the Social Brain Atlas (including the so-called Salience Network).

The third time window covered everything from 750 ms onwards, which corresponded with the phase during which further processing takes place within the Interaction Network, whereby the Construction (Default Mode) Network is co-activated in instances of strong personal engagement.

The recorded eye tracking data were pre-processed in Data Viewer, a software programme developed by SR-Research, the company behind the EyeLink eye tracking cameras. I applied the foveal interest areas and segmented the data in the time windows I described above before exporting the eye tracking recordings as a text file report that I imported in Microsoft Excel for further analysis.

In the analysis of the first experiments 'Snapshots', I investigated my first research questions in several ways. First of all, I focused on the temporal dynamics of the visual exploration patterns of the participants while they were shown the visual artworks and complex images for only 750 ms. If the Social salience model of visual exploration were accurate, it should be able to predict on which perceptual categories across the 32 figurative images participants would proportionally dwell on the longest.
The perceptual categories covered widely varying characteristics of that particular visual feature, including both whole and partial forms. For instance, the 'frontal human faces' category included foveal interest areas that covered entire faces in different media (photography, painting and print), but also foveal interest areas that only covered partial facial features, such as an eye or a nose for instance. If the Social Salience Model of Visual Exploration could predict the social salience of diverse perceptual features in visual scenes it would also provide support for the hypothesis that human visual exploration is guided by conceptual templates that are projected (top-down) onto incoming information from the outside world.

I expected the effects of top-down cortical processes to become visible in the foveal fixation patterns during the gist inference phase, the time window between 250 – 750 ms.

During the first 250 ms I expected that the vast majority of the fixations would fall in the central fixation area of each image, as the participants had been prompted to look there by a fixation cross on a grey screen that was shown prior to the image presentations. I reasoned that during the first 250 ms of visual processing, the brain would decide where to direct the visual attention next based on the information gleaned from the foveal vision and peripheral contours and contrasts.

Colour and contrast are perceptual features that are processed very early in the cortical visual processing system. If colour and contrast would be the leading characteristics during the early processing stages of a visual scene, it would be expected that the fixation patterns of the research participants would be similar for the figurative images and their distorted versions during the 750 ms image presentations in the Snapshots experiment. However, if social salience already guides the visual exploration during early visual processing phases, the distorted versions of the figurative images should elicit different visual exploration patterns during the 750 ms image presentations.

In order to test this hypothesis, I determined the ranking order of the average dwell time in each of the 14 perceptual categories across all the experiment trials for each individual research participant, segmented into a perceptual processing time window (0 – 250 ms) and a gist inference time window (250 – 750).
In the 'Snapshots' experiment I set a threshold for the dwell time proportion in each perceptual category at 7.14% to control for the possibility of random eye movements, which I calculated by dividing 100 by 14, the total number of perceptual categories.
The ranking order of the measured proportional dwell time in each perceptual category was determined with the RANK.EQ function in Excel, which allocates equal ranks when values are identical. Between the 14 predicted ranking positions of the perceptual categories, there was a maximum difference of 13 positions. The ranking positions closer to the middle had a lower maximum number of positions they could deviate from the predicted order. I constructed a rank match point system that took into account the maximum number of positions that a predicted rank could deviate from the measured rank.
For instance, the rank positions 1 and 14 each had a maximum of 13 rank match points, whereas the rank positions 7 and 8 each had a maximum of 7 rank match points.
For every position that the measured rank differed from the predicted rank, one point was deducted from the maximum amount of points for that rank position. A total score of 140 rank match points represented a perfect match between the predicted rank according to the Social salience model of visual exploration and the measured rank order based on proportional dwell time across all the 14 perceptual categories. I calculated for each participant a rank match percentage by dividing their total rank match score by 140 and multiplying this by 100.
I then aggregated these personal rank match percentages to analyse how well the social salience model matched with the measured dwell time patterns on a cohort level.

I calculated a 'perceptual salience factor' for each perceptual category, in an attempt to reflect the construction of the compositional elements across the image selection.
A perceptual salience factor was allocated to each of the 444 unique foveal interest areas that were spread across the image selection and weighed the following aspects:

- The centre distance ratio. This ratio gave a measure of how close each foveal interest area was placed to the image centre. In each image I measured the distance between the image centre and the centre coordinates of the foveal interest area that was furthest removed from the centre. I then divided the centre distance of all the foveal interest areas in the image by the maximum centre distance and subtracted the outcome from 1.

- The conceptual diversity ratio. This ratio gave a measure of the variation in representation in each image and was calculated by dividing 1 by the total number of different perceptual categories in each image.

- The perceptual prevalence ratio. This ratio represented how many foveal interest areas in that image belonged to the same perceptual category in each image. It was calculated by dividing the total number of foveal interest areas of a particular perceptual category in an image by the total count of foveal interest areas in that image.

Each ratio was given equal weight and the perceptual salience factor for each perceptual category was arrived at by averaging the individual ratios for each foveal interest areas and aggregating these across all image trials. The fixation heat maps of the distorted image versions showed that colour and contrast did not direct the visual exploration (see Figure 58), so these factors were not included in the model. Table 17 gives an overview of the weighted perceptual factors and average perceptual salience factors of the foveal interest areas within the 14 perceptual categories in the Wellcome image selection. It also includes a ranking order prediction based on the perceptual salience factor, which I used to compare to the social salience model of visual exploration.

I conducted Wilcoxon signed-rank tests within each cohort to compare the rank match percentages of the perception salience model and the Social salience model of visual exploration. I furthermore conducted non-parametric independent sample t tests between the cohorts to assess if there were group differences. In addition to assessing the predictive value of the Social salience model of visual exploration, I also compared the absolute and proportional dwell times between the research cohort.

In the second experiment of the Thinking Eyes project 'Perspectives', I explored the research questions with overlapping analyses from the 'Snapshots' experiment, which allowed me to study the possible effects of repeated exposure and longer viewing time on the visual exploration patterns. In order to be able to make comparisons between the first and second Thinking Eyes experiment, I only used the eye tracking data that were recorded during the silent viewing phase that followed each audio in the second experiment 'Perspectives'. Because the total viewing time was much longer in the 'Perspectives' experiment, I did not set a threshold and included all the averaged dwell times within each perceptual category in the analysis.

**Electrodermal activity analysis**

To assess the autonomic arousal of the participants during each experiment, I compared the electrodermal activity flux that I had recorded from both wrists to the personal average. The analysis method has been described under the Experimental Framework chapter.

**Internal state evaluation analysis**

My rationale for asking participants how much the artworks and complex images resonated with them, was that this could be a proxy measurement of the social brain mechanism that triggers a co-activation of the Construction Network (Default Mode), which happens when people are personally engaged while interacting with the outside world.
The concept of resonance was explained to the participants by a native speaking British female in an audio recording that was played at the start of the experiment. She read out the following description that I had formulated:

'What is meant by resonance is the feeling of being stirred inside by something that connects with you. An artwork or image can resonate with you because it relates to your personal experiences, or it can be something unfamiliar you intuitively connect with. When something resonates, it has personal meaning to you. You can resonate with both positive and negative emotions, what matters is how strongly you feel drawn in.'

I was particularly interested in investigating whether the first resonance rating, based on the gist inference made during the first 750 ms of viewing, would change when participants looked at

**Table 17: Perceptual salience factors of the Wellcome image selection**

| FOVEAL INTEREST AREAS | AVERAGE CENTRE DISTANCE RATIO | AVERAGE CONCEPTUAL DIVERSITY RATIO | AVERAGE PERCEPTUAL PREVALENCE RATIO | AVERAGE PERCEPTUAL SALIENCE FACTOR | AVERAGE RANKING PERCEPTUAL SALIENCE |
|---|---|---|---|---|---|
| ANIMATE IMAGE CENTRE | 1.00 | 0.19 | 0.09 | 0.43 | 2 |
| FRONTAL HUMAN FACES | 0.55 | 0.22 | 0.25 | 0.34 | 4 |
| FRONTAL ANIMAL FACES | 0.32 | 0.11 | 0.05 | 0.16 | 14 |
| SIDEWAYS HUMAN FACES | 0.49 | 0.18 | 0.29 | 0.32 | 7 |
| SIDEWAYS ANIMAL FACES | 0.55 | 0.12 | 0.14 | 0.27 | 12 |
| HUMAN HAND ACTIONS | 0.54 | 0.17 | 0.12 | 0.28 | 11 |
| HUMAN BODY ELEMENTS | 0.50 | 0.18 | 0.28 | 0.32 | 5 |
| ANIMAL BODY ELEMENTS | 0.50 | 0.22 | 0.20 | 0.31 | 9 |
| INANIMATE IMAGE CENTRES | 1.00 | 0.24 | 0.08 | 0.44 | 1 |
| TEXT ELEMENTS | 0.39 | 0.20 | 0.25 | 0.28 | 10 |
| HUMAN MADE OBJECTS | 0.46 | 0.22 | 0.49 | 0.39 | 3 |
| BUILT ENVIRONMENT ELEMENTS | 0.48 | 0.22 | 0.27 | 0.32 | 6 |
| NATURAL ELEMENTS | 0.44 | 0.18 | 0.31 | 0.31 | 8 |
| NUMBER ELEMENTS | 0.27 | 0.17 | 0.22 | 0.22 | 13 |

the same image again but for a longer period of time.
I also studied whether perceptual factors and different viewing strategies might have an influence on this.

**Auditory perception analysis**

The 'Perspectives' experiment enabled me to study the relationship between auditory perception and visual exploration. I approached this by measuring the proportional dwell time in foveal interest areas that I had labelled with an audio marker, which indicated that it contained a visual feature that was specifically referenced in the audio file that was played while the participants were looking at the image.

I then compared the proportional dwell times in foveal interest areas with audio markers to foveal interest areas belonging to the same perceptual category that didn't have audio markers. For this analysis I only looked at the construct inference phase (>750 ms), as participants would not be able to assess the meaning of the audio recordings during the earlier processing phases. I also compared the proportional dwell times in the foveal interest areas with audio markers during the time that the audio recording was played, with the dwell times during the silent viewing period that followed each audio recording.
I hypothesised that the foveal interest areas with an audio marker would attract the highest proportional dwell time while the audio recording was playing. I also predicted that during the following silent viewing period, the proportional dwell time on foveal interest areas with audio markers would be lower than during the audio phase.

**Speech production analysis**

One of the most valuable aspects of the Visual Thinking Strategies Method (VTS) is that it validates people's personal perspectives, encouraging them to explore how their interpretations are linked to visible references. Attempting to qualify people's responses to the VTS questions could undo this by giving off the impression that there are right and wrong ways to look at art after all. To avoid this, I developed a novel quantitative method to analyse the speech samples I had recorded during the third Thinking Eyes experiment, 'Panoramas'. I strived to align the parameters with the neural dynamics of language processing with the aim to develop a VTS-based social brain analysis method for speech production. While I developed this method in he context of people's verbal responses to visual artworks and complex images, I propose that the underlying principles will likely apply more generally to speech production in a social context. I will first describe the conceptual framework on which I built this analysis method, before detailing how I used it to analyse the speech samples.

The ventral and dorsal streams of visual attention have become a widely accepted model for cortical visual processing in the field of visual neuroscience (Corbetta, 2002; Goodale and Milner, 1992; Mishkin et al., 1983). The dorsal cortical processing pathway specialises in analysing spatial and dynamic visual information and the ventral cortical processing pathway specialises in analysing the semantic content (physical attributes and symbolic meaning) of visual information.

In the domain of verbal language, a distinction between dorsal and ventral processing also exists. Verbal language is a function that is most strongly regulated by the left brain in most people who are right-handed, in left-handed people in can be more evenly distributed across the hemispheres. For most people, speech comprehension takes place in predominantly left superior temporal areas – including Wernicke's area – and the angular gyrus, which align with a ventral cortical processing stream, whereas speech production is regulated by cortical areas in the predominantly left inferior frontal gyrus – including Broca's area –, which aligns with a dorsal processing stream.

However, to my knowledge it has not been investigated yet whether there might also exist a dorsal/ventral distinction in the domain of speech production. I reasoned that this could potentially have diagnostic and therapeutic value in the context of dementia syndromes, both also in relation to developmental

or non-degenerative acquired language disorders.
I set out to develop speech parameters that aligned with the dynamic dorsal stream and the conceptual ventral stream of cortical processing, by building further on the work of the American grammarian and lexicographer Charles Fries.
Fries introduced the concepts of 'content' and 'function' words to the field of linguistics in his seminal work 'The structure of English', published in 1952. Content words carry significant information, whereas function words contribute to the syntax structure and serve to create smooth sentences. In the English language, content words consist of nouns, adjectives, verbs and adverbs.
I started with a global literature search in the online PubMed database to find references of the use of content and function words as speech parameters in (neuro)psychological research.
I searched separately for 'function words', and 'content words' and also the combination 'content and function words'.
I will briefly outline two publication that were of relevance to my study.

A study by Howell et all (1999) into the linguistic mechanisms of stuttering, found that fluent speakers use a strategy of repeating function words to buy time when the execution plan for a subsequent content word has not been completed yet, whereas people who stutter attempt to execute the content word with an incomplete plan which leads to them to stumble over the word.
A study by Gordon (2012) investigated the lexical semantics of picture description in patients with Nonfluent and Fluent Aphasia following a stroke. Their findings suggested a trade-off between syntactic and semantic inputs in word retrieval, especially in nonfluent patients. A content word parameter which distinguished between different types of verbs was able to differentiate the Nonfluent and Fluent Aphasias (Gordon, 1999).

These studies demonstrated that content words can be a meaningful parameter in speech analysis. The next step I took was to divide the class of content words into two categories: Dynamic and semantic words. The dynamic words category consisted of verbs and adverbs and I reasoned that this category might align with a dorsal stream of speech production. The semantic category covered nouns and adjectives which I reasoned would be aligned with a ventral stream of speech production. In order to study the use of dynamic and semantic words in the participants' speech production, I defined four content words speech parameters:

- Content words count
(total nouns, adjectives, verbs and adverbs count)

- Content words ratio
(content words count/total words count)

- Semantic words ratio
(total nouns and adjectives count/total words count)

- Dynamic words ratio
(total verbs and adverbs count/total words count)

I included four additional quantitative speech parameters:
- Syllable ratio
(total syllable count/total words count)

- Type token ratio
(total unique words count/total words count)

- Number words ratio
(total number words/total words count)

- Emotion words ratio
(total emotion words/total words count)

Polysyllabic words are in general semantically more complex and also require more executive planning than monosyllabic words. I wanted to investigate whether there might be age-related differences in the ratio of syllables to the total word count and whether there might be effects of dementia.

Dementia, especially Typical Alzheimer's Disease, is often associated with repetitions of language. By including the type/token ratio in the speech analysis, I wanted to investigate to which extend it might be an effective metric to pick up on this phenomenon.

In clinical observations at the memory clinic of the UCL Queen Square Institute of Neurology in London, it has been found that people presenting with Semantic Primary Progressive Aphasia sometimes make more use of numbers to scaffold their speech production. This phenomenon is congruent with the functional connectivity profile of Semantic Primary Progressive Aphasia in the Social Brain Atlas, which shows a predominant involvement of anterior, inferior and medial temporal lobe areas and a relative sparing of parietal cortex areas, which regulate number processing (Dehaene et al., 2003). In order to investigate whether heightened emotional awareness – often reported in Typical Alzheimer's Disease – might be associated with a higher frequency of emotion words in spoken language, I also included an emotion words ratio in my speech analysis. Evaluating the emotional charge of words is challenging and highly subjective. In an attempt to define a logical rule that could be consistently applied to parsed speech samples, I defined emotion words as words that directly refer to emotions (such as 'angry', or 'happy'), including the words 'emotion', 'feeling' and 'affect'.

I had in total 300 speech recordings of 1 minute each, which were transcribed via a secure connection by the transcription company UK Transcription into an Excel template that I had designed to facilitate the quantitative analysis. I used two free online resources to identify the various linguistic aspects I was interested in. On the web page 'https://wordcounter.net', I identified the total word and syllable count in each speech sample. On the web page 'https://parts-of-speech.info', I parsed the speech samples into nouns, adjectives, verbs, adverbs and number words. While these algorithms greatly sped up the analysis process, it was necessary to manually check their performance for mistakes. For all the speech parameters I calculated individual averages across the 6 separate speech samples, which I then aggregated to analyse them on a cohort level. Based on the analysis of the speech patterns of the participants living with dementia, I also composed likely speech profiles for the different dementias.

### 4.2.3 RESULTS

**Visual exploration results**

**Perceptual processing phase (0 – 250 ms)**

When participants were shown visual artworks and complex images for 750 ms, their eyes mostly stayed fixated on the image centre during the initial perceptual processing phase (0 – 250 ms) as expected. Neurologically healthy young adults looked on average 95% (SD=6%) of the time on animate image centres during the perceptual processing phase. They looked on average 93% (SD=8%) on inanimate image centres during the perceptual processing phase. Neurologically healthy senior adults looked on average 93% (SD=9%) of the time on animate image centres during the perceptual processing phase. They looked on average 93% (SD=14%) on inanimate image centres during the perceptual processing phase. Senior adults living with dementia looked on average 80% (SD=19%) of the time on animate image centres during the perceptual processing phase. They looked on average 84% (SD=19%) on inanimate image centres during the perceptual processing phase.

There were no significant differences between the proportional dwell time on animate and inanimate elements in neurologically healthy young and senior adults. When comparing individual senior adults living with dementia to the neurologically healthy senior adults cohort, they were more likely to look less at the image centres than the neurologically healthy adults during the perceptual processing phase. This was in most cases related to a lower proportional dwell time on the fixation cross that preceded each image presentation. Tables 18 and 19 show the proportional average dwell time on the image centres of senior adults living

with dementia, compared to neurologically healthy senior adults during the first 250 ms of viewing. The results showed that the two participants diagnosed with Posterior Cortical Atrophy spent on average the least time looking at the image centres during the perceptual processing phase in comparison to neurologically healthy senior adults, but this effect was also present to a lesser extent in senior adults living with Typical Alzheimer's Disease.

**Table 18:**
**Animate image centres average dwell time (%)**
**Senior adults living with dementia compared to control cohort**
**Perceptual processing phase (0 — 250 ms)**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -26 | 0.010 | 8.3 |
| P2F_tAD | -20 | 0.039 | 2.9 |
| P3F_tAD | 5 | 0.555 | 1.0 |
| P6M_nfPPA | -11 | 0.226 | 1.1 |
| P7M_nfPPA | 6 | 0.496 | 1.0 |
| P8F_nfPPA | 6 | 0.513 | 1.0 |
| P10M_bvFTD | -15 | 0.099 | 1.6 |
| P11M_bvFTD | -5 | 0.577 | 1.0 |
| P12M_PCA | -39 | 0.000 | 127.6 |
| P13F_PCA | -49 | 0.000 | 1284.0 |
| P14M_UD | 7 | 0.448 | 1.0 |

**Table 19:**
**Inanimate image centres average dwell time (%)**
**Senior adults living with dementia compared to control cohort**
**Perceptual processing phase (0 — 250 ms)**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -28 | 0.071 | 2.0 |
| P2F_tAD | -12 | 0.427 | 1.0 |
| P3F_tAD | 5 | 0.738 | 1.0 |
| P6M_nfPPA | 4 | 0.775 | 1.0 |
| P7M_nfPPA | 7 | 0.655 | 1.0 |
| P8F_nfPPA | 5 | 0.724 | 1.0 |
| P10M_bvFTD | -13 | 0.370 | 1.0 |
| P11M_bvFTD | 6 | 0.692 | 1.0 |
| P12M_PCA | -40 | 0.012 | 6.9 |
| P13F_PCA | -40 | 0.012 | 6.8 |
| P14M_UD | 6 | 0.662 | 1.0 |

The Social salience model of visual exploration explained the exploration patterns during the perceptual processing phase no better than the perceptual salience model. The average match percentage was around 16% with both models for both the coherent and distorted image conditions and I observed no differences between the research cohorts.

**Visual exploration results**
**Gist inference phase (250 — 750 ms)**
During the gist inference phase (250 – 750 ms), the average proportional dwell time on the image centres dropped by more than half in all participants compared to the perceptual processing phase (0 – 250 ms). During this phase, participants looked significantly longer on animate image centres, than inanimate image centres. In neurologically healthy young adults, the average proportional dwell time on animate image centres was 39% (SD=12%), and 26% (SD=14%) on inanimate image centres during the gist inference phase. It was 508.6 times more likely that there was a significant difference between the proportional dwell time on animate and inanimate image centres during the gist inference phase, with a two-sided p value <.001. In neurologically healthy senior adults, the average proportional dwell time on animate image centres was 45% (SD=15%), and 30% (SD=18%) on inanimate image centres during the gist inference phase. It was 2647 times more likely that there was a significant difference between the proportional dwell time on animate and inanimate image centres during the gist inference phase, with a two-sided p value <.001. There were no significant differences between the young and senior adults.

In senior adults living with dementia, the average proportional dwell time on animate image centres was 34% (SD=17%), and 30% (SD=17%) on inanimate image centres during the gist inference phase. There was no significant difference between the proportional dwell time on animate and inanimate image centres during the gist inference phase. Individual dwell times on the image centres also did not differ from the neurologically healthy senior adults during this phase. Figures 55, 56 and 57 show how the average proportional dwell times (%) on the animate and inanimate image centres changed during the 750 ms viewing trials in the 'Snapshots' experiment in neurologically healthy adults and senior adults living with dementia.

The time that was spent looking away from the image centre during the gist inference phase was mostly directed towards image features within the animate domain. None of the perceptual categories within the inanimate domain attracted more than 7% proportional dwell time, which was the threshold value I set for the 750 ms viewing sessions.

Within the animate domain, the largest amount of dwell time during the gist inference was spent on frontal human faces, followed by sideways human faces, sideways animal faces and human hand actions. Senior adults spent on overage 4% less proportional dwell time looking frontal human faces than young adults. It was 6.7 times more likely that this was an effect of healthy ageing, with a two-sided p value of 0.012.

Table 20 shows that P10M_bvFTD and P12M_PCA, who were diagnosed with Behavioural Frontotemporal Dementia and Posterior Cortical Atrophy respectively, looked significantly longer at frontal human faces than neurologically healthy senior adults cohort during the gist inference phase.

**Table 20:**
**Frontal human faces average dwell times (%)**
**Senior adults living with dementia compared to control cohort**
**Gist inference phase (250 — 750 ms)**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -2 | 0.796 | 1.0 |
| P2F_tAD | -3 | 0.656 | 1.0 |
| P3F_tAD | 4 | 0.483 | 1.0 |
| P6M_nfPPA | 10 | 0.108 | 1.5 |
| P7M_nfPPA | 1 | 0.823 | 1.0 |
| P8F_nfPPA | 9 | 0.174 | 1.2 |
| P10M_bvFTD | 16 | 0.015 | 6.0 |
| P11M_bvFTD | 11 | 0.073 | 1.9 |
| P12M_PCA | 17 | 0.010 | 8.2 |
| P13F_PCA | 7 | 0.255 | 1.1 |
| P14M_UD | 0 | 0.944 | 1.0 |

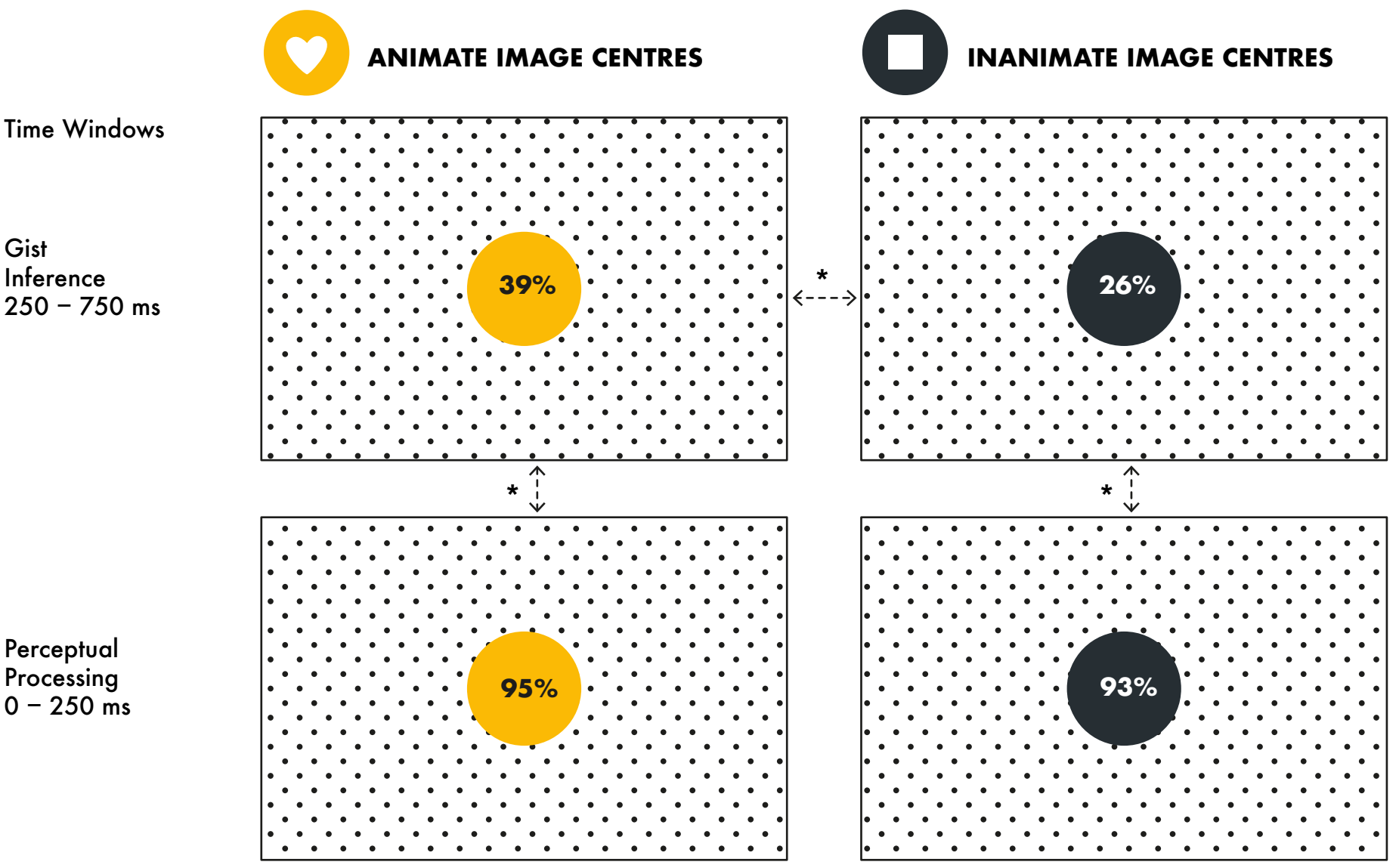
During the gist inference phase, the Social salience model of visual exploration matched significantly better with the exploration patterns than the perceptual salience model visual exploration when the participants were viewing the coherent (figurative) images. The perceptual salience model matched on average 29% (SD=4.1) with the exploration patterns of the young adults and it matched 30% (SD=4.1 and 4.5) with the exploration patterns of both the senior adults living without and with dementia.
The social salience model matched on average 36% (SD=5.5) with the exploration patterns of the young adults, 38% (SD=5.7) with the neurologically healthy senior adults and 37% (SD=6.6) with the senior adults living with dementia.
These differences between the two models were highly significant for all three cohorts, with two-sided p values below.001. It was 2e +7 more likely that the salience model matched better than the perceptual salience model in the young adults, 774 times more likely in the neurologically healthy senior adults and 9033 times more likely in the senior adults living with dementia.

Figure 55

# SNAPSHOTS EXPERIMENT PROPORTIONAL DWELL TIMES (%)

## FIGURATIVE VISUAL ART AND COMPLEX IMAGE CENTRES

### YOUNG ADULTS

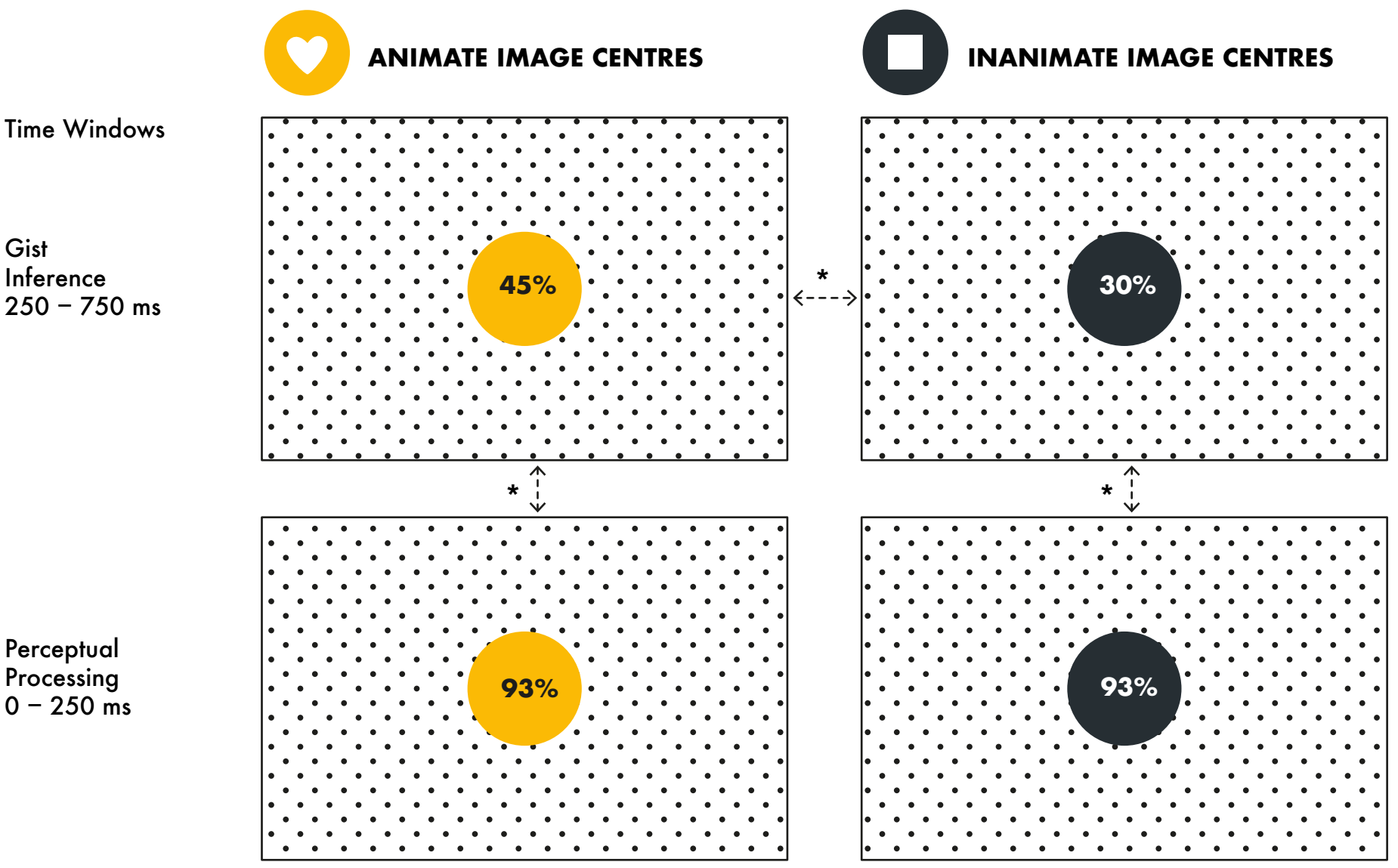



* Significant difference in average proportional dwell time on image centre (%)

Figure 56

# PROPORTIONAL DWELL TIME (%) ON IMAGE CENTRES
## SENIOR ADULTS

### THINKING EYES SNAPHOTS EXPERIMENT



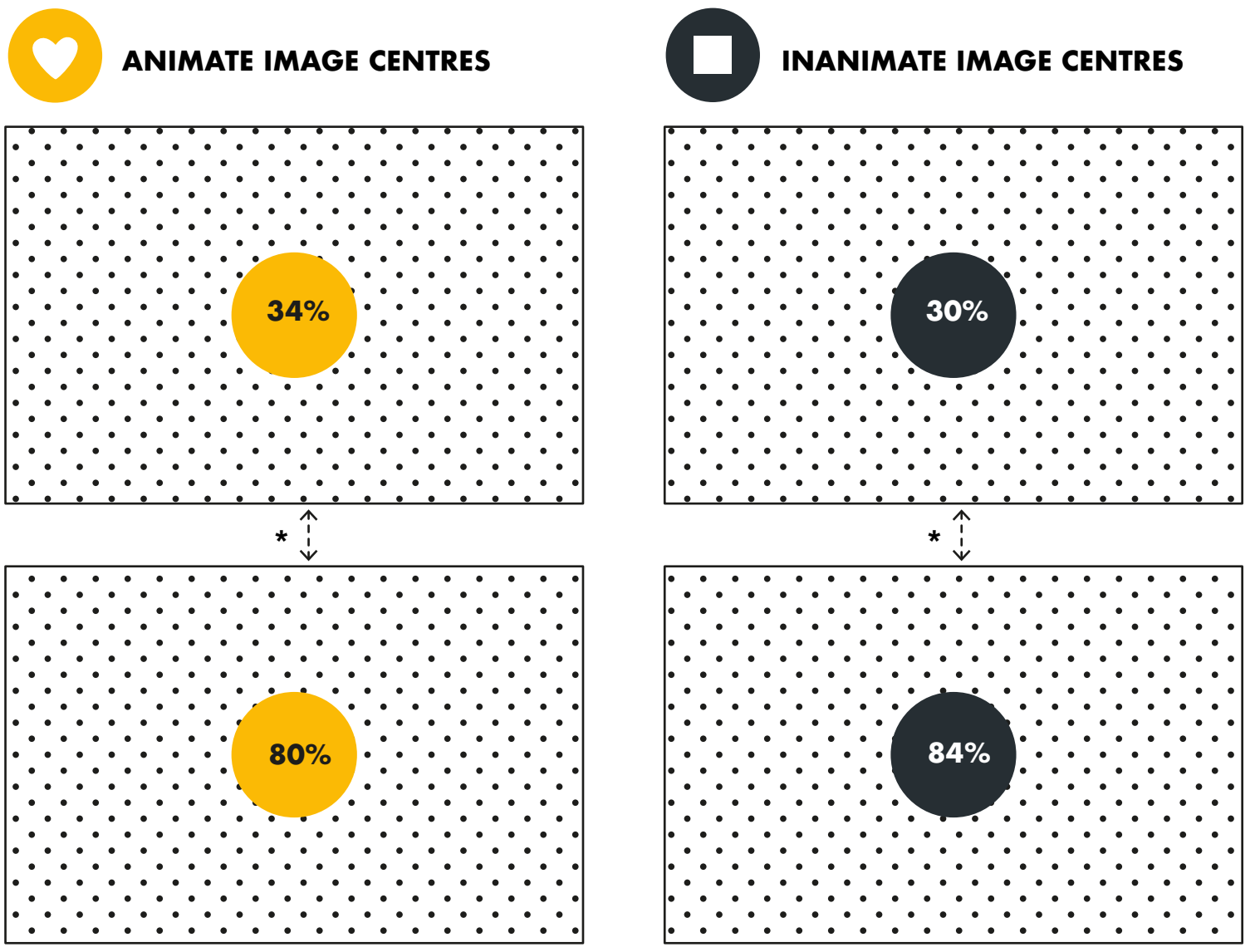

* Significant difference in average proportional dwell time on image centre (%)

Figure 57

# PROPORTIONAL DWELL TIME (%) ON IMAGE CENTRES

## SENIOR ADULTS LIVING WITH DEMENTIA

## THINKING EYES SNAPHOTS EXPERIMENT



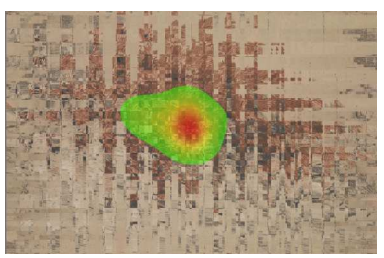
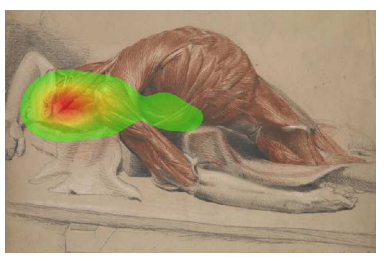
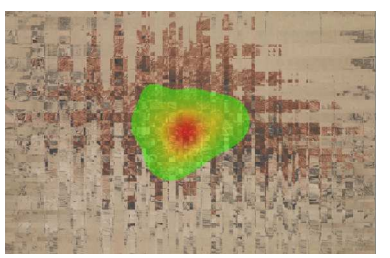
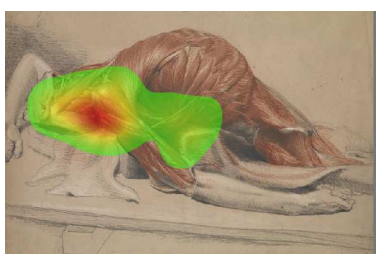

* Significant difference in average proportional dwell time on image centre (%)

**Figure 58**

# VISUAL EXPLORATION OF VISUAL ART AND COMPLEX IMAGES

## NEUROLOGICALLY HEALTHY ADULTS

## THINKING EYES SNAPSHOTS EXPERIMENT

| Time Windows | YOUNG ADULTS | | SENIOR ADULTS | |
|---|---|---|---|---|
| Construct Inference > 750 ms | X | X | X | X |
| Gist Inference 250 – 750 ms |  |  |  |  |
| Perceptual Processing 0 – 250 ms |  |  |  |  |
| | Distorted version | Coherent version | Distorted version | Coherent version |

Heatmaps of aggregated visual fixation patterns of image #1 from the Wellcome selection. The transparent overlay colours indicate the fixation duration density, from low (green) to moderate (yellow) and high (red).

Social salience model of visual exploration predictions:

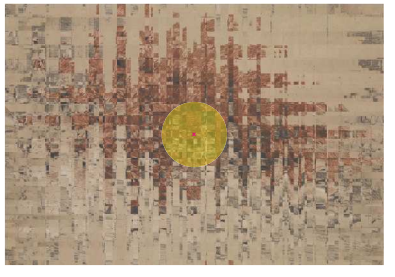




Figure 58 shows the heat maps of the average visual exploration patterns of young and senior adults during the 750 ms viewing window of image #1 from the Wellcome Collection during the 'Snapshots' experiment. The visual exploration patterns of the senior adults living with dementia were similar to neurologically healthy senior adults on a cohort level and therefore not presented in a separate figure.

## Visual exploration results

### Construct inference phase (> 750 ms)

The visual exploration patterns during the construct inference phase (>750 ms) – analysed during the silent viewing phase and excluding foveal interest areas with audio markers – matched even more significantly with the social salience model, compared to the gist inference phase. The social salience model matched on average 76% (SD=5.4) with the exploration patterns of the young adults, 80% (SD=5.2) with the neurologically healthy senior adults and 81% (SD=4.7) with the senior adults living with dementia.

In all three cohorts these differences were associated with two-sided p values below.001. It was 2e +8 times more likely that the social salience model matched the measured data better than the perceptual salience model in the young adults, 3e +9 times more likely in the neurologically healthy senior adults and 129602 times more likely in the senior adults living with dementia. The social salience model matched 4% better with the visual exploration patterns of the neurologically healthy senior adults, compared to the young adults. It was 2.9 times more likely that this was a true effect of healthy ageing, with a two-sided p value of 0.039.

In comparison, the perceptual salience model matched on average 55% with the visual exploration patterns of the young adults, 57% with the neurologically healthy senior adults and 60% with the senior adults living with dementia. The senior adults living with dementia showed a 3% closer match with the perceptual salience model when compared to the neurologically healthy senior adults. This was not a significant difference however. When comparing the average dwell times of the research cohorts during the silent viewing phase of the 20 seconds viewing sessions of the 'Perspectives' experiment, I did not observe any general effects of age. The measured average dwell times aligned very closely with the predicted hierarchy of the social salience model as is shown in Table 21.

**Table 21:**
**Silent viewing average dwell times (ms), excluding audio markers**

**Neurologically healthy adults**

**Construct inference phase (>750-20000 ms)**

| Perceptual category | Research cohort | Dwell time ms | Standard deviation |
|---|---|---|---|
| 1.0 Animate image centre | Young Adults<br>Senior Adults | 1659<br>1913 | 408<br>372 |
| 1.1 Frontal human faces | Young Adults<br>Senior Adults | 2938<br>2533 | 820<br>766 |
| 1.2 Frontal animal faces | Young Adults<br>Senior Adults | 2389<br>2322 | 800<br>500 |
| 1.3 Sideways human faces | Young Adults<br>Senior Adults | 1187<br>1197 | 200<br>180 |
| 1.4 Sideways animal faces | Young Adults<br>Senior Adults | 884<br>938 | 510<br>334 |
| 1.5 Human hand actions | Young Adults<br>Senior Adults | 793<br>835 | 289<br>234 |
| 1.6 Human body elements | Young Adults<br>Senior Adults | 662<br>676 | 124<br>108 |
| 1.7 Animal body elements | Young Adults<br>Senior Adults | 928<br>1074 | 414<br>265 |
| 2.0 Inanimate image centre | Young Adults<br>Senior Adults | 1162<br>1252 | 465<br>287 |
| 2.1 Text elements | Young Adults<br>Senior Adults | 318<br>328 | 199<br>165 |
| 2.2 Human made objects | Young Adults<br>Senior Adults | 438<br>441 | 78<br>59 |
| 2.3 Built environment elements | Young Adults<br>Senior Adults | 406<br>396 | 104<br>91 |
| 2.4 Natural elements | Young Adults<br>Senior Adults | 378<br>344 | 161<br>114 |
| 2.5 Number elements | Young Adults<br>Senior Adults | 72<br>53 | 137<br>83 |

As I predicted, all inanimate image features were looked at less compared to animate image features. Like during the gist inference phase, inanimate image centres were also looked at less than animate centres. Figures 59 and 60 show the dwell time patterns in young and senior adults cross the 3 time windows. During the construct inference phase frontal human and animal faces attracted on average longer dwell times than the image centres, underscoring the key social importance of direct facial communication. Neurologically healthy young adults looked on average 1280 ms longer at frontal human faces, compared to the animate image centres. It was 224.5 times more likely this was a true effect, with a two-sided p-value <.001. Young adults looked on average 730 ms longer at animal frontal faces, compared to the animate image centres. It was 41.8 times more likely this was a true effect with a two-sided p value of 0.001. Neurologically healthy senior adults looked on average 620 ms longer at frontal human faces, compared to the animate image centres. It was 19.7 times more likely this was a true effect, with a two-sided p-value of 0.003. Senior adults looked on average 409 ms longer at animal frontal faces, compared to the animate image centres. It was 19.3 times more likely this was a true effect with a two-sided p value of 0.003.
Senior adults living with dementia looked on average 1274 ms longer at frontal human faces, compared to the animate image centres. It was 12.3 times more likely this was a true effect, with a two-sided p-value of 0.006. Senior adults living with dementia looked on average 633 ms longer at animal frontal faces, compared to the animate image centres. It was 3.8 times more likely this was a true effect with a two-sided p value of 0.027. These findings show that the average fixation dwell times on frontal human and animal face were similar between young adults and senior adults living with dementia, but lower in neurologically healthy senior adults. Due to the large variance these cohort differences were not significant however.

During the construct inference phase it also became clear that the salience of text elements in visual artworks and complex images was lower than predicted based on the prominence of semantic language in the Social Brain Atlas. Neurologically healthy young adults looked on average 127 ms longer at human made objects than text elements (two-sided p value 0.005, odds 15.8), and 101 ms longer on built environment elements (two-sided p value 0.013, odds 6.6).
Neurologically healthy senior adults looked on average 113 ms longer at human made objects than text elements (two-sided p value 0.005, odds 14.7). Senior adults living with dementia did not look significantly longer at other inanimate elements compared to text elements  Based on the measured dwell times, it appears that text elements should be ranked below built environment elements in the social salience model of visual exploration for young adults and below human made objects for senior adults.

When I analysed the average dwell times across the 14 perceptual categories of the senior adults living with dementia on an individual level, I found that P10M_bvFTD looked on average 341ms less (two-sided p value <.001; odds 1645) and P12M_PCA looked on average 207 ms less (two-sided p value 0.003; odds 21) on human made objects during the construct inference phase, compared to neurologically healthy senior adults.

Next, I looked at the possible effects of different viewing strategies on visual exploration patterns when participants were looking at visual artworks and complex images for 20 seconds. To this purpose, I compared how much time participants spent looking at animate and inanimate visual features away from the image centres in the following three different viewing conditions:

- Internal perspective: exploring the image guided by the first VTS question ‘What is going on in this picture?”.
- External perspective: exploring the image while listening to another person reflecting on the image with VTS.
- External context: exploring the image while listening to a person reading out contextual information about the image.

Figure 59

# PROPORTIONAL DWELL TIME DISTRIBUTION (%)

## SILENT VIEWING OF VISUAL ART AND COMPLEX IMAGES

### YOUNG ADULTS

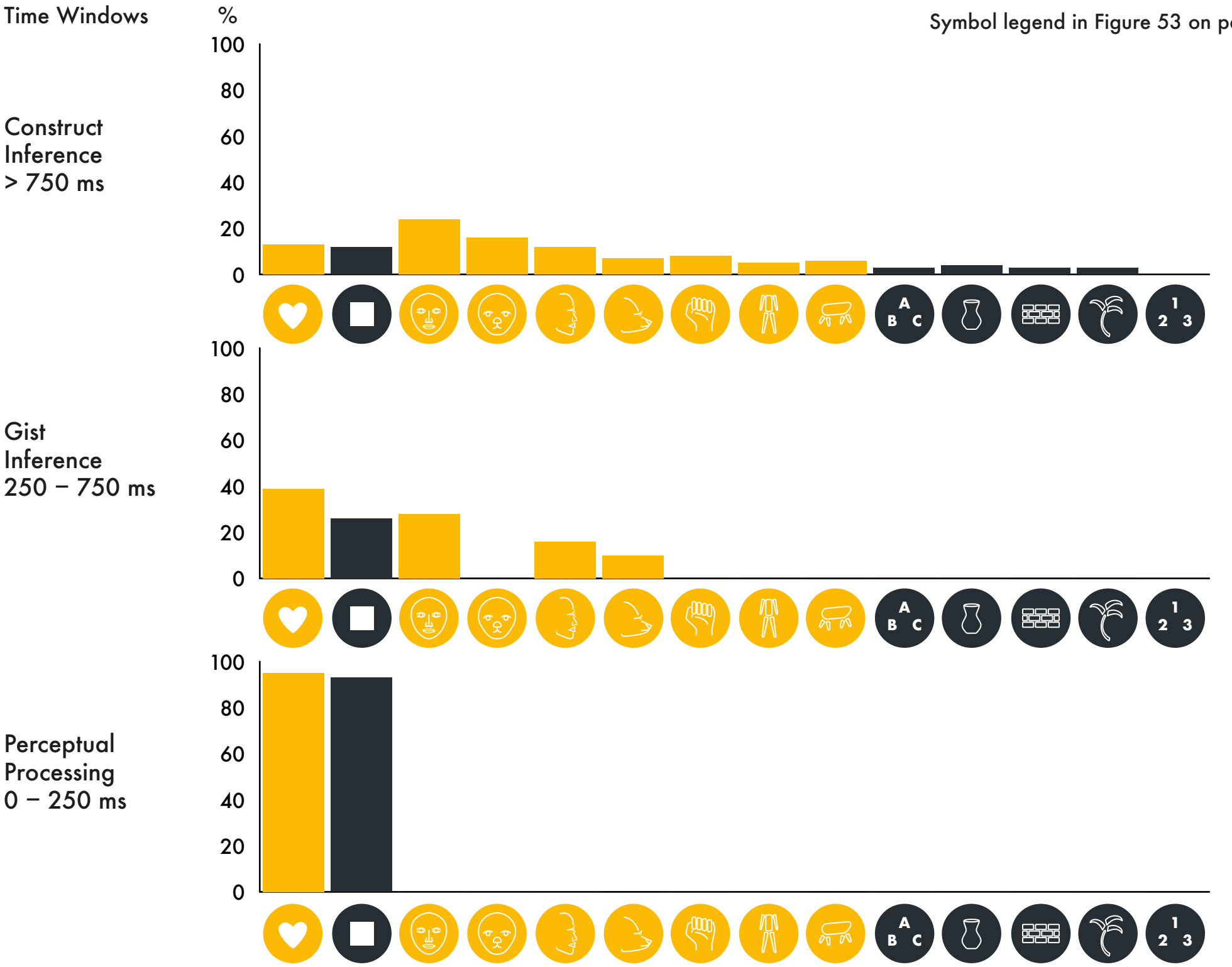
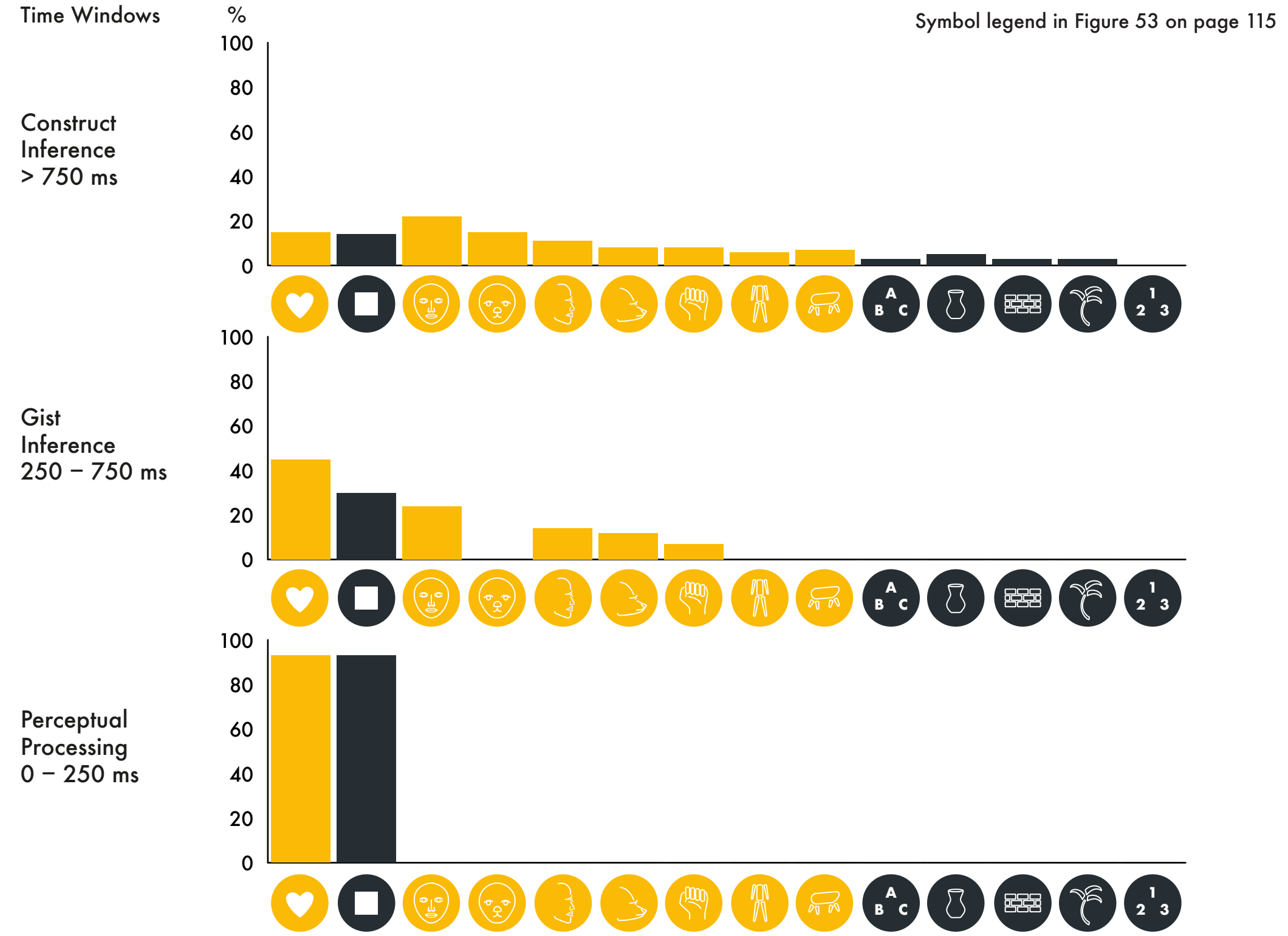


Figure 60

# PROPORTIONAL DWELL TIME DISTRIBUTION (%)

## SILENT VIEWING OF VISUAL ART AND COMPLEX IMAGES

### SENIOR ADULTS



The results showed that all participants spent much more time looking at animate features away from the centre when they were exploring the images with VTS, compared to when they were exploring the images while listening to contextual information.
Contextual information made the participants explore the image less overall, but look slightly longer at inanimate image features, compared to the VTS viewing conditions. I will first report the outcomes of the comparisons that I made within each research cohort between time spent looking at animate and inanimate image features under the different viewing conditions. I will then describe the results of the between-groups comparisons.

When the participants explored the images from their internal perspective with the first VTS question, young adults looked on average 2093 ms (SD=359) at animate features and 611 ms (SD=118) on inanimate image features. Neurologically healthy senior adults looked on average 2136 (SD=238) ms at animate features and 602 ms (SD=98) at inanimate image features. Senior adults living with dementia looked on average 1960 ms (SD=662) at animate features and 497 ms (SD=179) at inanimate features. These differences between the average animate and inanimate dwell times were very significant with p values below.001 for all three cohorts. It was 10e +8 times more likely that young adults looked longer at animate features than inanimate features during the internal VTS condition, a 3e +13 times higher likelihood in senior adults and a 7501 times higher likelihood in senior adults living with dementia.

When participants were exploring images while listing to someone else reflecting on the image with VTS, young adults looked on average 1434 ms (SD=163) at animate features, and 519 (SD=74) at inanimate image features. Neurologically healthy senior adults looked on average 1442 ms (SD=180) at animate features and 549 ms (SD=89) on inanimate image features. Senior adults living with dementia looked on average 1396 ms (SD=390) at animate features and 470 ms (SD=127)at inanimate features. These differences were also very significant, with p values <.001. It was 3e+11 times more likely that young adults looked more at animate features than inanimate features during the external VTS condition, compared to a 6e+11 times higher likelihood in senior adults and a 13006 times higher likelihood in senior adults living with dementia.
When participants were looking at an image while listing to someone else reading out contextual information, they looked on average less than half the amount of time at animate features, compared to the two VTS conditions. Participants looked equally long at animate and inanimate image features under the contextual information viewing condition, this was the case for all three research cohorts.
Young adults looked on average 748 ms (SD=157) at animate image features and 743 ms (SD=180) at inanimate image features. Neurologically healthy senior adults looked on average 791 ms (SD=139) at animate image features and 736 ms (SD=112) at inanimate image features. Senior adults living with dementia looked on average 693 ms (SD=245) at animate features and 632 ms (SD=161) at inanimate features.
Figures 59, 60, and 61 show the infographics of the visual exploration patterns away from the image centres for each cohort under the 3 different experimental viewing conditions.

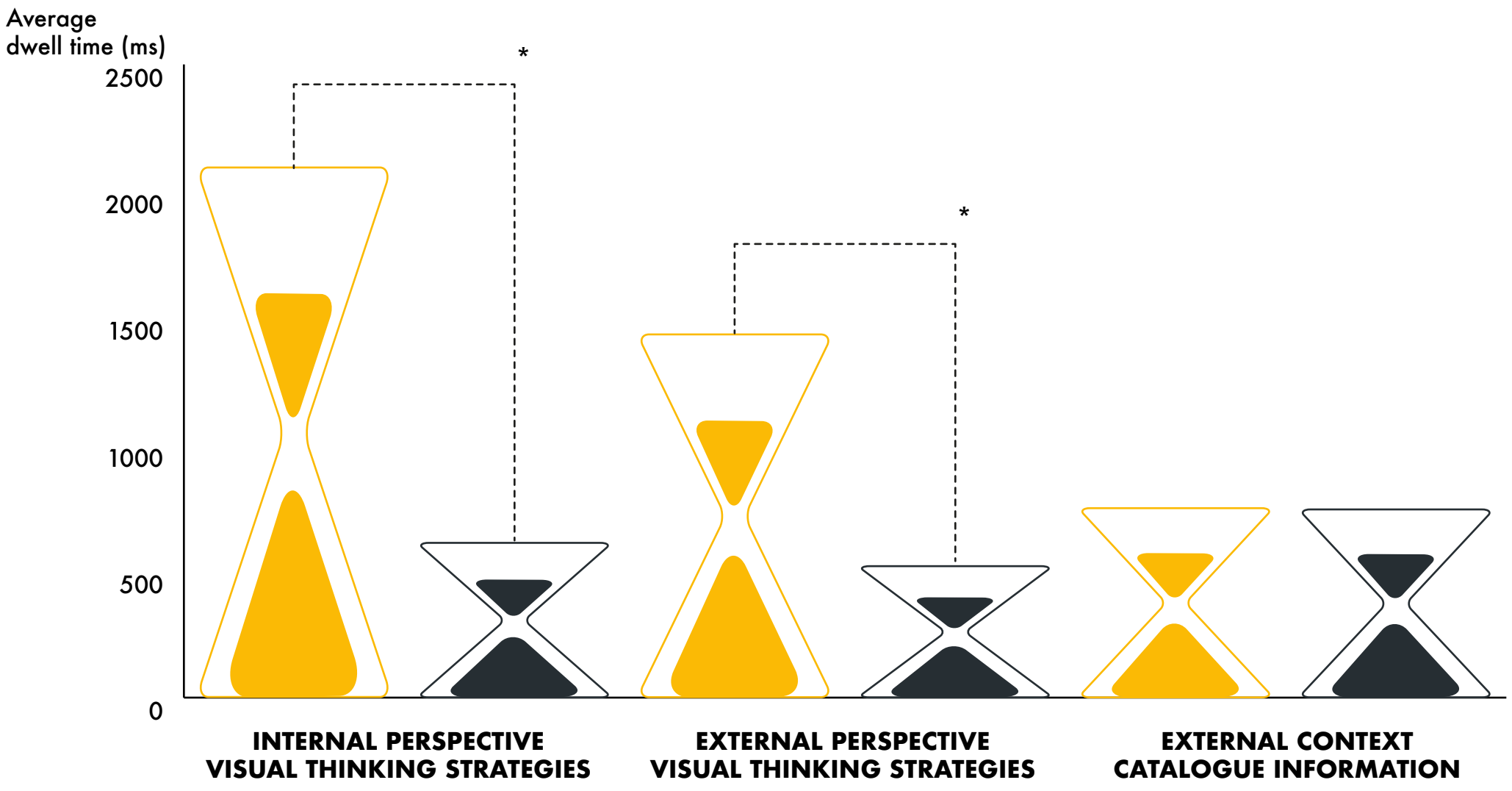
I found that participants tended to look slightly more at inanimate features when they were listening to external context information, compared to the two VTS conditions.
When listening to contextual information, young adults looked on average 132 ms longer on inanimate features, compared to the internal VTS perspective (two-sided p value <.001; odds 68) and 224 ms longer compared to the external VTS perspective (two-sided p value <.001; odds 1392). Neurologically healthy senior adults looked on average 134 ms longer on inanimate features, compared to the internal VTS perspective (two-sided p value <.001; odds 6173) and 186 ms longer compared to the external VTS perspective (two-sided p value <.001; odds 2e +6).
When senior adults living with dementia were listening to contextual information, they looked on average 134 ms longer on inanimate features, compared to the internal VTS perspective

Figure 61

# VISUAL EXPLORATION AWAY FROM THE IMAGE CENTRE

## YOUNG ADULTS

### THINKING EYES PERSPECTIVE EXPERIMENT




Animate image elements

Inanimate image elements

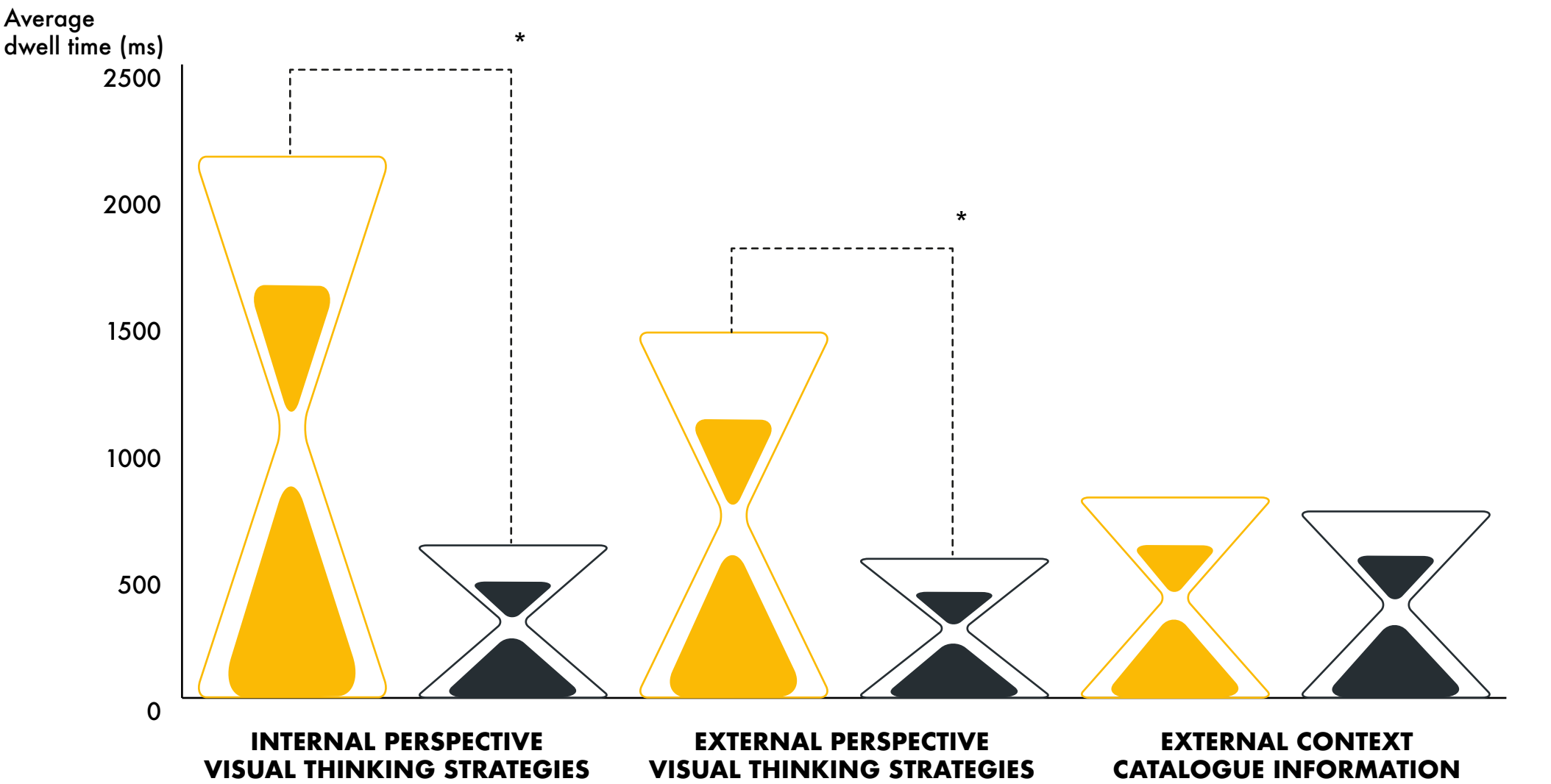
Significant difference in average dwell time (ms)

Figure 62

# VISUAL EXPLORATION AWAY FROM THE IMAGE CENTRE

## SENIOR ADULTS

### THINKING EYES PERSPECTIVE EXPERIMENT




Animate image elements

Inanimate image elements

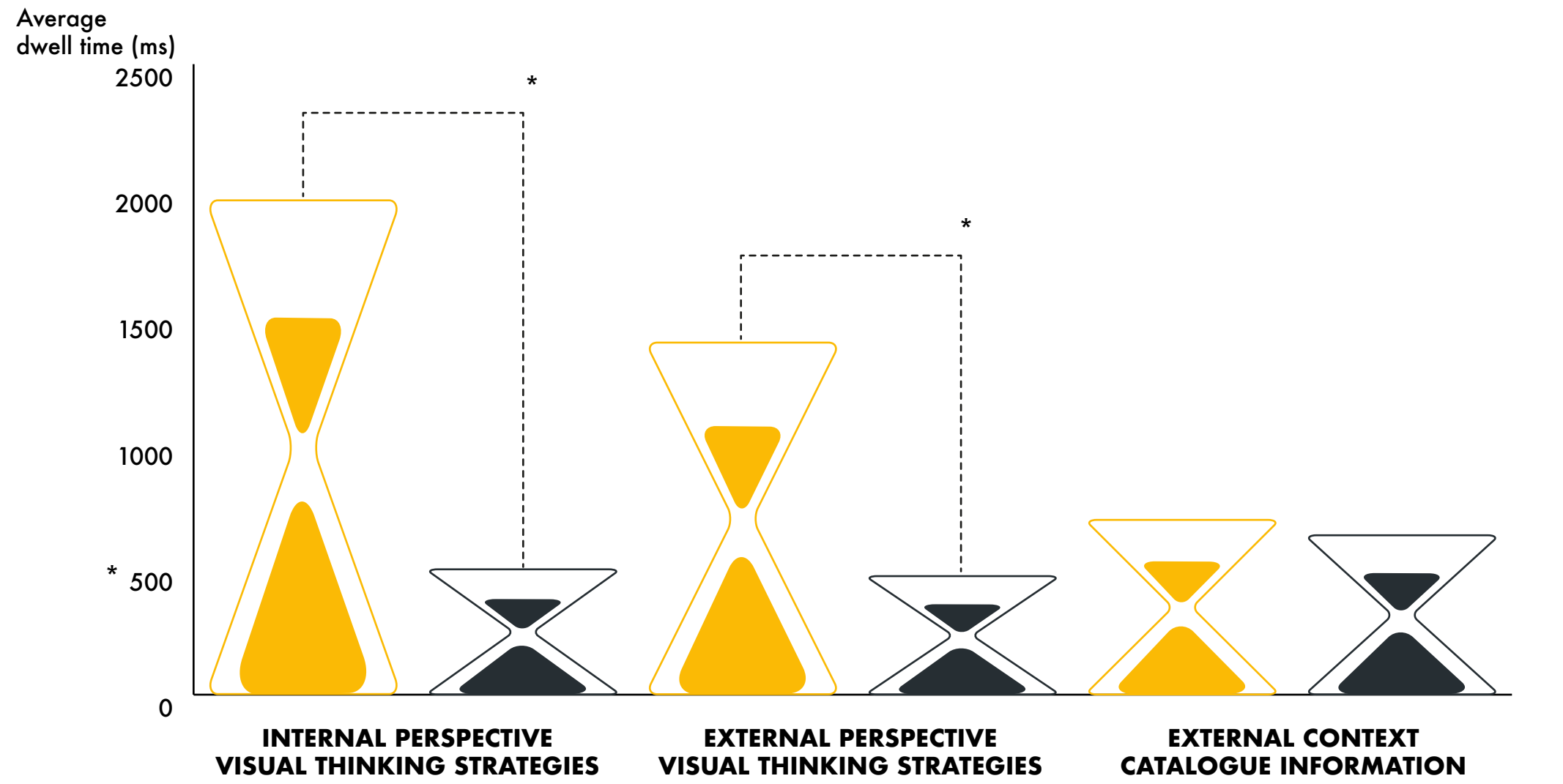
* Significant difference in average dwell time (ms)

Figure 63

# VISUAL EXPLORATION AWAY FROM THE IMAGE CENTRE

## SENIOR ADULTS LIVING WITH DEMENTIA

## THINKING EYES PERSPECTIVE EXPERIMENT




Animate image elements

Inanimate image elements

* Significant difference in average dwell time (ms)

(two-sided p value 0.007; odds 11) and 162 ms longer compared to the external VTS perspective (two-sided p value <.001; odds 1093). Figures 61, 62 and 63 show the visual exploration patterns of the 3 research cohorts across the different viewing conditions in the Perspectives experiment.
Comparing the visual exploration patterns between groups in the three different viewing conditions, did not bring any affects of healthy ageing or dementia  to light.

**Auditory perception results**

I first looked at how much time participants spent looking at visual features that were specifically mentioned in the audio recordings, while the audio was playing. I then compared that to how much time they spent looking at these features during the silent viewing phase that followed each audio recording.
In this analysis I focused on the two main perceptual domains: animate and inanimate visual features. This analysis was based on the 20 trials in the 'Perspectives' experiment, and only included the 'External perspective' and 'External context' conditions, when participants were listening to someone else talking about the image. All images were shown for 20 seconds, but because the audio recordings and the following silent viewing phase varied across the trials, I focused on the proportional instead of absolute dwell times in the analyses.

During the viewing phase when the audio was played, young adults looked on average 3.5% more at animate image features and on average 7.9% more at inanimate image features that were mentioned by the person in the audio recording.
These differences both had two-sided p values <.001 and the odds that young adults looked significantly more at image features that were referenced in the audio, compared to image features without audio markers, were 23463 and 3e +6 respectively. After the audio had finished, young adults still looked on average 1.9% more at animate image features and on average 2.3% more at inanimate image features that had been mentioned by the person in the audio recording. These findings show that while young people looked considerably less at image features that had been mentioned in the audio once it had finished, the audio effect was still noticeable during the silent viewing phase that followed each audio. The two-sided p values for the prolonged audio effect were <.001 for both the animate and inanimate image features.
It was 70 times more likely that young adults looked more at animate image features from the audio recording and 1159 times more likely they looked at inanimate image features that had been mentioned in the audio, during the silent viewing phase afterwards.

Neurologically healthy senior adults looked on average 3.2% more at animate image features and on average 5.2% more at inanimate image features that were mentioned in an audio recording, as they were listening to it. These differences both had two-sided p values <.001. The odds that senior adults looked significantly more at image features that were referenced in the audio recording, compared to image features without audio markers, were 6323 for the animate and 174525 for the inanimate features.
During the silent viewing phase after the audio had finished, senior adults looked on average 1.8% more at animate image features and on average 2.5% more at inanimate image features that had been mentioned by the person in the audio recording. Like in the young adults, the effect became less pronounced after the audio had finished, but was still present. The two-sided p values for the prolonged audio effect were <.001, with the odds of a true affect being 146 and 93 respectively.

When they were listening to the audio recording, senior adults living with dementia looked on average 3% more at animate image features and on average 4.5% more at inanimate image features that were mentioned by the person in the audio recording. For the animate features the two-sided p value was.001 and it was 47 times more likely this difference was due to the audio references. For the inanimate features the two-sided p value was <.001 and it was 198 times more likely this difference was due to the audio reference. After the audio

recording had finished, senior adults living with dementia still looked on average 1.7% more at animate image features and on average 2.9% more at inanimate image features that had been mentioned by the person in the audio recording. The two-sided p value for the prolonged audio effect was 0.005 for animate features with the odds of a true effect being 13. The two-sided p value for the inanimate features was <.001 with the odds of a true effect being 68.6.

I then compared the visual exploration patterns in response to auditory perception between the three research cohorts.
The results showed different visual exploration patterns in the inanimate perceptual domain between young and senior adults, as they were listening to an audio recording. Young adults spent less proportional time looking at inanimate features that were not mentioned, and more proportional time looking at inanimate features that were referenced in the audio recording, compared to the senior adults. The mean difference in proportional dwell time on the inanimate features without audio markers was -0.3%, with a two-sided p value of 0.001. It was 6.6 times more likely that this difference represented a true effect of healthy ageing. The mean difference in proportional dwell time on the inanimate features that were referenced in the audio recordings was 2.3%, with a two-sided p value of 0.002. It was 5.7 times more likely that this difference represented a true effect of healthy ageing. Figure 64 shows the heat maps of the average visual exploration patterns of young and senior adults during the audio and silent viewing phases of image #14 from the Wellcome Collection in the 'Perspectives' experiment.

When I compared the visual exploration patterns in response to auditory perception between neurologically healthy senior adults and senior adults living with dementia, I only found a significant difference in proportional dwell on inanimate image features without audio markers during the silent viewing phase. Senior adults living with dementia looked on average 0.4% less on inanimate features without audio markers during the silent viewing phase, with a two-sided p value of 0.037. It was 3 times more likely that this difference represented a general effect of dementia. As the dwell time (ms) analysis showed however, this effect was primarily driven by a strongly significant lower dwell time on human made objects by P10M_bvFTD and P12M_PCA

**Speech production results**

When comparing the VTS speech samples of the young adults to the neurologically healthy senior adults, I found no significant differences between the two age groups.
The average content words count in the 1-minute speech samples was 30 (SD=12) for the young adults and 32 (SD=12) for the senior adults. The average content words ratio was 53.8% (SD=3.2%) for the young adults and 55.5% (SD=3.8%) for the senior adults. The balance between semantic words and dynamics words was in young adults 24.0% (SD=4.9%) semantic words to 29.8% (SD=4.0%) dynamics words.
In senior adults the balance was 25.7% (SD=5.4%) semantic words to 29.9% (SD=5.0%) dynamics words. The average syllable ratio was 1.38 (SD=0.06) in young adults, to 1.44 (SD=0.13) in senior adults. The average type/token ration was 0.78 (SD=0.07) in young adults and 0.77 (SD=0.07) in senior adults. The average number words ratio was very low; only 0.8% (SD=0.5%) of the total word count in young adults and 0.6% (SD= 0.5%) in senior adults. The average emotion words ratio was 3% (SD=2.1) in young adults and 2.5% (SD=2.8%) in senior adults.

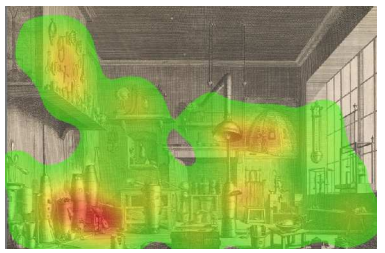
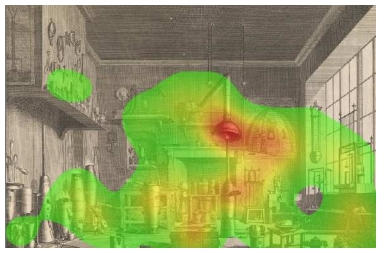
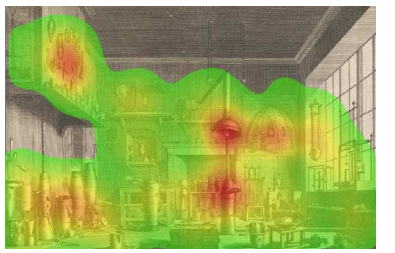
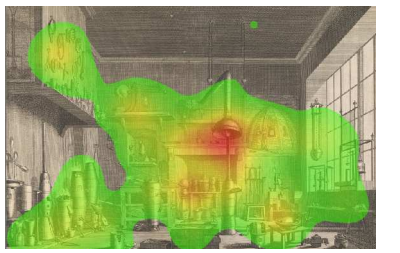
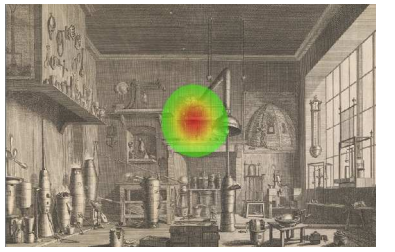
On a cohort level, senior adults living with dementia were most likely to have a lower semantic words ratio, compared to neurologically healthy senior adults. When including P8F_nfPPA in the analysis – who was effectively mute –, the mean difference in the semantic words ratio was -7.2%; with a two-sided p value of 0.023 and the odds of a true effect being 4.2. When P8F_nfPPA was excluded from the analysis, the mean difference in the semantic words ratio was 7.0%, with a two-sided p value of 0.006 and the odds of a true effect being 11.7.
On the other speech parameters, the variance among the senior adults living with dementia was very large, so I

**Figure 64**

# VISUAL EXPLORATION OF VISUAL ART AND COMPLEX IMAGES

## NEUROLOGICALLY HEALTHY ADULTS

## THINKING EYES PERSPECTIVES EXPERIMENT

| | YOUNG ADULTS | | SENIOR ADULTS | |
|---|---|---|---|---|
| Time Windows | | | | |
| Construct Inference > 750 ms |  |  |  |  |
| Gist Inference 250 – 750 ms |  | X |  | X |
| Perceptual Processing 0 – 250 ms |  | X |  | X |
| | Audio viewing phase | Silent viewing phase | Audio viewing phase | Silent viewing phase |

Heatmaps of aggregated visual fixation patterns of image #14 from the Wellcome selection. The transparent overlay colours indicate the fixation duration density, from low (green) to moderate (yellow) and high (red).

**AUDIO MARKER**: "I feel like this is some sort of guitar or musical instrument, in the left-hand corner,..."



investigated these differences with individual comparisons to the neurologically healthy senior adults cohort.
The Tables on the following pages compare the speech profiles of the senior adults living with dementia to the control cohort.

**Table 22:**
**Content words count**
**Senior adults living with dementia compared to control cohort**

| ID participant | Mean word difference | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | 29 | 0.026 | 3.8 |
| P2F_tAD | 1 | 0.914 | 1.0 |
| P3F_tAD | -5 | 0.710 | 1.0 |
| P6M_nfPPA | -20 | 0.111 | 1.5 |
| P7M_nfPPA | -28 | 0.032 | 3.3 |
| P8F_nfPPA | -32 | .0016 | 5.6 |
| P10M_bvFTD | -9 | 0.460 | 1.0 |
| P11M_bvFTD | 15 | 0.221 | 1.1 |
| P12M_PCA | -11 | 0.390 | 1.0 |
| P13F_PCA | 7 | 0.549 | 1.0 |
| P14M_UD | -22 | 0.086 | 1.7 |

**Table 23:**
**Content words ratio**
**Senior adults living with dementia compared to control cohort**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -4.4 | 0.278 | 1.0 |
| P2F_tAD | 11.6 | 0.008 | 9.4 |
| P3F_tAD | -2.2 | 0.584 | 1.0 |
| P6M_nfPPA | -17.6 | <.001 | 165.7 |
| P7M_nfPPA | 10.8 | .0013 | 6.6 |
| P8F_nfPPA | -55.5 | 0.000 | 9e +8 |
| P10M_bvFTD | 0.6 | 0.877 | 1.0 |
| P11M_bvFTD | -0.7 | 0.868 | 1.0 |
| P12M_PCA | -10.7 | .0014 | 6.3 |
| P13F_PCA | -11.5 | 0.009 | 8.9 |
| P14M_UD | -10.8 | .0013 | 6.4 |

**Table 24:**
**Semantic words ratio**
**Senior adults living with dementia compared to control cohort**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -11.3 | 0.055 | 2.3 |
| P2F_tAD | 1.2 | 0.828 | 1.0 |
| P3F_tAD | -5.9 | 0.301 | 1.0 |
| P6M_nfPPA | -15.0 | .0014 | 6.1 |
| P7M_nfPPA | 20.1 | 0.002 | 32.1 |
| P8F_nfPPA | -25.7 | <.001 | 234.4 |
| P10M_bvFTD | -5.2 | 0.357 | 1.0 |
| P11M_bvFTD | -11.0 | 0.061 | 2.2 |
| P12M_PCA | -9.1 | 0.119 | 1.5 |
| P13F_PCA | -11.4 | 0.053 | 2.3 |
| P14M_UD | -5.4 | 0.343 | 1.0 |

**Table 25:**
**Dynamic words ratio**
**Senior adults living with dementia compared to control cohort**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | 6.9 | 0.190 | 1.2 |
| P2F_tAD | 10.4 | 0.055 | 2.3 |
| P3F_tAD | 3.7 | 0.477 | 1.0 |
| P6M_nfPPA | -2.6 | 0.621 | 1.0 |
| P7M_nfPPA | -9.3 | 0.085 | 1.8 |
| P8F_nfPPA | -29.9 | <.001 | 2624.5 |
| P10M_bvFTD | 5.9 | 0.266 | 1.0 |
| P11M_bvFTD | 10.4 | 0.056 | 2.3 |
| P12M_PCA | -1.7 | 0.749 | 1.0 |
| P13F_PCA | -0.1 | 0.986 | 1.0 |
| P14M_UD | -5.4 | 0.306 | 1.0 |

**Table 26:**
**Syllable ratio**

**Senior adults living with dementia compared to control cohort**

| ID participant | Mean ratio difference | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -0.05 | 0.687 | 1.0 |
| P2F_tAD | 0.10 | 0.448 | 1.0 |
| P3F_tAD | -0.03 | 0.848 | 1.0 |
| P6M_nfPPA | -0.20 | 0.143 | 1.3 |
| P7M_nfPPA | -0.05 | 0.693 | 1.0 |
| P8F_nfPPA | -1.44 | <.001 | 1e +7 |
| P10M_bvFTD | -0.11 | 0.415 | 1.0 |
| P11M_bvFTD | -0.10 | 0.468 | 1.0 |
| P12M_PCA | -0.09 | 0.517 | 1.0 |
| P13F_PCA | -0.07 | 0.612 | 1.0 |
| P14M_UD | -0.20 | 0.151 | 1.3 |

**Table 27:**
**Type/token ratio**

**Senior adults living with dementia compared to control cohort**

| ID participant | Mean ratio difference | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -0.10 | 0.173 | 1.2 |
| P2F_tAD | 0.04 | 0.575 | 1.0 |
| P3F_tAD | -0.05 | 0.487 | 1.0 |
| P6M_nfPPA | -0.02 | 0.724 | 1.0 |
| P7M_nfPPA | 0.18 | .0013 | 6.5 |
| P8F_nfPPA | -0.77 | <.001 | 3e +7 |
| P10M_bvFTD | 0.08 | 0.233 | 1.1 |
| P11M_bvFTD | -0.03 | 0.684 | 1.0 |
| P12M_PCA | -0.03 | 0.618 | 1.0 |
| P13F_PCA | -0.06 | 0.385 | 1.0 |
| P14M_UD | -0.03 | 0.712 | 1.0 |

**Table 28:**
**Number words ratio**

**Senior adults living with dementia compared to control cohort**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | -0.6 | 0.308 | 1.0 |
| P2F_tAD | -0.3 | 0.592 | 1.0 |
| P3F_tAD | 0.0 | 0.993 | 1.0 |
| P6M_nfPPA | -0.6 | 0.308 | 1.0 |
| P7M_nfPPA | -0.6 | 0.308 | 1.0 |
| P8F_nfPPA | -0.6 | 0.308 | 1.0 |
| P10M_bvFTD | 2.2 | .001 | 80.0 |
| P11M_bvFTD | 1.4 | .0019 | 4.9 |
| P12M_PCA | -0.3 | 0.558 | 1.0 |
| P13F_PCA | -0.6 | 0.308 | 1.0 |
| P14M_UD | 2.2 | .001 | 76.0 |

**Table 29:**
**Emotion words ratio**

**Senior adults living with dementia compared to control cohort**

| ID participant | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P1M_tAD | 1.8 | 0.544 | 1.0 |
| P2F_tAD | 4.6 | 0.131 | 1.4 |
| P3F_tAD | 4.4 | 0.142 | 1.3 |
| P6M_nfPPA | -0.1 | 0.964 | 1.0 |
| P7M_nfPPA | -2.5 | 0.397 | 1.0 |
| P8F_nfPPA | -2.5 | 0.397 | 1.0 |
| P10M_bvFTD | -2.5 | 0.397 | 1.0 |
| P11M_bvFTD | -2.2 | 0.459 | 1.0 |
| P12M_PCA | -1.3 | 0.653 | 1.0 |
| P13F_PCA | 0.7 | 0.818 | 1.0 |
| P14M_UD | -2.5 | 0.397 | 1.0 |

It should be noted that the speech parameter profiles of P8F_nfPPA do not give a realistic reflection of her actual speech abilities. As I mentioned earlier, she was practically mute at the time she took part in my research, but I decided to analyse her speech samples – which contained no content words at all – nonetheless to show the progression of loss of speech that is caused by Nonfluent Primary Progressive Aphasia in my analysis.

Based on the individual speech parameter analysis, I derived speech profiles for the different dementia phenotypes of the participants that took part in my research.

**Table 30:**
**Typical Alzheimer's Disease speech profile**

| Speech parameter | Likely difference |
|---|---|
| Content words count | ++ |
| Content words ratio | ++ |
| Semantic words ratio | - |
| Dynamic words ratio | + |
| Syllable ratio | = |
| Type/token ratio | = |
| Number words ratio | - |
| Emotion words ratio | + |

**Table 31:**
**Nonfluent Primary Progressive Aphasia speech profile**

| Speech parameter | Likely difference |
|---|---|
| Content words count | - – / – - - |
| Content words ratio | - – /++ / – - - |
| Semantic words ratio | - – /++ / – - - |
| Dynamic words ratio | - |
| Syllable ratio | = |
| Type/token ratio | - /++ |
| Number words ratio | - |
| Emotion words ratio | - |

**Table 32:**
**Behavioural Frontotemporal Dementia speech profile**

| Speech parameter | Likely difference |
|---|---|
| Content words count | = |
| Content words ratio | = |
| Semantic words ratio | - |
| Dynamic words ratio | + |
| Syllable ratio | = |
| Type/token ratio | = |
| Number words ratio | ++ / +++ |
| Emotion words ratio | - |

**Table 33:**
**Posterior Cortical Atrophy speech profile**

| Speech parameter | Likely difference |
|---|---|
| Content words count | = |
| Content words ratio | - - |
| Semantic words ratio | - |
| Dynamic words ratio | = |
| Syllable ratio | = |
| Type/token ratio | = |
| Number words ratio | - |
| Emotion words ratio | = |

The speech profile for Nonfluent Primary Progressive Aphasia shows the different speech dynamics during different stages of the disease, indicated by ..../.../...., whereby each entry separated by a slash symbol signifies a different stage. P6M_nfPPA was still in an early stage at the time he took in my research. His speech production was hesitant and he had a noticeable reduction in content and semantic words ratio. P7M_nfPPA had more limited speech production at the time he took part in my research. While his speech output was more reduced, it contained a higher ratio of content and semantic words (it became more condensed in content). As I already mentioned, P8F_nfPPA was effectively mute at the time she took part in my research. Her content and semantic words ratio were therefore reduced to zero.

The speech profile of P14M_UD, who has been diagnosed with an unspecified dementia, overlapped with the speech profiles for Nonfluent Primary Progressive Aphasia and Behavioural Frontotemporal Dementia, which is in line with the suspected underlying corticobasal pathology.

The speech profile of semantic Primary Progressive Aphasia would most likely overlap with the speech profiles for Typical Alzheimer's Disease and Behavioural Frontotemporal Dementia.

**Internal state evaluation results**

When participants were shown visual artworks and complex images for only 750 ms, neurologically healthy young adults gave the figurative images on average a resonance rating of 3.5 (SD=0.89) – leaning towards little resonance – and the distorted versions on average a rating of 3.0 (SD=0.70), reflecting a moderate resonance. The difference was not significant however. They gave coloured images on average a resonance rating of 3.0 (SD=0.73) and they gave greyscale images on average the same rating of 3.0 (SD=0.84).

Neurologically healthy senior adults gave the figurative images on average a resonance rating of 3.2 (SD=0.93) – a moderate resonance – and the distorted versions on average a rating of 2.5 (SD=0.72), a moderate to strong resonance. This mean difference of 0.67 points (on a 5-point scale) was significant, with a two-sided p value of 0.028. The odds that this was a true effect were 3.7. They gave coloured images on average a resonance rating of 2.5 (SD=0.79) – a moderate to strong resonance – and they gave greyscale images on average a resonance rating of 2.4 (SD=0.84), leaning towards a strong resonance. This difference was not significant.

Senior adults living with dementia gave the figurative images on average a resonance rating of 2.9 (SD=0.62) – leaning towards a moderate resonance – and the distorted versions on average a rating of 2.6 (SD=0.50), also leaning towards a moderate resonance. This difference was not significant.

They gave colour images on average a resonance rating of 2.6 (SD=0.52) – leaning towards a moderate resonance – and they also gave greyscale images on average a resonance rating of 2.6 (SD=0.84).

When I compared the resonance ratings for the 750 ms viewings between the cohorts, I found that the neurologically healthy senior adults resonated more strongly with several image categories, compared to the young adults. The senior adults resonated on average 0.54 points stronger with the distorted images. The two-sided p value for this difference was 0.027 and the odds that this represented a true effect were 3.8. Senior adults also resonated more strongly with greyscale images during the brief image presentations; on average 0.61 points more than the young adults. The two-sided p value for this difference was 0.026 and it was 3.9 times more likely that this represented a significant difference.
When I compared the resonance ratings of the neurologically healthy senior adults during the 750 ms presentations with those of the senior adults living with dementia, I found no significant differences.

Next, I compared the resonance ratings from the 'Snapshots' experiment to the resonance ratings from the 'Perspectives' experiment, where the same images were shown again but then for 20 seconds instead of 750 ms. I started by comparing the resonance ratings between the two experiments based on their perceptual features. The neurologically healthy young adults gave similar resonance ratings to the images, regardless of viewing time, when they were grouped on perceptual features. Senior adults, regardless of neurological health, resonated on average more strongly with the figurative images when they had more time to look at them. The average mean difference was 0.74 points, with a two-sided p value of 0.007. It was 10 times more likely that this was a significant difference. In addition, senior adults living with dementia resonated on average less with greyscale images when they had more time to look at them. The average mean difference was 0.24 points, with a two-sided p

value of 0.022. It was 4.4 times more likely that this was a significant difference. When I compared the research cohorts with each other, I found that senior adults, independent of neurological health, resonated more strongly with the entire selection of visual artworks and complex images compared to young adults during the 20 second viewings. The mean difference in resonance rating was 0.57, with a two-sided p value of 0.015. The odds that this difference was a true effect of ageing were 5.9.

I then grouped the resonance ratings of the 'Perspectives' experiment under the 3 viewing conditions: internal perspective (VTS); external perspective (VTS) and external context.
I compared the average resonance ratings for each viewing condition, with the average resonance ratings that the participants had given to the images in each group during the 'Snapshots' experiment, when they only had 750 ms to look at them. This allowed me to study the possible effects of the different viewing conditions on how much the visual artworks and complex images resonated with the participants.

Young adults resonated more strongly with the images after they had explored them for 20 seconds from their internal perspective with VTS, compared to the first snapshot viewing. The average mean difference was 0.35 points, with a two-sided p value <.001. It was 206 times more likely that this was a significant difference. Their resonance appeared to be unaffected by listening to someone else reflecting on the images with VTS.
In contrast, they resonated less with the images after they had been listening to contextual information, compared to the first snapshot viewing. The average mean difference was 0.33 points, with a two-sided p value of 0.001. It was 6.6 times more likely that this was a significant difference. None of the 3 different viewing conditions appeared to affect the resonance ratings of the neurologically healthy senior adults.
The resonance ratings of the senior adults living with dementia, were not impacted by the VTS viewing conditions. However, like the young adults, they resonated less with the images after listening to contextual information. The average mean difference was 0.41 points, with a two-sided p value <.001. It was 250 times more likely that this was a significant difference.
Figures 65, 66 and 67 show the effect of viewing condition on the resonance rating for each research cohort.

**Electrodermal activity results**
The electrodermal activity (EDA) flux patterns of the neurologically healthy participants is detailed in the following Tables.

**Table 34:**
**Thinking Eyes experiments EDA flux (%) young adults**

| Experiment | Wrist | EDA flux % | St deviation |
|---|---|---|---|
| Snapshots | Left | 15 | 54 |
| Snapshots | Right | 40 | 74 |
| Perspectives | Left | -9 | 32 |
| Perspectives | Right | 6 | 32 |
| Panoramas | Left | 15 | 34 |
| Panoramas | Right | 39 | 62 |

**Table 35:**
**Thinking Eyes experiments EDA flux (%) senior adults**

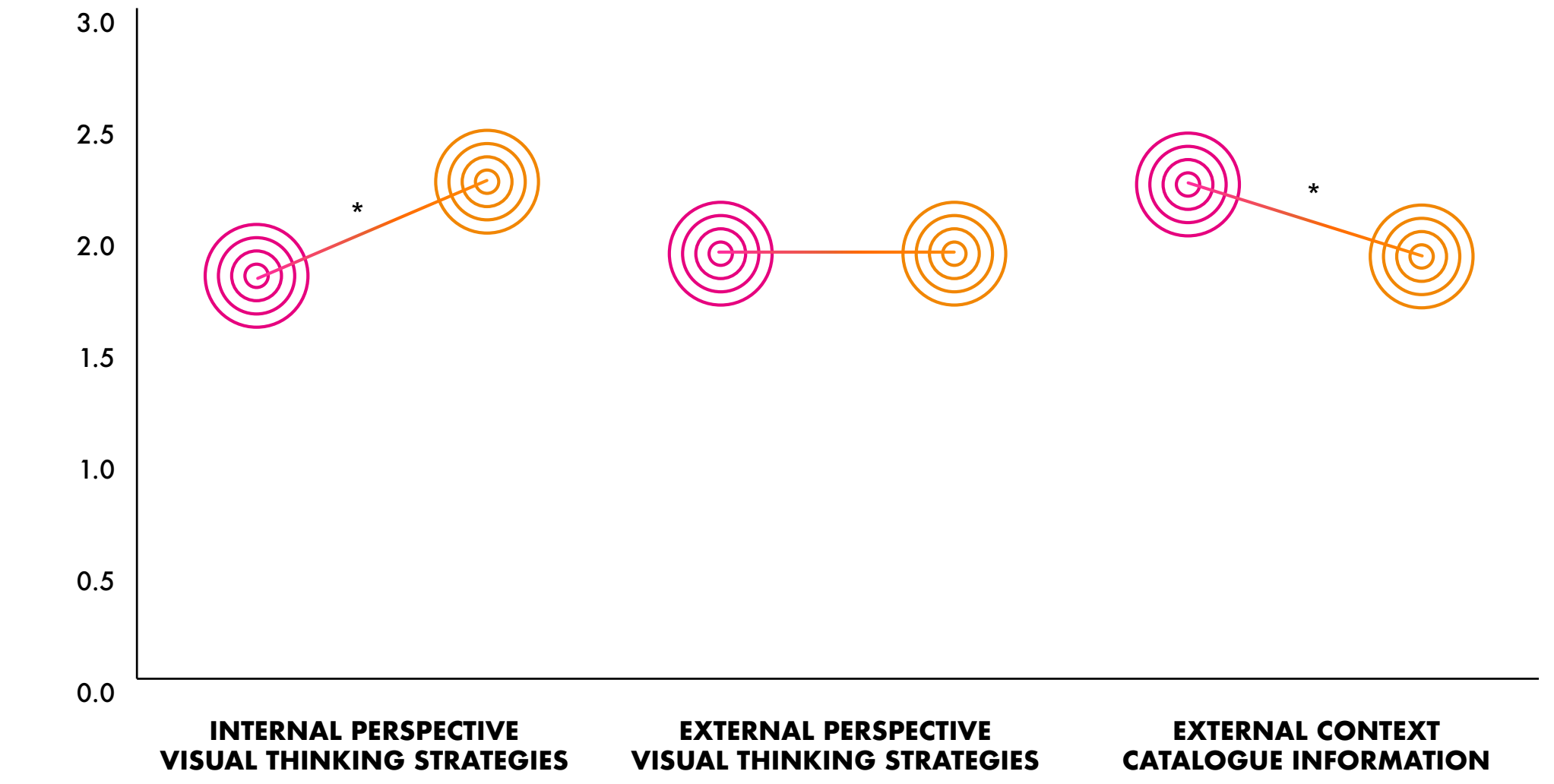
| Experiment | Wrist | EDA flux % | St deviation |
|---|---|---|---|
| Snapshots | Left | -5 | 40 |
| Snapshots | Right | 52 | 88 |
| Perspectives | Left | -28 | 50 |
| Perspectives | Right | 12 | 38 |
| Panoramas | Left | -20 | 60 |
| Panoramas | Right | 4 | 51 |

The EDA flux of the young adults stayed on average within the boundaries of a maximum of 40% increase and a maximum of 39% decrease from their personal average across the entire research visit, taking only active research time into account.
When I compared their left wrist with the right wrist EDA activity, I found no significant differences across all three Thinking Eyes experiments, which is shown in Table 36.

Figure 65

# RESONANCE WITH VISUAL AND COMPLEX IMAGES
## YOUNG ADULTS

### THINKING EYES PERSPECTIVES EXPERIMENT



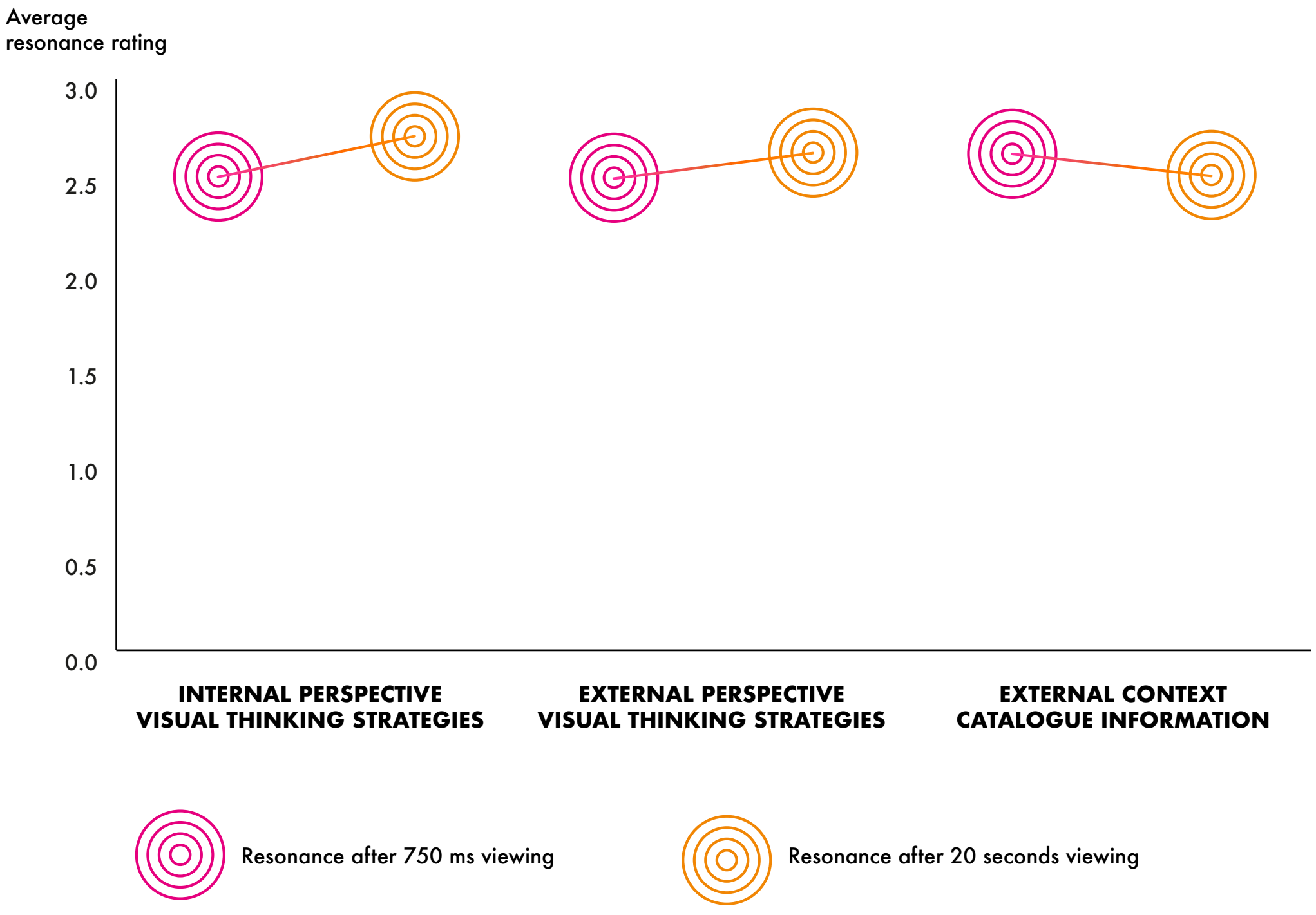

* Significant effect of viewing condition on resonance with visual artworks and complex images

Figure 66

# RESONANCE WITH VISUAL ART AND COMPLEX IMAGES

## SENIOR ADULTS

### THINKING EYES PERSPECTIVES EXPERIMENT



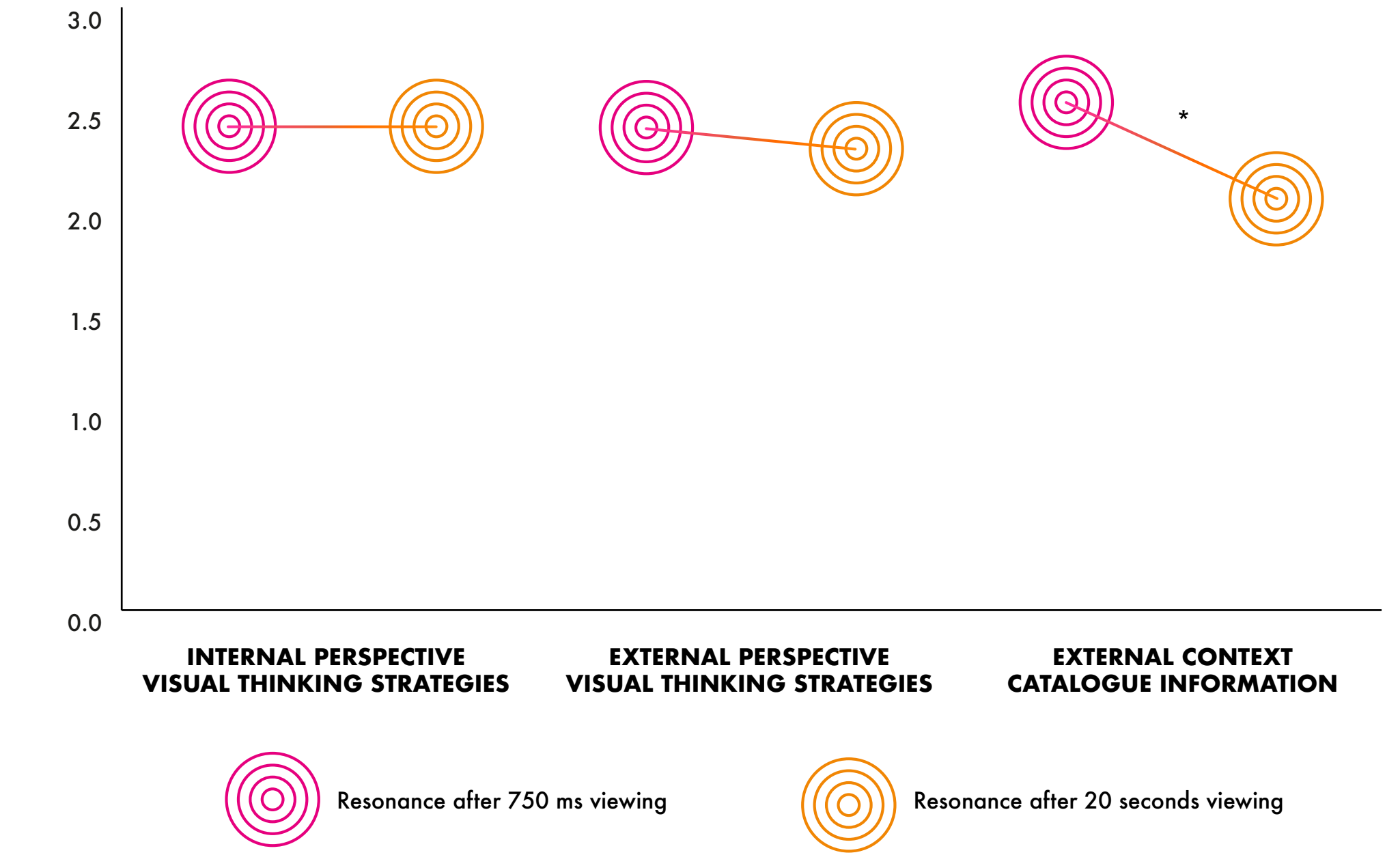

No significant effect of viewing condition on resonance with visual artworks and complex images

Figure 67

# RESONANCE WITH VISUAL ART AND COMPLEX IMAGES

## SENIOR ADULTS LIVING WITH DEMENTIA

### THINKING EYES PERSPECTIVES EXPERIMENT




* Significant effect of viewing condition on resonance with visual artworks and complex images

**Table 36:**
**Left/right EDA flux (%) young adults**
**Thinking Eyes experiments**

| Experiment | Difference left/right % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Snapshots | -26 | 0.162 | 1.2 |
| Perspectives | -16 | 0.245 | 1.1 |
| Panoramas | -11 | 0.421 | 1.0 |

The EDA flux of the neurologically healthy senior adults stayed on average within the boundaries of a maximum of 52% increase and a maximum of 28% decrease from their personal average across the entire research visit. Comparing their left and right wrist EDA activity, I found significant differences in the 'Snapshots' and 'Perspectives' experiments, which is detailed in Table 37.

**Table 37:**
**Left/right EDA flux (%) senior adults**
**Thinking Eyes experiments**

| Experiment | Difference left/right % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Snapshots | -66 | .0011 | 7.5 |
| Perspectives | -43 | 0.029 | 3.6 |
| Panoramas | -28 | 0.142 | 1.3 |

The asymmetry between the electrodermal activity in the left and right wrist during the 'Snapshots' experiment in neurologically healthy senior adults could be an indication of an increased emotional arousal. Since the right wrist EDA flux increased to 52% above the personal average, this might signal a stress response. In contrast, during the 'Perspectives' experiment, the EDA asymmetry was related to a lower electrodermal activity in the left wrist EDA, compared to the personal average. This might be indicative of a more relaxed autonomic state. During the Panoramas experiment, their EDA patterns were similar.

When I compared the EDA responses of the young adults with the senior adults, I only found a significant difference in the left wrist EDA flux patterns during the Panoramas experiment, which is shown in Table 38.

**Table 38:**
**EDA flux (%) differences healthy adults**
**Thinking Eyes experiments**

| Experiment | Wrist | Location parameter % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| Snapshots | Left | 21 | 0.211 | 1.1 |
| Snapshots | Right | -11 | 0.684 | 1.0 |
| Perspectives | Left | 20 | 0.19 | 1.2 |
| Perspectives | Right | -6 | 0.633 | 1.0 |
| Panoramas | Left | 45 | 0.007 | 10.8 |
| Panoramas | Right | 33 | 0.133 | 1.4 |

While the EDA flux of the young adults was on average only 15% higher than their personal average across the entire research visit, it might be a possibility that the neurologically senior adults were still more comparatively more at ease during the Panoramas experiment.

On the next pages I will present the data Tables with the differences in EDA flux of the senior adults living with dementia, in comparison to the neurologically healthy senior adults.

**Table 39:**

**EDA flux (%) Snapshots experiment**

**Senior adults living with dementia compared to control cohort**

| ID participant | Wrist | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P1M_tAD | Left | -56 | 0.189 | 1.2 |
| P1M_tAD | Right | -12 | 0.811 | 1.0 |
| P2F_tAD | Left | -89 | 0.044 | 2.7 |
| P2F_tAD | Right | -122 | 0.028 | 3.6 |
| P3F_tAD | Left | 5 | 0.898 | 1.0 |
| P3F_tAD | Right | -70 | 0.190 | 1.2 |
| P6M_nfPPA | Left | -43 | 0.304 | 1.0 |
| P6M_nfPPA | Right | -26 | 0.622 | 1.0 |
| P7M_nfPPA | Left | -48 | 0.255 | 1.1 |
| P7M_nfPPA | Right | 29 | 0.584 | 1.0 |
| P8F_nfPPA | Left | -56 | 0.186 | 1.2 |
| P8F_nfPPA | Right | -97 | 0.074 | 1.9 |
| P10M_bvFTD | Left | -50 | 0.240 | 1.1 |
| P10M_bvFTD | Right | -80 | 0.135 | 1.4 |
| P11M_bvFTD | Left | 13 | 0.759 | 1.0 |
| P11M_bvFTD | Right | -79 | 0.140 | 1.3 |
| P12M_PCA | Left | -14 | 0.731 | 1.0 |
| P12M_PCA | Right | -57 | 0.279 | 1.0 |
| P13F_PCA | Left | -87 | 0.047 | 2.6 |
| P13F_PCA | Right | 56 | 0.290 | 1.0 |
| P14M_UD | Left | x | x | x |
| P14M_UD | Right | -121 | 0.029 | 3.5 |

**Table 40:**

**EDA flux (%) Perspectives experiment**

**Senior adults living with dementia compared to control cohort**

| ID participant | Wrist | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P1M_tAD | Left | -5 | 0.929 | 1.0 |
| P1M_tAD | Right | -79 | 0.056 | 2.3 |
| P2F_tAD | Left | -62 | 0.240 | 1.1 |
| P2F_tAD | Right | -83 | 0.046 | 2.6 |
| P3F_tAD | Left | 34 | 0.512 | 1.0 |
| P3F_tAD | Right | -23 | 0.567 | 1.0 |
| P6M_nfPPA | Left | -22 | 0.676 | 1.0 |
| P6M_nfPPA | Right | 16 | 0.683 | 1.0 |
| P7M_nfPPA | Left | -47 | 0.366 | 1.0 |
| P7M_nfPPA | Right | 75 | 0.071 | 2.0 |
| P8F_nfPPA | Left | -17 | 0.740 | 1.0 |
| P8F_nfPPA | Right | -46 | 0.249 | 1.1 |
| P10M_bvFTD | Left | 3 | 0.957 | 1.0 |
| P10M_bvFTD | Right | 57 | 0.159 | 1.3 |
| P11M_bvFTD | Left | 48 | 0.359 | 1.0 |
| P11M_bvFTD | Right | -24 | 0.549 | 1.0 |
| P12M_PCA | Left | 50 | 0.341 | 1.0 |
| P12M_PCA | Right | 0 | 0.995 | 1.0 |
| P13F_PCA | Left | -65 | 0.222 | 1.1 |
| P13F_PCA | Right | -72 | 0.081 | 1.8 |
| P14M_UD | Left | x | x | x |
| P14M_UD | Right | -63 | 0.125 | 1.4 |

**Table 41:**
**EDA flux (%) Panoramas experiment**
**Senior adults living with dementia compared to control cohort**

| ID participant | Wrist | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P1M_tAD | Left | 18 | 0.770 | 1.0 |
| P1M_tAD | Right | -3 | 0.956 | 1.0 |
| P2F_tAD | Left | -70 | 0.269 | 1.0 |
| P2F_tAD | Right | -64 | 0.238 | 1.1 |
| P3F_tAD | Left | 39 | 0.532 | 1.0 |
| P3F_tAD | Right | -7 | 0.892 | 1.0 |
| P6M_nfPPA | Left | -15 | 0.808 | 1.0 |
| P6M_nfPPA | Right | 17 | 0.749 | 1.0 |
| P7M_nfPPA | Left | -77 | 0.226 | 1.1 |
| P7M_nfPPA | Right | 47 | 0.379 | 1.0 |
| P8F_nfPPA | Left | 4 | 0.949 | 1.0 |
| P8F_nfPPA | Right | -48 | 0.367 | 1.0 |
| P10M_bvFTD | Left | -68 | 0.280 | 1.0 |
| P10M_bvFTD | Right | -65 | 0.232 | 1.1 |
| P11M_bvFTD | Left | 66 | 0.296 | 1.0 |
| P11M_bvFTD | Right | -52 | 0.330 | 1.0 |
| P12M_PCA | Left | 106 | 0.101 | 1.6 |
| P12M_PCA | Right | 143 | .0013 | 6.5 |
| P13F_PCA | Left | -68 | 0.285 | 1.0 |
| P13F_PCA | Right | 101 | 0.069 | 2.0 |
| P14M_UD | Left | x | x | x |
| P14M_UD | Right | -76 | 0.164 | 1.2 |

These results show that most senior adults living with dementia had similar EDA flux patterns during the Snapshots experiment, compared to the neurologically healthy senior adults. Their EDA flux patterns tended to be lower than the personal averages of the neurologically healthy senior adults, so they might have comparatively been more at ease. Most senior adults living with dementia also had similar EDA flux patterns during the Perspectives experiment, compared to the neurologically healthy senior adults.

This means they were likely to be equally at ease during this research section. The majority of senior adults living with dementia also had similar EDA flux patterns during the Panoramas experiment, compared to the neurologically healthy senior adults, indicating they were likely equally at ease during this research section. I did observe a significantly higher EDA activity in the right wrist of P12M_PCA. In light of the perceptual difficulties associated with Posterior Cortical Atrophy, he might have felt comparatively more stress when asked to reflect out loud about what he were thought was going on in the images.

## 4.2.4 DISCUSSION

The experimental data of the Thinking Eyes project elucidated many aspects of my research questions and hypotheses, which I have reflected on in this chapter.

### Visual exploration discussion

My 1st research question was: 'How does visual perception relate to visual imagination and other social functions?'

The findings from the 3 Thinking Eyes experiments showed that during the initial perceptual processing phase (0 – 250 ms) when looking at visual artworks and complex images, visual imagination was informed by the image elements that happen to fall in the central 5% of the visual field, which was in this study the centre of each image.

During the gist inference phase that followed (250 – 750 ms), top-down effects of social salience began to influence the visual exploration patterns. My research findings showed that during this phase, people would stay mostly fixated on the centre when viewing distorted images, but direct their foveal vision towards animate image features (in particular frontal and sideways human faces and hand actions) when looking at figurative images.

A novel social salience model of visual exploration that I developed, based on the principles of foveal vision and the functional profiles of the Social Brain Atlas, predicted the visual exploration patterns of all 3 research cohorts with significantly higher accuracy than an alternative model that only took perceptual image factors into account.

My research findings also showed that during the construct inference phase (>750 ms), auditory processing and different viewing strategies interact with the visual exploration and social salience valuations of visual artworks and complex images. When participants were listening to an audio recording of someone else talking about the image they were looking at, they would direct their foveal vision to image elements that were specifically mentioned in the audio recording. Even after the audio recording had finished, people would still spend significantly more time looking at image features that had been mentioned in the audio recording than other image elements.

When participants were exploring a visual artwork or complex figurative image with the Visual Thinking Strategies (VTS) method, people would spend much more time looking at animate image elements. When people were exploring a visual artwork or complex figurative image while listening to contextual (museum catalogue) information, they would look much less at animate image features, but focus slightly more on inanimate features.
When participants were asked to reflect out loud about an visual artwork or complex image with the VTS method, their speech profiles gave insight into their neurological health.

I have further elaborated on the findings I described above in relation to my other research questions and hypotheses.

My additional research questions were:

Q2. Does healthy ageing have an effect on visual imagination and other social brain functions?

Q3. Do different forms of dementia have general effects on visual imagination and other social brain functions?

Q4. Do different forms of dementia have specific effects on visual imagination and other social brain functions?

With respect to these research questions, I had formulated the following hypotheses:

H1. Neurologically healthy young adults are likely to show more sensitive perceptual (bottom-up) and flexible cognitive (top-down) behavioural responses to visual artworks and complex images than neurologically healthy senior adults.

H2. Neurologically healthy senior adults are likely to rely more strongly on semantic knowledge in cognitive (top-down) responses to visual artworks and complex images than neurologically healthy young adults.

H3. The functional profiles of the dementia syndromes that I have mapped onto the Social Brain Atlas will align with the behavioural measurements.

H4. Given the prominence of semantic language in all dementia profiles in the Social Brain Atlas, it is likely that dementia is in general associated with decreased semantic language access in responses to visual artworks and complex images, compared to neurologically healthy senior adults.

The results from the 3 Thinking Eyes experiments showed effects of healthy ageing and dementia on visual imagination during various temporal phases and behavioural modalities.

During very brief presentations (750 ms) of visual artworks and complex images, I did not find significant differences between the visual explorations patterns of the neurologically healthy young and senior adults in the initial perceptual processing phase (0 – 250 ms).

More than 90% of the fixations were directed at the image centres during this phase in all neurologically healthy adults.

During the first 250 ms, I did observe significant lower dwell times on the image centres in participants living with Posterior Cortical Atrophy, and to a lesser degree also in participants living with Typical Alzheimer's Disease. This finding was related to a reduced ability to focus on the small fixation cross in the centre of a middle grey screen that was shown before each image presentation to direct the gaze to the centre of the screen. These findings are congruent with previous research by Shakespeare et al. (2015), which reported difficulties with fixating the gaze on a stationary target in both Posterior Cortical Atrophy and Typical Alzheimer's Disease, associated with reduced cerebellar grey matter volume in the latter and a more generalised reduced cortical thickness in the former. These anatomical associations don't easily translate onto the functional networks of the Social Brain Atlas and will have to be further investigated in future research.

Young adults looked on average significantly longer at frontal human faces during the gist inference phase (250 – 750 ms) than neurologically healthy senior adults. This finding supports my first hypothesis. Two participants living with dementia, who had been diagnosed with Behavioural Frontotemporal Dementia and Posterior Cortical Atrophy respectively, looked significantly longer at frontal human faces than the neurologically healthy senior adults during the gist inference phase. Given that Posterior Cortical Atrophy affects perceptual processing, this finding appears to contradict my third hypothesis. However, the two other participants who were diagnosed with Behavioural Frontotemporal Dementia and Posterior Cortical Atrophy respectively did not show this pattern however, so further research will have to be conducted before it can be contextualised in the Social Brain Atlas.

**Internal state evaluation discussion**

Senior adults, independent of neurological health, needed a longer viewing time to resonate with complex figurative visual artworks and images, compared to young adults. For senior adults living with dementia, this also applied to colour images. During longer presentations (20 seconds), exploring the images from a personal perspective with the VTS method made young adults look more at animate elements and resonate more strongly with the images. In contrast, exploring the images while listening to contextual (museum catalogue) information, made them explore the images much less in general, while focusing slightly more on inanimate elements.

Listening to contextual information led to a lower personal resonance in young adults. The visual exploration patterns of the senior adults, independent of neurological health, in response to the different viewing conditions was similar to the young adults. However, I did observe effects of healthy ageing and dementia on the resonance ratings in relation to the different viewing conditions. Unlike the young adults, the personal resonance with the images of the neurologically healthy senior adults was not affected by different viewing strategies, a finding which aligned with my second hypothesis.

In senior adults living with dementia I observed that listening to contextual information lowered their personal resonance with the images. The audio recordings with contextual information about the images (which came from Wellcome Collection) had a much higher semantic word ratio than the audio recordings of personal VTS reflections. This means that listening to contextual information made heavier demands on participants' semantic processing abilities. This could provide an explanation for the negative impact that listening to contextual information had on personal resonance in young adults and senior adults living with dementia, which would support both my first and my fourth hypothesis.

In addition, the electrodermal activity, indicative of autonomic arousal, was considerably lower during the arts-based experiments in senior adults living with and without dementia, compared to the standard neuropsychometric test section of the research.

These finding suggests that arts-based neuropsychometric instruments –building on the VTS method – could have diagnostic as well as an therapeutic value, which will be further explored in future research.

**Auditory perception discussion**

I found no significant differences between the effects of auditory processing on visual exploration between neurologically healthy young and senior adults. However, I did find significant differences between senior adults living with dementia and neurologically healthy senior adults in the visual exploration patterns during the silent viewing phase after an audio recording.

Participants diagnosed with Behavioural Frontotemporal Dementia, Posterior Cortical Atrophy, and Typical Alzheimer's Disease looked significantly less at inanimate elements that had not been mentioned in the audio recordings with contextual information, compared to neurologically healthy adults. These three dementia phenotypes primary affect different networks in the Social Brain Atlas, and the only hub these networks have in common is the hippocampus. This could possibly point to difficulties with working memory and flexibly redirecting the visual attention to inanimate elements after processing auditory information with a heavy semantic load.

In contrast, the visual exploration patterns showed that participants who had been diagnosed with Nonfluent Primary Progressive Aphasia looked significantly more at inanimate elements that had not been mentioned in audio recordings of a person giving a personal reflection on the image. This finding could perhaps be explained by a reduced after-effect of the audio recordings on visual explorations in Nonfluent Primary Aphasia, compared to neurologically healthy adults. Why I only observed this effect in response to audio recordings with personal reflections is unclear however and will have to be further investigated.

**Speech production discussion**

My VTS speech samples analysis showed that the semantic words ratio was the most likely speech parameter to be affected by dementia on a cohort level, which offered further support for my fourth hypothesis. On an individual level, this effect was most pronounced in participants diagnosed with Nonfluent Primary Progressive Aphasia. While the diagnostic consensus describes semantic language as relatively intact in Nonfluent Primary Progressive Aphasia, this finding is actually congruent with the disease profile in the Social Brain Atlas that predicts an impact on speech and semantic language functions associated with affected core hubs in the Interaction Network (IFG_L, AI_L).
The content words ratio (representing the proportional use of combined semantic and dynamic words), was also significantly affected in Nonfluent Primary Aphasia, and in Posterior Cortical Atrophy as well. Posterior Cortical Atrophy initially affects the Perception Network in the Social Brain Atlas, which also shows high likelihood ratios for involvement in speech and semantic language functions in all core hubs (FG, MT/V5, pSTS).
However, another possible explanation for a reduced content words ratio in Posterior Cortical Atrophy could be that it is related to perceptual difficulties (it is hard to talk about something you struggle to perceive).

The content words ratio was also significantly reduced in the participant who had been diagnosed with an unspecified dementia, with possible subcortical and/or vascular involvement. Nonfluent Primary Progressive Aphasia is also associated with a risk to develop subcortical disorders and this could point to a possible link between basal ganglia projections to the anterior Interaction Network and content words production.

Finally, the number words ratio was also significantly increased in the participant with the unspecified form of dementia, as well as in the two participants who had been diagnosed with Behavioural Frontotemporal Dementia. Number processing is predominantly regulated by various networks in the posterior parietal cortex (Dehaene et al., 2003), a brain region that is relatively spared in Behavioural Frontotemporal Dementia. This finding is therefore congruent with the functional disease profile in the Social Brain Atlas and could possibly be of diagnostic value. I should mention that the higher use of number words might not be clearly noticeable in natural conversation, as the number words ratio in neurologically healthy senior adults was only 0.6% and the observed increases in this ratio did not exceed 2.2%. With respect to the participant diagnosed with an unspecified form of dementia, this finding provided further evidence of a behavioural overlap with Frontemporal Dementia phenotypes which could be indicative of the underlying pathology.

Follow-up research with larger cohorts will have to be conducted to refine and validate the Thinking Eyes experiments as reliable instruments to assess visual imagination and other social brain functions in healthy ageing and dementia.

Beyond the potential of the Thinking Eyes experiments as cognitive assessments instruments, the research findings are also informative for arts-based learning programmes.
The outcomes suggest that the most effective way to optimise people's engagement with visual artworks and complex would be to start with a VTS viewing session, before introducing any contextual information. This could be followed up by further VTS conversations to integrate the added contextual information into the personal framework of understanding and allow for critical reflection. In this order of events, contextual information is only introduced after a personal connection has been established.

This approach would follow in the footsteps of Arnheim's writings on visual thinking and would also closely align with Vygotsky's Zone of Proximal Development (1978) and Bruner's Constructivist theory (1960). It also aims to expand Housen's proposed 5 stages of aesthetic development, by placing them in a broader framework of perceptual understanding in a social context. I want to emphasise however that VTS conversations can also be very effective when no contextual information is provided at all about the visual art or complex images, which develops participants' trust in their own perceptual meaning making and their ability to cope with uncertainty. These are life skills that are of equal importance to neurologically healthy adults as to those who are living with dementia.

Especially in the context of the finding that contextual information on average reduced the personal resonance and visual exploration, the value of VTS is most evident in its power to engage people personally with visual art and complex images. This also provides support my hypothesis that VTS triggers a co-activation of the Construction Network with the Interaction Network of the Social Brain Atlas, which reflects the active recruitment of personal values, experiences and knowledge while interacting with the outside world.

## 4.3 COLOUR SPACES PROJECT
### 4.3.1 INTRODUCTION

How colours affect our feelings, thoughts and actions has been studied extensively from artistic, scientific and commercial perspectives. Yet colours are a fickle matter, not in the least because their very existence is context dependent.

In February 2015, a casually photographed dress became a viral internet sensation, because it turned out that people experienced its colours wildly differently ('The dress', Wikipedia. Retrieved 11 January 2020). Some people saw it as a blue and black dress, for others it was brown and blue and for a third category the colours of the dress were a combination of white and gold. A neuroscientist from New York University investigated the phenomenon and concluded that the profound differences in colour perceptions were most strongly driven by the (implicit) assumptions that people made about the lighting conditions under which the dress was photographed (Wallisch, 2017). Based on the presupposed lighting conditions, people's brains made an automatic colour-adjustment. Anyone who has ever fiddled with the camera settings on their smartphone, is familiar with the huge difference in colour tone when you switch from a daylight to a tungsten lighting setting for instance, which is effectively the same mechanism as our brain performs.
This anecdote illustrates how even the most mundane everyday objects can be perceived fundamentally different, due to the complex interactions between light and chroma.

Long before the existence of social media memes, this fraught relationship between light and colour qualities was already a source of fierce scientific debate in the Western world. In 1705, the English natural philosopher Isaac Newton published 'Opticks', a dissertation on the nature and properties of light. Newton had identified 7 colours in the light spectrum visible to humans:

Red; Orange; Yellow; Green; Blue; Indigo and Violet.

Newton's classification was not so much based on the colours that he could actually distinguish, but guided by the number of notes in the Western musical scale, as Newton was convinced that colour is analogous to music. Newton reasoned that the wavelength spectrum was equivalent to an octave and he added orange between red and yellow and indigo between blue and violet as half tones in an octave. It turned out however that the wavelengths of visible light ranged between 400 – 700 nanometres and were in reality more a major sixth (Isacoff, 2003).

In 1810, the German writer Johann Wolfgang von Goethe's published his 'Theory of Colours'. Expressing a point of view that would become widely derided by colour scientists, Goethe disagreed with Newton that colour was purely determined by physical properties. He argued that the phenomenal experience of colours was dependent on context, medium and human perception. Goethe also believed that darkness has a presence and a direct interaction with light and colour, functioning as the opposite pole of light instead of the absolute absence of light. Goethe devised a colour wheel with 6 complementary colours:

Purple; Orange; Yellow; Green; Blue; Violet.

Goethe assigned these aesthetic qualities of colours to 4 categories of cognitive function:

- Vernunft (rationality): Red and Orange
  The beautiful and the noble
- Verstand (intellect): Yellow and Green
  The good and the useful
- Sinnlichkeit (sensuality): Green and Blue
  The useful and the common
- Phantasie (imagination): purple and red)
  The unnecessary and the beautiful

In 1852, the German physicist Hermann von Helmholtz took a less poetic approach to colour perception took it upon him to study the mechanisms in the human eye that enable colour vision. He put forward the theory that there are three different types of cone cells in the human retina which prefer specific wavelengths that are associated with 3 primary colours:

Blue (short); Green (medium); and Red (long) wavelengths.

Credited alongside the earlier scientific work by the English polymath Thomas Young, who proposed the existence of 3 different types of cones, von Helmholtz's scientific discoveries would become collectively known as the Young-Helmholtz trichromatic theory of colour vision.
The Young-Hemholtz trichromatic theory is often mentioned in relation to the ground-breaking experiments of the Scottish physicist James Clerk Maxwell. In collaboration with the English photographer Thomas Sutton, Maxwell introduced colour photography to the world in a lecture at the Royal Institution of Great Britain in 1861 (Figure 68). This first colour photograph was a practical execution of a though-experiment Maxwell had published in 1857, in which he reasoned that if a sum of any three lights could reproduce any perceivable colour, then colour photographs could be produced with a set of three coloured filters. To create the first ever colour photograph, Sutton took 3 black and white photographs of a tartan ribbon through 3 different colour filters: red, green blue. By superimposing the resulting photographs over each other, the different colour hues of the ribbon became visible.

The German physiologist Ewald Hering put in 1878 yet another model of colour perception forward. His colour opponency theory proposed that colour perception is generated through specific mechanisms in the human vision system that are sensitive to three pairs of opponent colours:

Blue versus Yellow; Red versus Green; Black versus White.

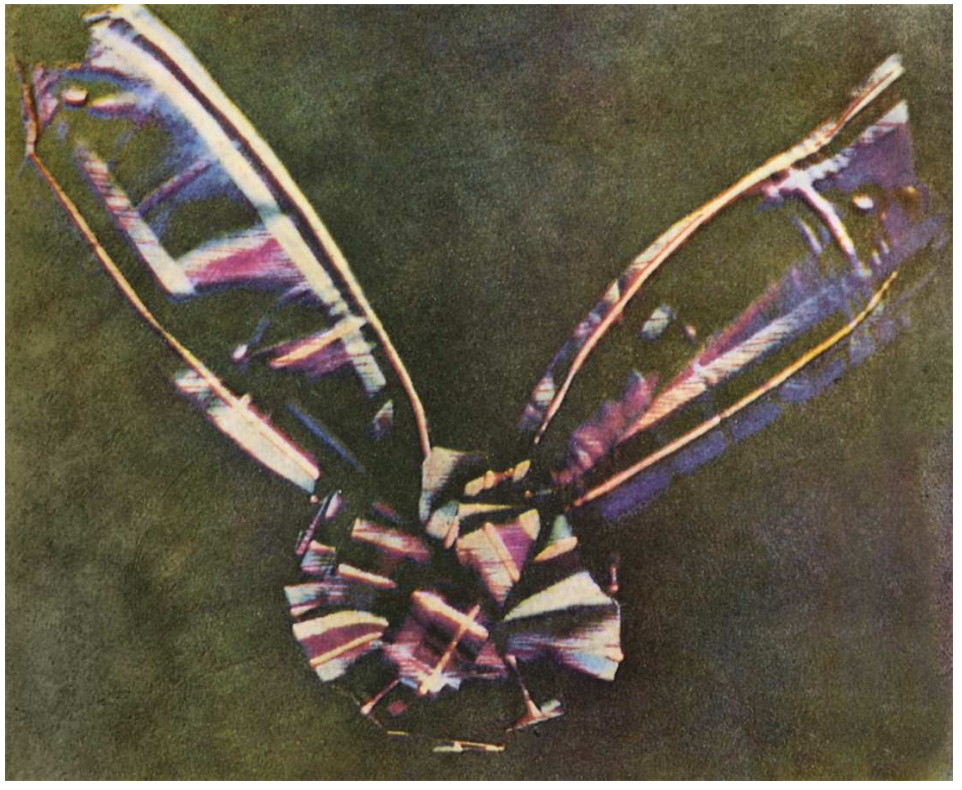


**Figure 68: The first colour photograph (Sutton and Maxwell, 1861).**

Von Helmholtz would spend a large part of his later scientific career arguing against Hering's theory, but the discovery of colour opponent ganglion cells in the retina and lateral geniculate nucleus eventually proved that both theories are correct and the two different mechanisms form a complementary dynamic of colour perception in human vision (Conway, 2009).

In the lateral geniculate nucleus, the luminance channel is processed in the magnocellular layer, the red – green channel in the parvocellular layer and the blue – yellow channel in the koniocellular layer and they remain in separate neural pathways traveling into the visual cortex. However, despite the separate retinal and cortical processing mechanisms for colour vision and luminance perception, to date no behaviour or neural pathway has been identified that is solely informed by colour, completely independent of luminance (Gegenfurtner, 2003; Longdon, 2016). On a cortical level, colour-sensitive neurons in the primary visual cortex (V1) respond to wide ranges of colours,

and the majority of these cells are also responsive to variations in luminance. Neurons that have a more narrow selectivity for colours have been identified in V2 and to a lesser extend V1 as well (Gegenfurtner, 2003).

Acquired achromatopsia – an inability to perceive colours – in humans has been associated with damage to the extrastriate cortical area V4. Gegenfurtner (2003) summarised neuroimaging studies that showed that V4 was also the area that responded most strongly to colour stimuli. V4 has been called the colour area of the human brain for this reason, but Gegenfurtner has highlighted that this claim is questionable since numerous areas in the visual cortex (in particular V1 and V2) are also highly sensitive to colours and V4 is not solely selectively responsive to colour stimuli either. Zeki and Marini (1998) proposed that the V4 area is specifically responsible for colour constancy, which is the ability to perceive objects in the same colour under varying lighting conditions. Referring to a case study report from Heywood et al. (1991), Gegenfurtner (2003) has suggested that V4 appears to play an important role in assigning colours to separate objects. In the same review, Gegenfurtner also argued that beyond efforts to localise brain areas that are involved in colour processing, more research needs to be done on how colours influence mental operations (Gegenfurtner, 2003).

The relationship between the substance and the psychology of colour experiences has already been explored by visual artists throughout the ages. Ultramarine was historically the finest and most expensive blue pigment, made from the precious stone lapis lazuli. In the Western world it became known as the colour of the divine, as it was often reserved for the robes of the virgin Mary in Renaissance paintings. The lasting fascination of Western artists with the mystical properties of ultramarine was exemplified when in 1960 the French artist Yves Klein developed his own synthetic ultramarine under the name 'International Klein Blue'.

The visceral effects of colours were explored extensively in the 20th century by American colour field painters such as Barnett Newman (1905-1970). Influenced by the atrocities of the World War II, Newman wanted his paintings to induce overwhelming physiological and emotional responses (https://www.moma.org/artists/4285. Retrieved 11 January 2020). His monochrome painting series 'Who's Afraid of Red, Yellow and Blue', composed of a huge canvasses with bright red surfaces flanked by thin stripes of blue and yellow, sparked two vandalism attacks which were a grim testimony that the painting evidently succeeded in evoking intense emotions ('Who's Afraid of Red, Yellow and Blue', Wikipedia. Retrieved 11 January, 2020).

The ability of colours to communicate profound experiences was also foremost on the mind of the American painter Mark Rothko (1903-1970), who allegedly said about his evocative paintings:

"If you are only moved by color relationships, you are missing the point. I am interested in expressing the big emotions – tragedy, ecstasy, doom."

(https://www.theartstory.org/artist/rothko-mark/. Retrieved 11 January, 2020)

This brief overview of the Western history of colour research shows only a glimpse on the complex relationship between the physical properties of colours, their psychological effects and cultural relevance. Goethe's phenomenological approach to colour research was widely derided by colour scientists at the time, who painted his paranormal propositions as the muddled thinking of a writer who was trying to dabble in the natural sciences. Yet colours are so deeply intertwined with human culture, that we could never get a comprehensive understanding of their properties and importance if we only study them from a physiological perspective. This point becomes clear in the book 'Colour and Culture', published in 1993 by the British art historian John Gage, in which he laid out the myriad ways in which colours have shaped Western culture.

In the two multi-modal neuroscientific experiments that I developed for the Colour Spaces project, I aimed to strike a balance between the exacting essence of scientific research and the phenomenological nature of the arts, by studying the interaction between physiological and psychological aspects of colour experiences in a closely controlled experimental setting. My aim was to gain a greater understanding of how physical and contextual properties of colours in images (relating to bottom-up retinal and cortical processing) interact with their imagined aspects beyond the physical surface of a colour image (driven by top-down cortical processing).
This is relevant in the context of healthy ageing, as well as dementia. While many studies have reported differences in colour perception or preferences associated with age or neurological health, the underlying dynamics between the sensory processing of colours and their internal representations have not been comprehensively studied yet. Gaining a better insight into these dynamics could inform the use of colours in cultural settings, but also the design of physical environments for instance.

In the next section I have first described the experimental design, followed by the novel quantitative analyses methods that I developed, before presenting and discussing the results.

## 4.3.2 MATERIAL AND METHODS

I will begin by describing the colour stimuli I created for the two eye tracking experiments that I designed to investigate multi-modal aspects of colour experiences in the context of the social brain. I will then detail the experimental set-up and outline how I analysed the visual exploration patterns, electrodermal activity, internal state evaluations, before presenting and discussing the results in the following chapters.

### Experimental design

I created a set of 26 colours, varying in systematic degrees of hue, saturation and lightness based on the Pantone colour system, an international standard for the design and printing industry. There are other widely used colour systems, such as the Munsell system for instance, but the advantage of the Pantone system is that it defines the colour properties across both digital and print media.

This was especially relevant for my study, in which I wanted to compare participants' responses to colours in different spatial contexts when they were presented on a computer screen to their responses to the same colours presented as high quality photographic prints.
I started by selecting four equally distributed greyscale colours:

Black (5% lightness); Dark Grey (43% lightness); Light Grey (63% lightness); and White (95% lightness).

I complemented these by five saturated hues:

Purple; Blue; Green, Yellow; and Red.

I chose the purple, green and yellow hue from the base colours range in the Pantone Color Bridge Coated Guide. For the red saturated hue, I selected the Pantone colour that most closely matched with the red from Barnett Newman's painting 'Who's Afraid of Red, Yellow and Blue III'.For the saturated blue hue I selected the Pantone spot colour that came closest to the deep ultramarine of Yves Klein's 'International Klein Blue'.

Next, I created a muted, light and dark variation of each of the selected 5 saturated hues in Adobe Photoshop CC.
For each modification, I applied a separate Hue/Saturation layer that was set to normal blending mode. To create a muted variant of each hue, I set the Hue/Saturation layer to -50% in the Saturation channel. For the light variant, I set the Hue/Saturation layer to +50% in the Lightness channel and in the

dark variants I set the Lightness channel to -50%. I included two additional colour hues to the selection. The first was the supposedly least appealing colour in the world: Pantone 448C, also mystically named 'Opaque couché'.
This dark orange/brown hue was granted the dubious honour in a survey on colour preferences among 1000 smokers, which was commissioned by the Australian government. As a result of this survey, Pantone 448C is currently the mandatory plain colour of tobacco packages in Australia, France, Israel, Norway and the UK ('Pantone 448C', Wikipedia. Retrieved 11 January, 2020).
I wanted to find out if I could replicate this finding in my research, which would be an indication that this colour has indeed uniformly disliked qualities. The other extra hue I added to the selection was a saturated orange hue, which was on the same chroma axis as the Pantone 448C hue, but with a lightness level twice as high. Orange is associated with joy and warmth in Western societies and the colour has in Asian cultures often religious significance. I was interested to explore whether this hue on the other side of the brightness spectrum of the supposedly most unpleasant colour, might have also have the opposite emotional effect on the participants in my research.

Figure 69 shows a visual overview of the colour field images, and Table 42 details the numerical values of the colour selection. The properties of the colours are described in three different ways in this table. The LAB numbers describe the colours according to the colour opponency model, in which the first number represents the lightness level (L) between black (0) and white (100). The second number (A) represents the green – red axis with negative values for green and positive values for red. The third number (B) represents the blue – yellow axis with negative numbers for blue and positive numbers for yellow.
The RGB numbers describe the colours according to the trichromatic model, in which the successive numbers indicate the proportions of red (R), green (G) and blue (B) with values between 0 and 255. The HEX codes describe the colour values for internet applications in 6-unit combinations (hence the HEX reference) of Arabic numerals and Latin letters.

I created two different spatial dimensions for the colour selection: colour fields (2-D) and colour rooms (3-D). For the colour rooms images, I made a set of 25 monochromatic room models of the basic hue selection and Pantone 448C. I chose to make the room models in dimensions that aligned with the Golden Ratio: w: 301 mm; h: 186 mm; d: 186 mm. The Golden Ratio is a proportional relationship of 1.618:1, also called the number 'Phi', after the Greek sculptor Phidias (500 B.C. – 432 B.C.). Phidias is thought to have applied the Golden Ratio to the sculptures he created for the Parthenon. The Golden Ratio was widely used in Ancient Greek architecture because it was considered to result in the most aesthetically pleasing balance between various architectural elements, such as the width to height ratio of a building. Plato (428 B.C. – 347 B.C.) even went as far as saying that the Golden ratio to be the most universally binding of mathematical relationships. By creating the room models in Golden Ratio proportions, I aimed to optimise the spatial experience of the colour rooms images, and also counterbalance the potential claustrophobic effect of a windowless space.

I photographed the models with a wide-angle lens, lit by two daylight lamps to make them appear like life-size spaces in natural daylight. Figure 70 shows the room models and Figures 71 and 72 show the series of photographs that I made from the room models. My motivation to make physical room models, rather than creating these digitally, was that the centuries-long artistic tradition of careful manipulations of the plastic nature of colour has convinced me that the physical properties of colours create an atmospheric substance that simulated spaces can not convey to same degree (despite the technological advances of computer-generated-imagery).

I carefully colour calibrated the resulting photographs in Adobe Photoshop CC on an Eizo ColorEdge CG2420 24-inch LCD monitor. To balance out the shadows in each room photograph, I used a custom-made 5-point calibration template. The centre wall was exactly calibrated to the Lab values of the reference

colour swatch and natural shading on the side walls, floor and ceiling was allowed to be up to 4 points lower only in the lightness channel of the LAB colour mode. For the orange colour room image no separate room model was created and the image was created by changing the hue gradient of the saturated red room image in Photoshop.

From this set of 26 colour fields and 26 colour rooms, I made a digital version and a high-quality photographic version. The print versions of the colour spaces were printed on Fuji Lustre photo paper and produced by a professional photo lab. I made several iterations of the prints until they precisely matched the spot colours of my colour selection that were defined by the Pantone Color Bridge Coated Guide. Because I also wanted to study the participants' autonomic responses to colours, it was important that the colours would take up a significant part of their visual field. The limiting factor herein was the Eizo monitor that I used to display the Digital Colour Spaces, which had a screen width of 50 cm. The industry standard of photographic prints that most closely matches this width, is the 18 x 12 inch format (45,72 x 30,48 cm), so I chose this as the size for the print images.

I resized the digital colour images to 1574 x 700 pixels, so that they matched the surface of the print colour images. The participants were sat at a distance of 75 cm from the image displays, which was necessary for the eye tracking camera to work properly. Looking at the colour images from this distance meant that the colour surfaces took up approximately 17 degrees temporally in each eye (away from the nose in horizontal direction) and 11.5 degrees above and below the horizontal meridian.

Before the start of the colour spaces eye tracking experiments, I assessed the baseline colour perception abilities of the participants. The neurologically healthy adults were all able to distinguish between the different hues and brightness levels in the selection of 26 colours. Among the senior adults living with dementia, several participants had demonstrated difficulties with colour perception and two participants possibly had a acquired green/red colour-blindness due to their dementia (full results reported under the Contextual Information chapters).

**Digital Colour Spaces experiment**

In the Digital Colour Spaces experiment, participants were sat in a black-out room behind a narrow table with their chin and forehead stabilised in a Table-mounted headrest attached to the edge of the Table. An Eyelink 1000 Plus eye tracking camera, calibrated with a 9-point grid, recorded binocular eye movement and pupil dilation at 55 cm distance from the headrest. The colour spaces were displayed to participants on an Eizo ColorEdge CG2420 24-inch LCD monitor, placed at 75 cm distance from the headrest and calibrated with an Eye-One Display 2 and ColorNavigator software in the sRGB colour space.

At the start of the experiment a pre-recorded audio file was played in which a native female British voice introduced the experiment. After this introduction, the first block of 26 colour fields were shown to the participants. The colour fields were shown in randomised order for 5 seconds each against a black background. After each colour field trial, a middle grey screen was presented with the Affect Amplitude Scale, a 5-point visual rating scale that I had designed to create an abstract representation of valence. In between the trials, a middle grey screen with a small central black fixation cross was presented for 5 seconds to neutralise the pupil dilations and to reorientate the gaze to the centre of the screen.

In the second block the colour rooms were presented for 5 seconds each in randomised order. In another pre-recorded audio instruction, participants were requested to imagine themselves standing in the middle of each room. After each colour room trial, a middle grey screen was presented with the Affect Amplitude Scale. In between the trials, a middle grey screen with a small central black fixation cross was presented for

**Figure 69: Colour fields images overview**



**Table 42: Colour selection numerical values**

| HUE | DARK | MUTED | SATURATED | LIGHT |
|---|---|---|---|---|
| **GREYSCALE** | LAB 5,0,0 | LAB 43,0,0 | LAB 63,0,0 | LAB 95,0,0 |
| | RGB 16,16,16 | RGB 102,102,102 | RGB 153,153,153 | RGB 243,243,243 |
| | HEX 121212 | HEX 666666 | HEX 999999 | HEX F1F1F1 |
| **PURPLE** | LAB 23,40,-26 | LAB 44,39,-27 | LAB 47,68,-44 | LAB 71,37,-26 |
| | RGB 94,21,94 | RGB 150,77,150 | RGB 187,41,187 | RGB 221,148,221 |
| | HEX 5E155E | HEX 964D96 | HEX BB29BB | HEX DD94DD |
| **BLUE** | LAB 5,26,-45 | LAB 22,21,-44 | LAB 17,46,-77 | LAB 57,16,-40 |
| | RGB 8,3,80 | RGB 49,44,120 | RGB 16,6,159 | RGB 135,130,207 |
| | HEX 080350 | HEX 312C78 | HEX 10069F | HEX 8782CF |
| **GREEN** | LAB 31,-27,4 | LAB 48,-30,2 | LAB 62,-45,8 | LAB 79,-30,0 |
| | RGB 0,85,67 | RGB 42,127,109 | RGB 0,179,138 | RGB 127,212,194 |
| | HEX 005543 | HEX 2A7F6D | HEX 00AA86 | HEX 7FD4C2 |
| **YELLOW** | LAB 47,-1,53 | LAB 71,-3,56 | LAB 86,4,85 | LAB 94,-5,55 |
| | RGB 127,111,0 | RGB 190,173,63 | RGB 252,211,11 | RGB 254,238,127 |
| | HEX 7F6F00 | HEX BEAD3F | HEX FCD 30C | HEX FEEE7F |
| **RED** | LAB 28,41,33 | LAB 54,38,25 | LAB 56,71,59 | LAB 74,36,22 |
| | RGB 125,28,17 | RGB 195,99,88 | RGB 249,56,34 | RGB 252,155,144 |
| | HEX 7D1C11 | HEX C36358 | HEX F93822 | HEX FC9B90 |

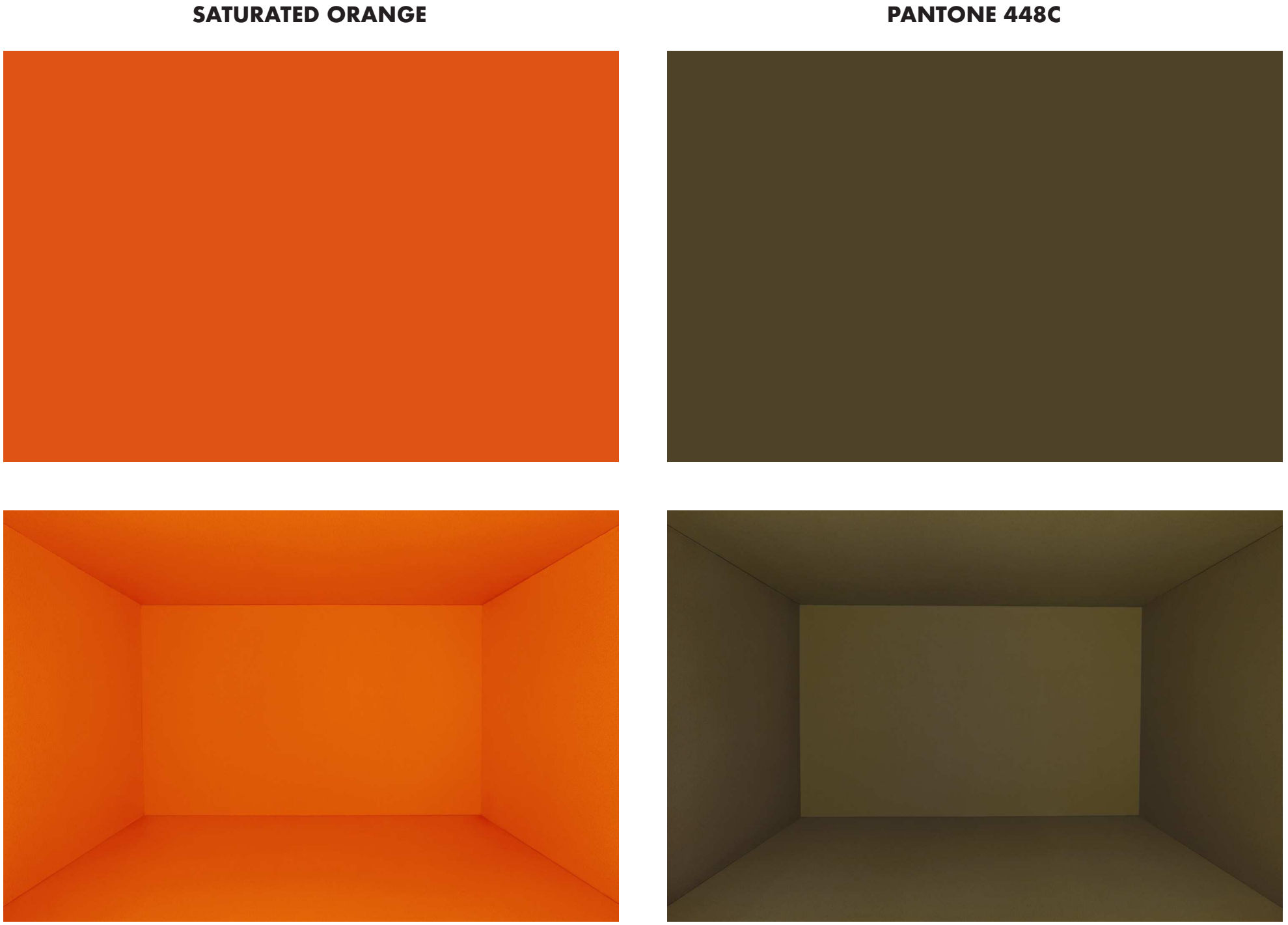
**Figure 70: Colour rooms models overview**



**Figure 71: Colour rooms photographs overview**



**Figure 72: Saturated orange and Pantone 448C colour fields and rooms**



5 seconds to neutralise the pupil dilations and to reorientate the gaze to the centre of the screen.

I reasoned that asking participants to imagine themselves standing in the middle of the colour rooms, would stimulate a sensation of feeling surrounded by that colour. Previous research has shown that neurologically healthy people vary in their ability to visualise scenes inside their minds (Zeman et al., 2015). I therefore also reasoned that people who had a lower ability to imagine themselves standing in a depicted scene, would be more likely to show little difference between their affective ratings of colours in a non-spatial image (colour fields) and the same colours in a spatial image (colour rooms).

Based on the 'imagined objects/scenes' and 'mental rotation' mental operations in the functional profiles of the Social Brain Atlas, I predicted that the ability to imagine oneself standing in the middle of the room images, would most likely recruit the right hippocampus and the ventromedial prefrontal cortex in the Animation Network, as well as the left middle temporal gyrus, the left temporal pole and the dorsomedial prefrontal cortex in the Construction Network (Alcala-Lopez et al., 2017).

**Print Colour Spaces experiment**

The experimental design of the Print Colour Spaces experiment was exactly the same as the Digital Colour Spaces experiment, except for the display conditions of the images. Participants were shown the same colour images on high quality photographic prints which were illuminated by a daylight lamp in a blackout room. The strictly controlled conditions allowed me to make direct comparisons between the physiological and psychological responses to colour spaces in digital and print images. As in the first experiment, participants were played a pre-recorded audio file in which a native female British voice gave the experiment instructions. While the monitor was still in place, the Eyelink camera was calibrated with a 9-point grid.

After the camera was calibrated to the dimensions of the display space, I placed the monitor the back of table and covered it with a black sheet while it kept running the experiment software in the background. I then placed a black table easel on the exact location where the monitor had stood. The table easel was lit by a rectangular daylight lamp that I placed directly above the table easel in a near 90 degrees angle. The daylight lamp's width was 23,6 inches, which nearly identical to the monitor's width of 24 inches. The white point of the daylight lamp and the monitor was in both cases 6500 K. The light output of the daylight lamp was 100 Lux, which I had measured with a light meter from the centre of a middle grey test print.
This equalled the monitor's brightness, which I had calibrated to a brightness level of 100 cd/m2 with a contrast of 225:1 to match the maximum contrast achieved in print (Daalder, J., 2015). The daylight lamp created a natural gradient in the light distribution across the colour surfaces of the photographic prints, which gave them a different appearance compared to the colour images that were presented on the evenly back-lit monitor.

I had mounted the prints on acid-free cardboard and placed them in a stack on the table easel. In each trial, I manually uncovered the prints wearing white cotton gloves to protect their vulnerable surfaces. To ensure that I aligned each presentation with the trial timings of the experimental software, which processed the recorded eye tracking data, I practiced the routine with the aid of a research assistant who clocked my presentation timings until I had developed a rhythm that was as closely in sync with the computer as possible. After each colour print presentation I placed a screen with the Affect Amplitude Scale in front of it and at the same time I inserted a grey screen with a fixation cross in between the scale screen and the next colour print. After the participants had expressed their affect rating, I typed in their response on my laptop which triggered the next image trial. At this point I would lift the screen with the Affect Amplitude Scale to uncover the grey screen with the central fixation cross which I showed for 5 seconds, before removing it to uncover the next colour print.

**Visual exploration analysis**
In the Materials and Methods section of the Thinking Eyes project, I described the social salience model of visual exploration that I developed to analyse the eye tracking recordings that I collected in my experiments. For the visual exploration analysis of Colour Spaces experiments, I used the same model and expanded the perceptual category of built environment elements with four sub-categories: corners, horizontal edges, vertical edges and diagonal edges.

I wanted to further investigate which spatial cues would be most salient when the participants explored the colour rooms images. Previous research has found that cardinal lines are easier to process for the human visual processing system (Nasr and Tootell, 2012). I therefore predicted that the corners in the room pictures would be looked at for the longest period of time as they would convey information on two cardinal dimensions. I expected that cardinal (vertical and horizontal) edges would be looked at in equal measure and I predicted that diagonal lines would attract the lowest amount of dwell time. In line with the premises of the social salience model, I expected the differences in visual exploration patterns to emerge during the gist inference phase (250 – 750 ms) and beyond.
I predicted that when participants explored the colour fields, their fixations would stay clustered around the image centre, as there would be no spatial cues to explore.

To analyse the temporal dynamics of the visual exploration of the colour spaces, I segmented the measured dwell times in each perceptual category into the same three time windows that I also used in the Thinking Eye project: Perceptual Processing ( 0 – 250 ms); Gist Inference (250 – 750); Construct Inference (> 750).

The recorded eye tracking data were pre-processed in the software programme Data Viewer. I applied the foveal interest areas and segmented the data in the time windows I described above before exporting the eye tracking recordings as a text file report that I imported in Microsoft Excel for further analysis.

**Pupil dilation analysis**
Pupil responses to the colour image presentation were analysed by subtracting the average pupil dilation in the right eye during the 5 second grey screen presentations before each colour trial, from the average pupil dilation during the Construct Inference (750 - 5000 ms) phase for each colour image presentation.

**Electrodermal activity analysis**
To assess the autonomic arousal of the participants during each experiment, I compared the electrodermal activity flux that I had recorded from both wrists to the personal average (see also under the Experimental Framework chapter).

**Internal state evaluation analysis**
I argued that investigating how the colour spaces made participants feel, would give me insight into their emotional value systems of colours. Based on the distribution of 'Emotion', 'Reward' and 'Colour Vision' mental operations in the functional profiles of the Social Brain Atlas, I predicted that this would most likely recruit multiple social brain networks, including the Animation, the Interaction Network and the Construction Network. The concept of affective response was introduced to the participants in a pre-recorded audio by a native female British voice as follows:

“You will be shown a series of colours. After each viewing you will be asked ‘How does this make you feel?."

### 4.3.3 RESULTS

**Visual exploration results**
**Perceptual processing phase (0 — 250 ms)**
During the initial perceptual processing phase (the first 250 ms) after presenting the colour images, the vast majority of the participants’ fixations stayed at the centre of the images, regardless of the depicted spatial context.

During the perceptual processing phase, neurologically healthy young adults looked on average 96% (SD=7%) of the time at the image centres of digital colour field images and on average 97% (SD=4%) of the time at the centre of the digital colour room images. This was not a significant difference. During this phase, young adults looked on average 44% (SD=25%) of the time at the image centre of print colour fields images, compared to 52% (SD=31%) on the image centres of print colour room images. This was not a significant difference.

During the perceptual processing phase, neurologically healthy senior adults looked on average 86% (SD=14%) of the time at the image centre of digital colour field images and on average 84% (SD=12%) of the time at the centre of the digital colour room images. This was not a significant difference. During this phase, senior adults looked on average 32% (SD=25%) at the image centre of print colour field images and on average 26% (SD=17%) of the time at the image centre of print colour room images. This was not a significant difference.

During the perceptual processing phase, senior adults living with dementia looked on average 79% (SD=25) of the time at the image centre of digital colour field images and on average 75% (SD=27) of the time at the centre of the digital colour room images. This was not a significant difference. Senior adults living with dementia looked on average 30% (SD=21) at the image centre of print colour field images, compared to 23% (SD=22) at the image centre of print colour rooms during the perceptual processing phase. This was not a significant difference.

During the perceptual processing phase, senior adults looked on average 10% less at the image centre of the digital colour field images. It was 6.5 times more likely that this was a significant effect of healthy ageing, with a two-sided p value of 0.013. This effect was already visible during the fixation cross presentations that preceded each image. The proportional dwell time distribution was not normal for the digital colour room images in the young adults cohorts and there was an unequal variance between the young and senior adults so I could not perform a t test on this parameter. I did not find any significant differences between the neurologically healthy senior adults and senior adults living with dementia on a cohort level in the average proportional dwell time on the image centre of the digital colour spaces. I did not make between groups analyses of the print colour spaces for the perceptual processing phase, because the data was too unreliable during this phase due to the manual presentation of the stimuli.

**Visual exploration results**
**Gist inference phase (250 — 750 ms)**
During the gist inference phase (250 – 750 ms), the proportional time spent looking at the centre of the colour spaces images dropped significantly in all 3 research cohorts, compared to the initial perceptual processing time window. This effect was only observed in digital colour spaces condition, but it likely that the recorded data during the first 250 ms in the print colour spaces condition were unreliable due to the manual presentations.

During the gist inference phase, neurologically healthy young adults looked on average 73% (SD=23%) of the time at the image centre of digital colour fields. It was 70 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value <.001. During the gist inference phase, young adults looked on average 58% (SD=25%) of the time at the centre of the digital colour room images. It was 2173.9 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value <.001. It was 4.5 times more likely that there was a significant difference between the proportional dwell times on the image centre of digital colour field and room images during the gist inference phase, with a two-sided p value of 0.021.

During the gist inference phase, young adults looked on average 63% (SD=26%) of the time at the image centre of print colour

fields. It was not more likely that this was a significant difference in comparison to the perceptual processing phase. They looked on average 48% (SD=29%) of the time at the image centre of print colour rooms during the gist inference phase.
This was not a significant difference in comparison to the perceptual processing phase. However, it was 3.1 times more likely that there was a significant difference between the proportional dwell times on the image centre of print colour field and room images during the gist inference phase, with a two-sided p value of 0.036.

During the gist inference phase, neurologically healthy senior adults looked on average 64% (SD=23%) of the time at the image centre of digital colour fields. It was 1192.8 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value <.001.
During the gist inference phase, senior adults looked on average 43% (SD=21%) of the time at the centre of the digital colour room images during the gist inference phase. It was 14645.2 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value <.001. It was 1676.6 times more likely that there was a significant difference between the proportional dwell times on the image centre of digital colour field and room images during the gist inference phase, with a two-sided p value <.001.
During the gist inference phase, neurologically healthy senior adults looked on average 28% (SD=23%) of the time at the image centre of print colour fields. It was 2.4 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value of 0.05.
During the gist inference phase, senior adults looked on average 20% (SD=13%) of the time at the image centre of print colour rooms during the gist inference phase. It was 3.2 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value of 0.03.
There was no significant difference between the proportional dwell times on the image centre of print colour field and room images during the gist inference phase.

During the gist inference phase, senior adults living with dementia looked on average 66% (SD=23%) at the image centre of digital colour fields. It was 25.4 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value of 0.002.
During the gist inference phase, senior adults living with dementia looked on average 45% (SD=20%) of the time at the centre of the digital colour room images. It was 160.4 times more likely that this was a significant difference in comparison to the perceptual processing phase, with a two-sided p value <.001. It was 268.7 times more likely that there was a significant difference between the proportional dwell times on the image centre of digital colour field and room images during the gist inference phase, with a two-sided p value <.001.

During the gist inference phase, senior adults living with dementia looked on average 29% (SD=19%) of the time at the image centre of print colour field images. It was not more likely that this was a significant difference in comparison to the perceptual processing phase.
During the gist inference phase, senior adults living with dementia looked on average 22% (SD=15%) of the time at the image centre of print colour room images. This was not a significant difference in comparison to the perceptual processing phase. There was also no significant difference between the proportional dwell times on the image centre of print colour field and room images during the gist inference phase.

Comparing the visual exploration patterns of the cohorts with each other, I found that neurologically healthy senior adults looked on average 40% less at the centre of the print colour field images during the gist inference phase than young adults. It was 135.5 times more likely that this was an effect of healthy ageing, with a two-sided p value <.001. Neurologically healthy senior adults also looked on average 29% less at the centre of the print colour room images during the gist inference phase, compared to young adults. It was 132.4 times more likely that

this was an effect of healthy ageing, with a two-sided p value <.001. There was no difference in proportional dwell times on the image centres between the neurologically healthy senior adults and the senior adults living with dementia during the gist inference phase of the print colour image presentations.
I also found no effects of healthy ageing or dementia on the visual exploration of the digital images of colour spaces.

These findings show that during the gist inference phase, all participants, regardless of age or neurological health, looked significantly less at the image centres of the digital colour rooms, compared to the digital colour fields. During the print presentations, an effect of depicted spatial context on the proportional dwell time on the image centres was only found to be significant in the young adults however.

During the gist inference phase, young adults looked on average proportionally the most at the left vertical edge of the digital room images (μ=8%, SD=22%), followed by the bottom left corner (μ=4%, SD=17%). All the other spatial cues attracted less than 2% proportional dwell time during the gist inference phase. In the print room images, young adults looked on average proportionally the most at the right vertical edge of the (μ=3%, SD=13%) during the gist inference phase, followed by the bottom horizontal edge (μ=3%,SD=13%). All the other spatial cues received less than 2% proportional dwell time during the gist inference phase.

Neurologically healthy senior adults also looked on average proportionally the most at the left vertical edge of the digital room images (μ=6%, SD=16%), followed by the bottom left corner (μ=5%, SD=18%), and the right vertical edge (μ=4%, SD=15%). All the other spatial cues received less than 2% proportional dwell time during the gist inference phase.
Neurologically healthy senior adults looked on average proportionally the most at the bottom horizontal edge of the print room images (μ=8%, SD=22%), followed by the left vertical edge (μ=4%, SD=17%), and the right vertical edge (μ=2%, SD=11%). All the other spatial cues received less than 2% proportional dwell time during the gist inference phase.
Senior adults living with dementia also looked on average proportionally the most at the bottom horizontal edge of the print room images (μ=7%, SD=21%), followed by the bottom right corner (μ=3%, SD=12%), the top left corner (μ=2%,SD=12%), and the left vertical edge (μ=2%, SD=10%). All the other spatial cues received less than 2% proportional dwell time during the gist inference phase. Senior adults living with dementia looked on average proportionally the most at the bottom horizontal edge of the digital room images (μ=4%, SD=14%), followed by the left vertical edge (μ=3%, SD=13%). All the other spatial cues received less than 2% proportional dwell time during the gist inference phase.
As these findings show, there was strong variance within each cohort in the proportional dwell times on the various spatial cues in the room images during the gist inference phase.

The only difference that prominently stood out when I compared the research cohorts with each other, was the proportional dwell time on the bottom horizontal edge in the print colour rooms images. Senior adults, regardless of neurological health, looked on average 5% more at the bottom horizontal edge in the print colour rooms images than young adults. However, the data were not normally distributed among the young adults on this parameter and there were also unequal variances between the young and senior adults, which meant I was unable to quantify this difference with an independent samples t test.

**Visual exploration results**
**Construct inference phase (750 — 5000 ms)**
During the construct inference phase, neurologically healthy young adults looked on average 38% (SD=25%) of the time at the image centre of digital colour fields. It was 64545.2 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value <.001.
During the construct inference phase, young adults looked on average 27% (SD=19%) of the time at the centre of the digital

colour room images. It was 10106.2 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value <.001. There was no significant difference between the proportional dwell times on the image centre of digital colour field and room images during the construct inference phase.

During the construct inference phase, young adults looked on average 44% (SD=25%) of the time at the image centre of print colour fields. It was 45.6 time more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value of 0.001. Young adults looked on average 30% (SD=29%) of the time at the image centre of print colour rooms during the construct inference phase. It was 12.8 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value of 0.006. It was 20.4 times more likely that there was a significant difference between the proportional dwell times on the image centre of print colour field and room images during the gist inference phase, with a two-sided p value of 0.003.

During the construct inference phase, neurologically healthy senior adults looked on average 41% (SD=28%) of the time at the image centre of digital colour fields. It was 22.1 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value of 0.003.
During the construct inference phase, senior adults looked on average 18% (SD=19%) of the time at the centre of the digital colour room images. It was 477.5 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value <.001. It was 561.7 times more likely that there was a significant difference between the proportional dwell times on the image centre of digital colour field and room images during the construct inference phase, with a two-sided p value <.001

During the construct inference phase, senior adults looked on average 28% (SD=17%) of the time at the image centre of print colour fields. It was not more likely that this was a significant difference in comparison to the gist inference phase.
Senior adults looked on average 16% (SD=9%) of the time at the image centre of print colour rooms during the construct inference phase. It was not more likely that this was a significant difference in comparison to the gist inference phase. It was 36.7 times more likely that there was a significant difference between the proportional dwell times on the image centre of print colour field and room images during the gist inference phase, with a two-sided p value of 0.003.

During the construct inference phase, senior adults living with dementia looked on average 33% (SD= 23%) of the time at the image centre of digital colour fields. It was 19022.8 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value <.001.

During the construct inference phase, senior adults living with dementia looked on average 16% (SD= 11%) of the time at the centre of the digital colour room images. It was 7503.7 times more likely that this was a significant difference in comparison to the gist inference phase, with a two-sided p value <.001.
It was 23.3 times more likely that there was a significant difference between the proportional dwell times on the image centre of digital colour field and room images during the construct inference phase, with a two-sided p value of 0.003.

During the construct inference phase, senior adults living with dementia looked on average 24% (SD= 20%) of the time at the image centre of print colour fields. It was not more likely that this was a significant difference in comparison to the gist inference phase. Senior adults living with dementia looked on average 15% (SD= 15%) of the time at the image centre of print colour rooms during the construct inference phase.
It was 26.1 times more likely that this was a significant difference in comparison to the gist inference phase with a two-sided p value of 0.002. There was no significant difference between the proportional dwell times on the image centre of print colour field

and room images during the gist inference phase.
Figures 73, 74 and 75 show the proportional dwell times (%) on the image centre of the digital and print colour spaces across the three time windows in the 3 research cohorts.
Figures 76 and 77 show the heat maps of the visual exploration patterns of the young and senior adults in the different material and spatial contexts. The senior adults living with dementia showed a similar profile on the cohort level with neurologically senior adults, so I did not create a separate figure for this cohort.

I then compared the proportional dwell times on the spatial elements in the colour room images during the construct inference phase with the gist inference phase within each cohort. The following Tables detail the results of these analyses.

**Table 43:**
**Digital colour rooms average dwell times (%)**
**Neurologically healthy young adults**
**Gist inference phase compared to construct inference phase**

| Spatial element | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Corner bottom left | 2.8 | 0.05 | 2.5 |
| Corner bottom right | 5.2 | < .001 | 99.9 |
| Corner top left | 3.8 | < .001 | 70.1 |
| Corner top right | NA | NA | NA |
| Horizontal edge bottom | 1.8 | 0.041 | 2.8 |
| Horizontal edge top | 0.6 | < .001 | 70.1 |
| Vertical edge left | 0.5 | 0.548 | 1.0 |
| Vertical edge right | 3.7 | < .001 | 96.2 |

The results in Table 43 show that compared to the gist inference phase, young adults looked significantly more at all spatial cues in the digital colour room images – except the left vertical edge – during the construct inference phase. The diagonal edges were barely looked at and therefore not included in the Table. The top right corner data could not be analysed with a paired samples t test, as none of the young adults had looked at it during the gist inference phase.

**Table 44:**
**Print colour rooms average dwell times (%)**
**Neurologically healthy young adults**
**Gist inference phase compared to construct inference phase**

| Spatial element | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Corner bottom left | 2 | 0.029 | 3.6 |
| Corner bottom right | 2.8 | 0.013 | 6.3 |
| Corner top left | 1.6 | < .001 | 58.7 |
| Corner top right | 2.5 | 0.017 | 5.2 |
| Horizontal edge bottom | 1.2 | 0.057 | 2.3 |
| Horizontal edge top | 0.9 | .001 | 41.7 |
| Vertical edge left | 1.7 | 0.038 | 3.0 |
| Vertical edge right | 1.9 | 0.065 | 2.1 |

These findings show that compared to the gist inference phase, young adults looked significantly more at all spatial cues in the print colour room images, during the construct inference phase. The diagonal edges were barely looked at and therefore not included in the table.

**Table 45:**
**Digital colour rooms average dwell times (%)**
**Neurologically healthy senior adults**
**Gist inference phase compared to construct inference phase**

| Spatial element | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Corner bottom left | 1.7 | 0.24 | 1.1 |
| Corner bottom right | 4.1 | < .001 | 61.9 |
| Corner top left | 2.2 | 0.029 | 3.5 |
| Corner top right | 2.7 | 0.003 | 19.3 |
| Horizontal edge bottom | 2 | 0.002 | 26.6 |
| Horizontal edge top | 1.5 | < .001 | 343.7 |
| Vertical edge left | 1.4 | 0.351 | 1.0 |
| Vertical edge right | 3.9 | 0.056 | 2.3 |
| Corner top left | 0.4 | 0.724 | 1.0 |
| Corner top right | 2.8 | 0.003 | 24.3 |
| Horizontal edge bottom | 1.7 | 0.228 | 1.1 |
| Horizontal edge top | 0.6 | 0.033 | 3.3 |
| Vertical edge left | 0.3 | 0.776 | 1.0 |
| Vertical edge right | 4.5 | < .001 | 56.5 |

These findings show that compared to the gist inference phase, senior adults looked significantly more at all spatial cues in the digital colour room images -except the bottom left corner and the left vertical edge- during the construct inference phase. The diagonal edges were barely looked at and therefore not included in the table.

**Table 46:**
**Print colour rooms average dwell times (%)**
**Neurologically healthy senior adults**
**Gist inference phase compared to construct inference phase**

| Spatial element | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Corner bottom left | 0.6 | 0.625 | 1.0 |
| Corner bottom right | 1.4 | 0.139 | 1.3 |

These findings show that compared to the gist inference phase, senior adults looked significantly more at the top right corner, the top horizontal edge and the right vertical edge in the print colour room images, during the construct inference phase. The diagonal edges were barely looked at and therefore not included in the table.

During during the construct inference phase, there was no significant difference between the proportional dwell times on the image centres between the neurologically healthy young and senior adults across both spatial and material conditions. In the analysis of the proportional dwell time on spatial elements in senior adults living with dementia, I focused on the spatial cues which attracted the greatest proportional increase in dwell time during the construct inference phase, compared to the gist inference phase in neurologically healthy senior adults.

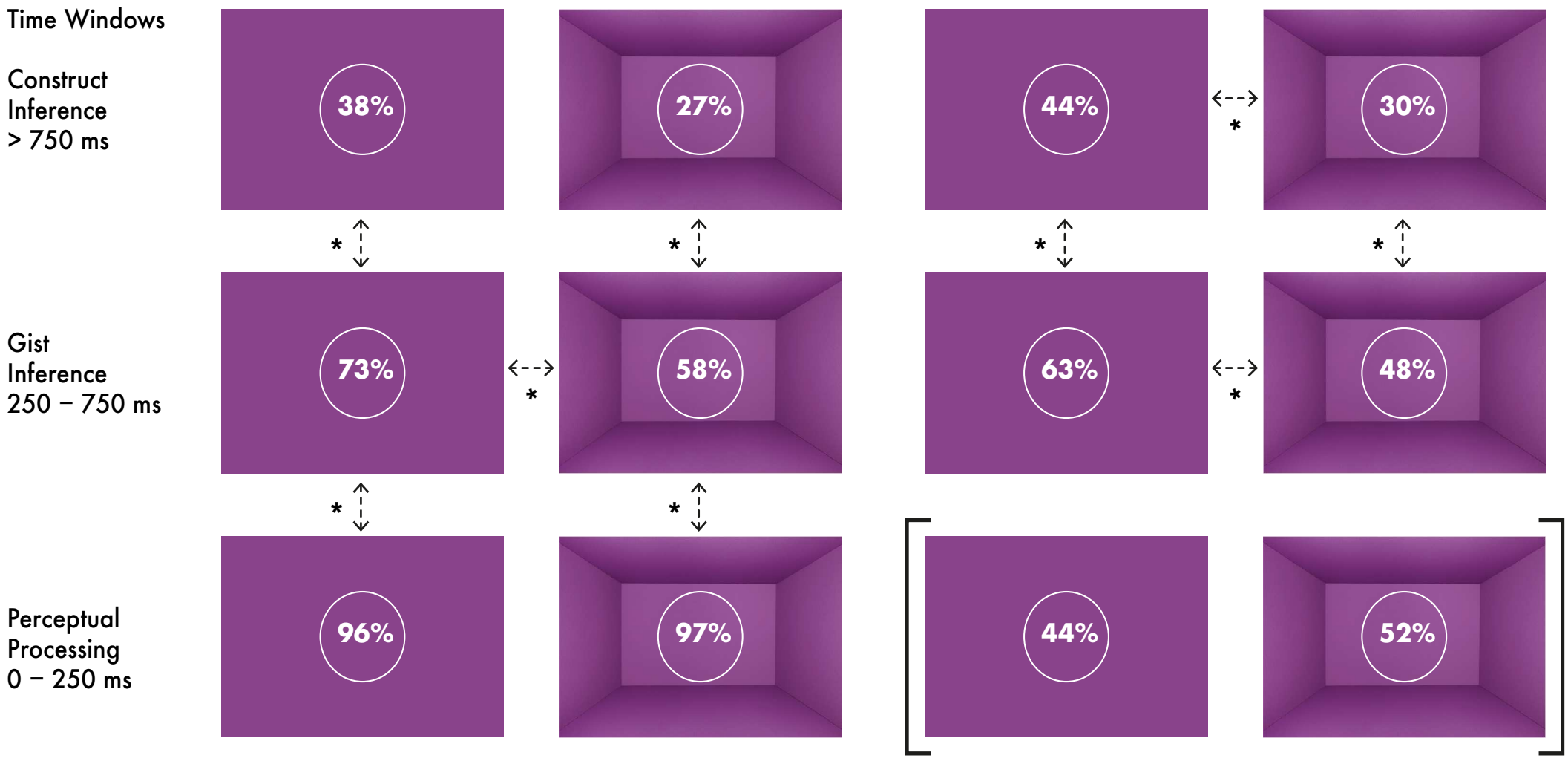
In the digital rooms condition, I looked at the proportional dwell time on the bottom right corner (DC_BR) and the bottom and top horizontal edge (DHE_B & DHE_T). In the print rooms condition, I looked at the top right corner (PC_TR) and the right vertical edge (PVE_R). The results are presented in Table 47. P1M_tAD and P4M_svPPa only took part in the Digital Colour Spaces experiment, which is why there are no data for the print rooms.

Figure 73

# COLOUR SPACES EXPERIMENTS PROPORTIONAL DWELL TIMES (%)

## DIGITAL AND PRINT COLOUR IMAGE CENTRES

### YOUNG ADULTS




* Significant difference in average proportional dwell time on image centre (%)

[ ] Unreliable data due to manual presentation of stimuli

Colour selection

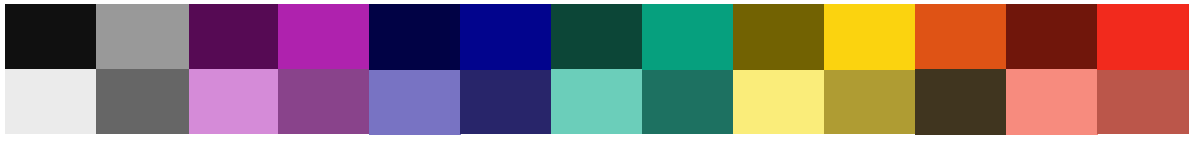
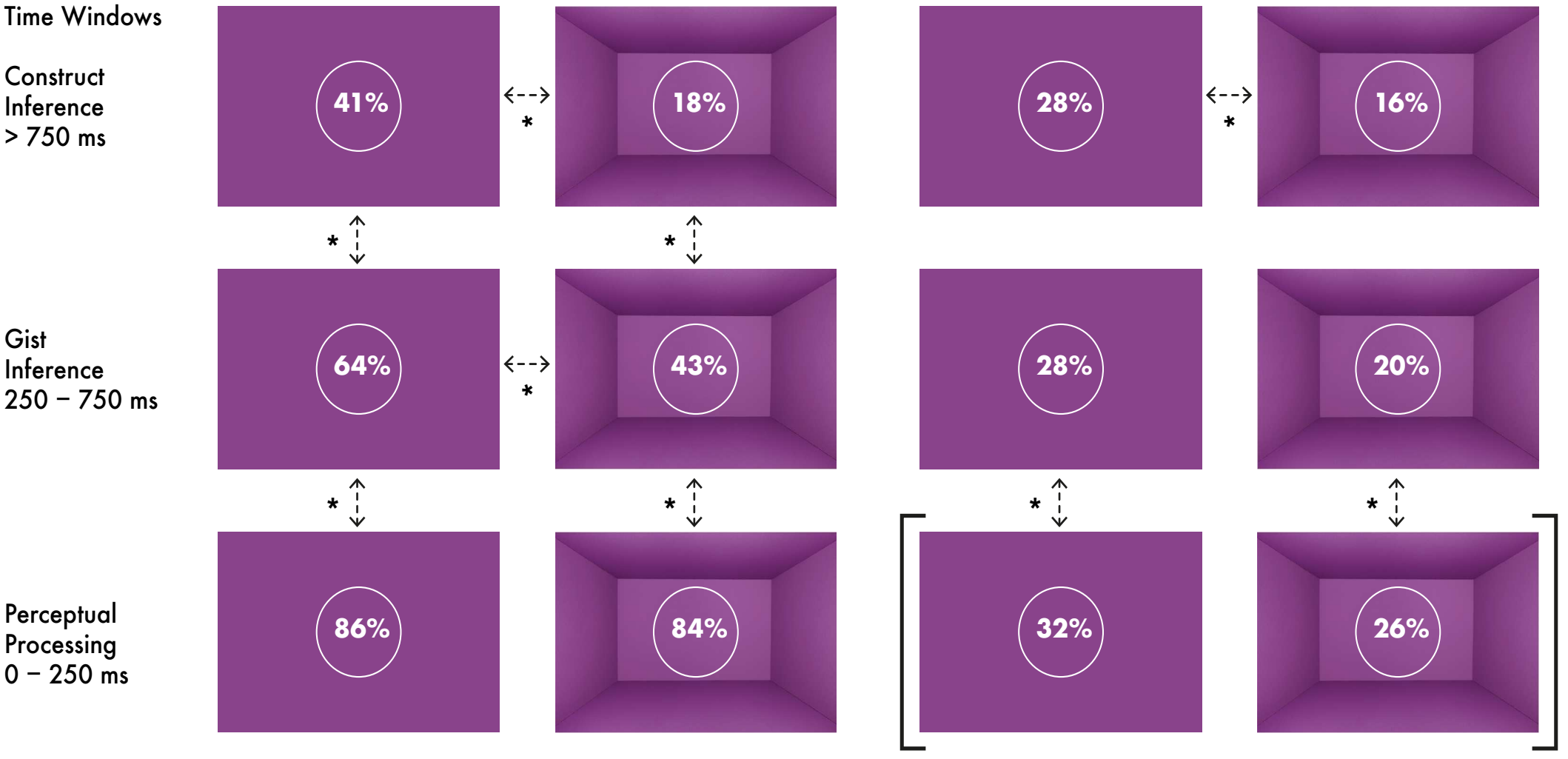


Figure 74

# COLOUR SPACES EXPERIMENTS PROPORTIONAL DWELL TIMES (%)

## DIGITAL AND PRINT COLOUR IMAGE CENTRES

### SENIOR ADULTS




* Significant difference in average proportional dwell time on image centre (%)

[ ] Unreliable data due to manual presentation of stimuli

Colour selection

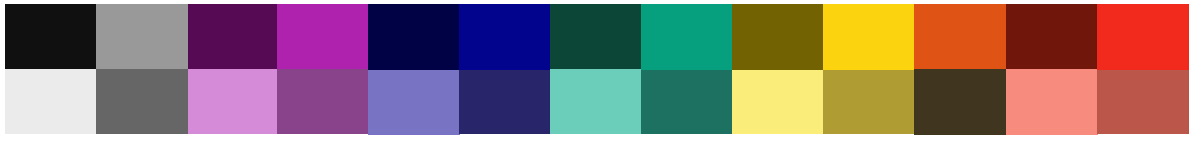
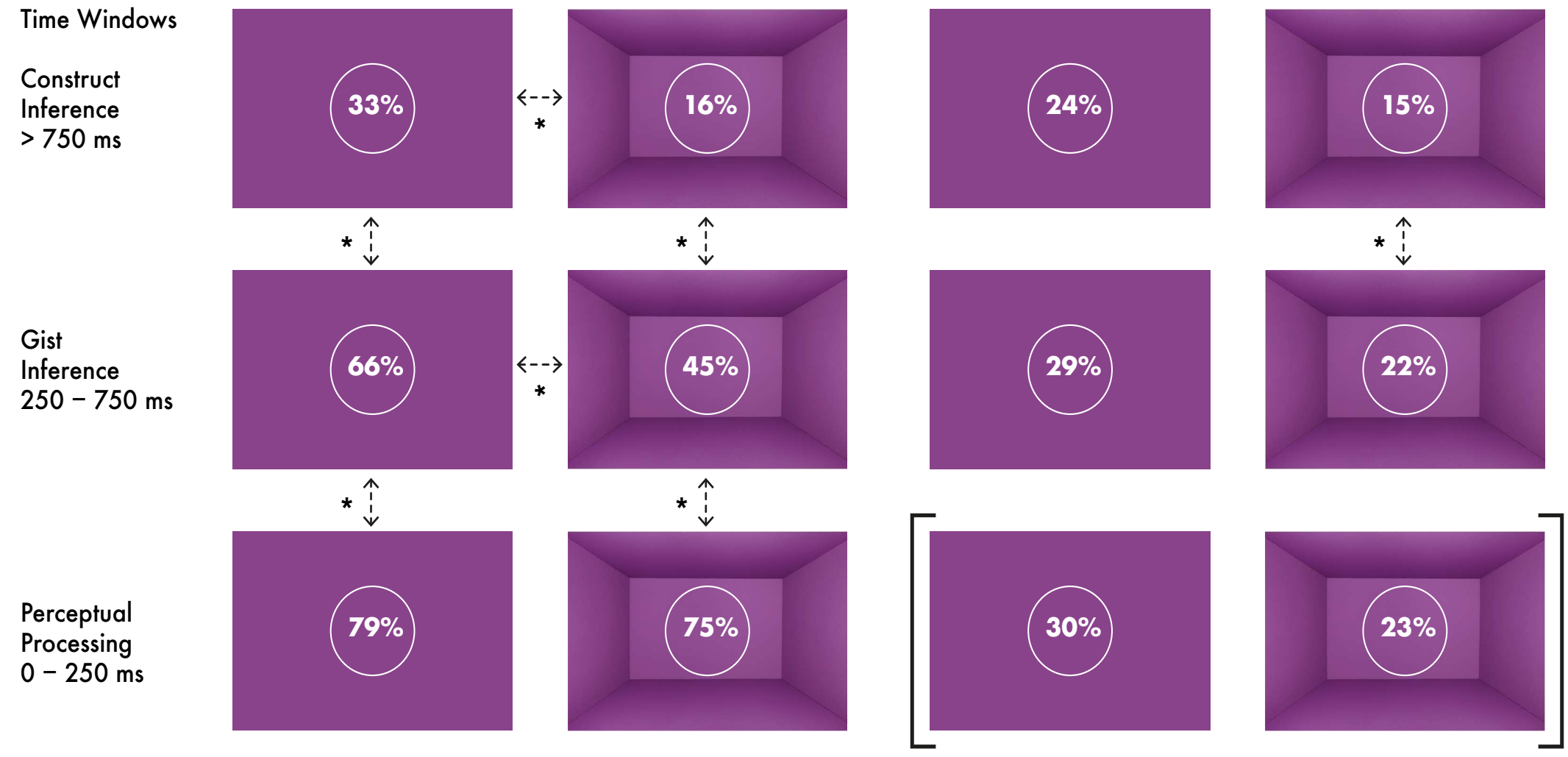


Figure 75

# COLOUR SPACES EXPERIMENTS PROPORTIONAL DWELL TIMES (%)

## DIGITAL AND PRINT COLOUR IMAGE CENTRES

### SENIOR ADULTS LIVING WITH DEMENTIA




* Significant difference in average proportional dwell time on image centre (%)

[ ] Unreliable data due to manual presentation of stimuli

Colour selection

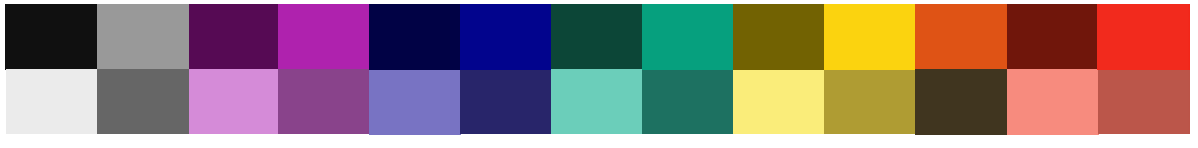
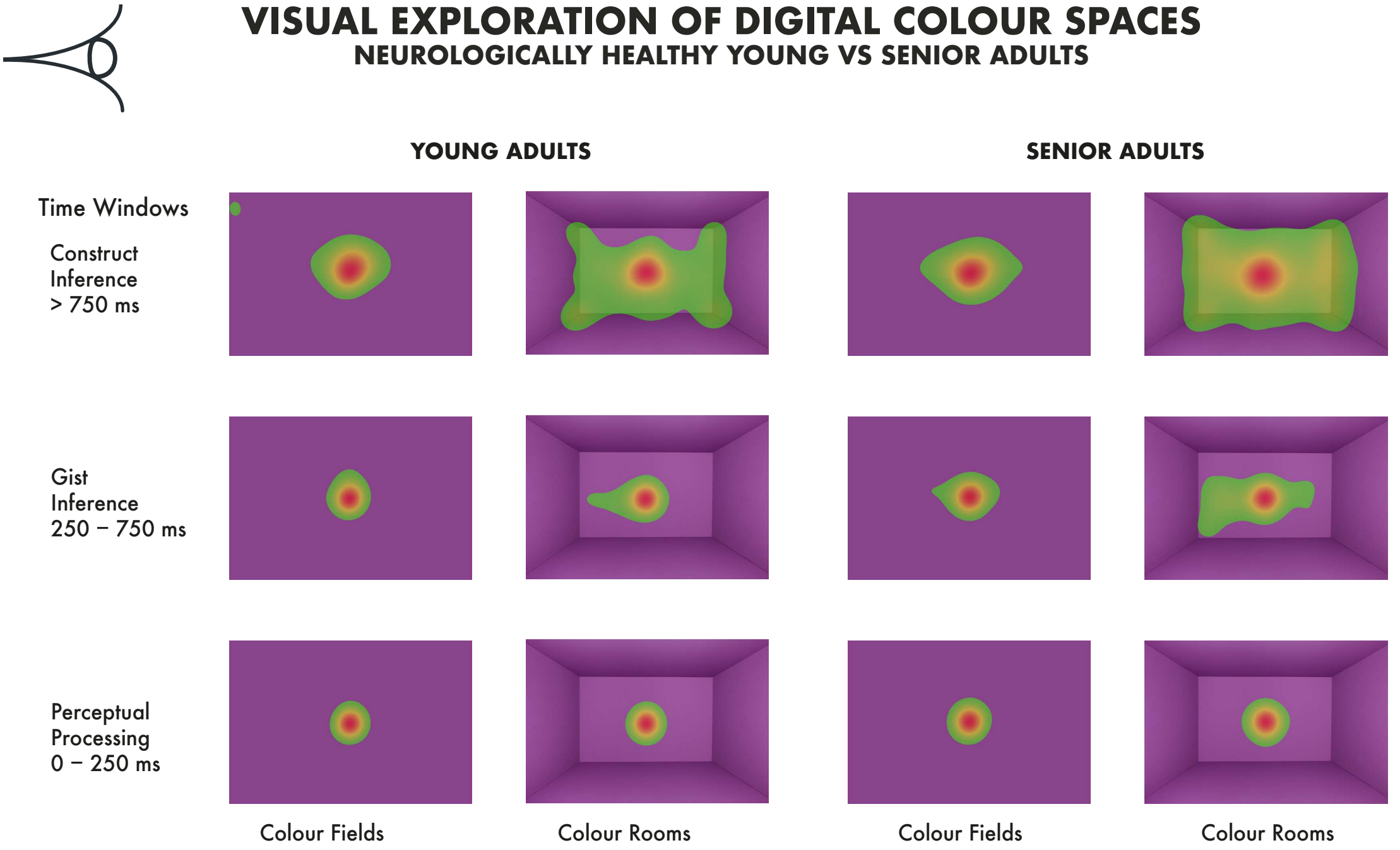


Figure 76

# VISUAL EXPLORATION OF DIGITAL COLOUR SPACES

## NEUROLOGICALLY HEALTHY YOUNG VS SENIOR ADULTS




Heatmaps of aggregated visual fixation patterns across the total range of colour image trials. The transparent overlay colours indicate the fixation duration density, from low (green) to moderate (yellow) and high (red).

Colour selection

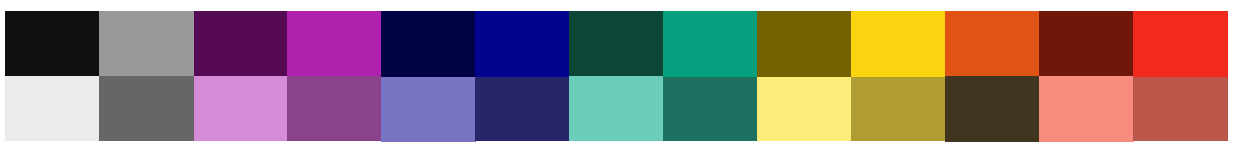
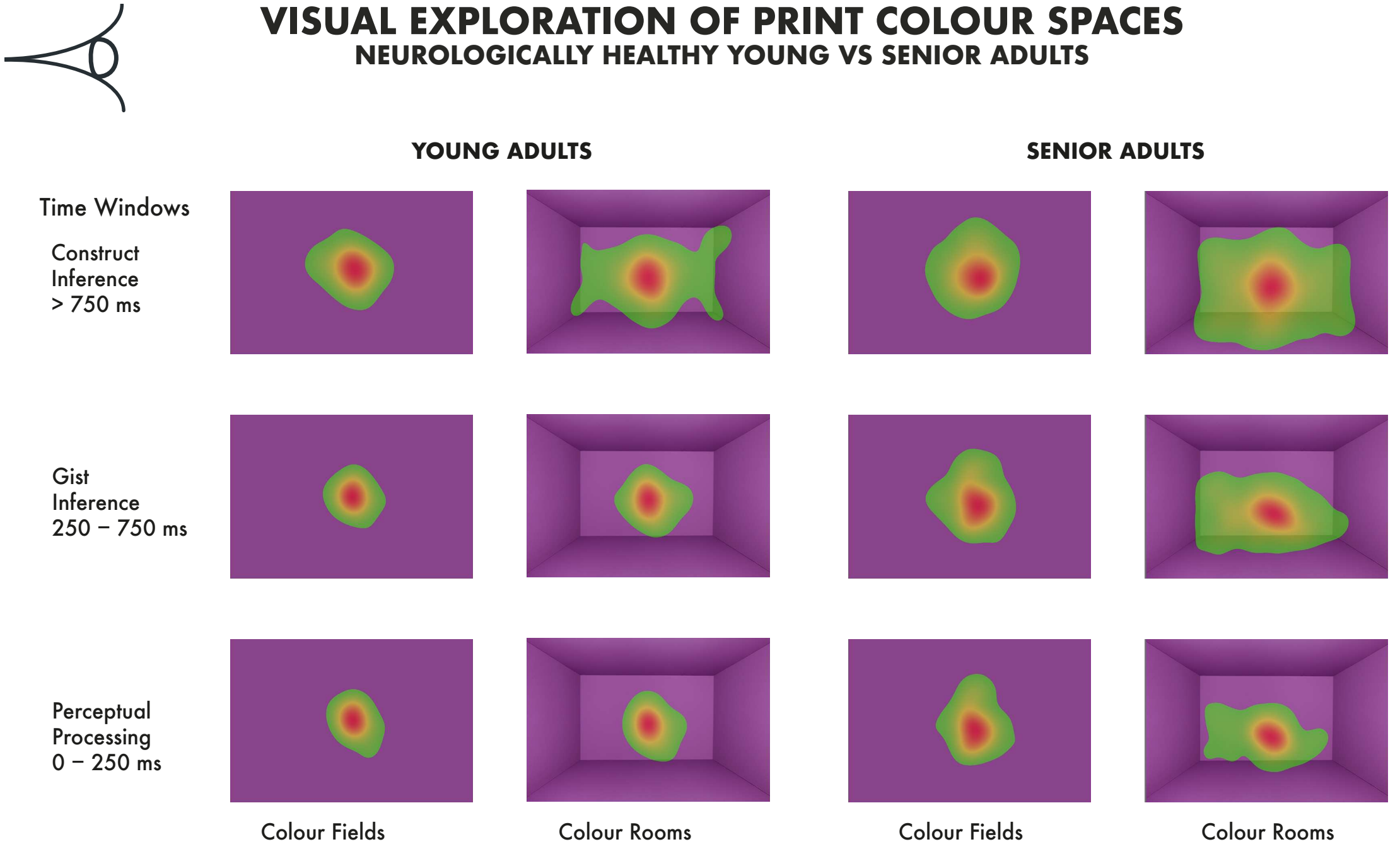


Figure 77

# VISUAL EXPLORATION OF PRINT COLOUR SPACES

## NEUROLOGICALLY HEALTHY YOUNG VS SENIOR ADULTS




Heatmaps of aggregated visual fixation patterns across the total range of colour image trials. The transparent overlay colours indicate the fixation duration density, from low (green) to moderate (yellow) and high (red).

Colour selection

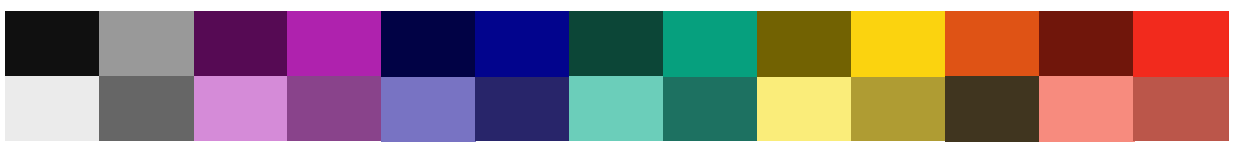


**Table 47:**

**Colour rooms average dwell times on spatial cues (%)**

**Senior adults living with dementia compared to control cohort**

**Construct inference (750 — 50000 ms)**

| ID participant | Spatial cue | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P1M_tAD | DC_BR | -1.5 | 0.715 | 1.0 |
| P1M_tAD | DHE_B | 1.2 | 0.612 | 1.0 |
| P1M_tAD | DHE_T | 5.4 | 0.006 | 12.6 |
| P2F_tAD | DC_BR | 1.1 | 0.791 | 1.0 |
| P2F_tAD | DHE_B | 2.6 | 0.266 | 1.0 |
| P2F_tAD | DHE_T | -1.1 | 0.528 | 1.0 |
| P2F_tAD | PC_TR | -2.0 | 0.561 | 1.0 |
| P2F_tAD | PVE_R | -4.6 | 0.511 | 1.0 |
| P3F_tAD | DC_BR | -2.9 | 0.495 | 1.0 |
| P3F_tAD | DHE_B | -3.3 | 0.154 | 1.3 |
| P3F_tAD | DHE_T | -1.1 | 0.551 | 1.0 |
| P3F_tAD | PC_TR | -1.7 | 0.622 | 1.0 |
| P3F_tAD | PVE_R | -6.6 | 0.345 | 1.0 |
| P4M_svPPA | DC_BR | -2.7 | 0.521 | 1.0 |
| P4M_svPPA | DHE_B | -0.4 | 0.875 | 1.0 |
| P4M_svPPA | DHE_T | 3.4 | 0.069 | 2.0 |
| P5M_svPPA | DC_BR | 7.4 | 0.086 | 1.7 |
| P5M_svPPA | DHE_B | 6.3 | 0.012 | 6.9 |
| P5M_svPPA | DHE_T | -1.7 | 0.333 | 1.0 |
| P5M_svPPA | PC_TR | -2.0 | 0.561 | 1.0 |
| P5M_svPPA | PVE_R | -2.0 | 0.778 | 1.0 |
| P6M_nfPPA | DC_BR | -4.7 | 0.266 | 1.0 |
| P6M_nfPPA | DHE_B | 3.4 | 0.143 | 1.3 |
| P6M_nfPPA | DHE_T | 4.2 | 0.025 | 4.0 |
| P6M_nfPPA | PC_TR | -2.0 | 0.561 | 1.0 |
| P6M_nfPPA | PVE_R | -7.2 | 0.307 | 1.0 |
| P7M_nfPPA | DC_BR | -0.4 | 0.915 | 1.0 |
| P7M_nfPPA | DHE_B | 1.5 | 0.508 | 1.0 |
| P7M_nfPPA | DHE_T | 1.6 | 0.376 | 1.0 |
| P7M_nfPPA | PC_TR | 1.7 | 0.626 | 1.0 |
| P7M_nfPPA | PVE_R | -5.5 | 0.434 | 1.0 |
| P8F_nfPPA | DC_BR | -4.3 | 0.303 | 1.0 |
| P8F_nfPPA | DHE_B | 3.3 | 0.163 | 1.2 |
| P8F_nfPPA | DHE_T | -1.3 | 0.464 | 1.0 |
| P8F_nfPPA | PC_TR | -1.8 | 0.610 | 1.0 |
| P8F_nfPPA | PVE_R | -6.6 | 0.346 | 1.0 |
| P10M_bvFTD | DC_BR | -4.6 | 0.280 | 1.0 |
| P10M_bvFTD | DHE_B | -1.7 | 0.465 | 1.0 |
| P10M_bvFTD | DHE_T | 2.3 | 0.196 | 1.2 |
| P10M_bvFTD | PC_TR | -1.9 | 0.574 | 1.0 |
| P10M_bvFTD | PVE_R | -6.9 | 0.329 | 1.0 |
| P11M_bvFTD | DC_BR | -3.7 | 0.374 | 1.0 |
| P11M_bvFTD | DHE_B | -2.1 | 0.364 | 1.0 |
| P11M_bvFTD | DHE_T | -0.3 | 0.855 | 1.0 |
| P11M_bvFTD | PC_TR | 0.1 | 0.978 | 1.0 |
| P11M_bvFTD | PVE_R | -1.0 | 0.891 | 1.0 |
| P12M_PCA | DC_BR | -4.2 | 0.317 | 1.0 |
| P12M_PCA | DHE_B | 9.8 | 0.000 | 137.7 |
| P12M_PCA | DHE_T | 1.4 | 0.426 | 1.0 |
| P12M_PCA | PC_TR | -1.1 | 0.750 | 1.0 |
| P12M_PCA | PVE_R | -6.8 | 0.336 | 1.0 |
| P13F_PCA | DC_BR | -2.9 | 0.495 | 1.0 |
| P13F_PCA | DHE_B | 16.9 | 0.000 | 57727.6 |
| P13F_PCA | DHE_T | -1.9 | 0.289 | 1.0 |
| P13F_PCA | PC_TR | -2.0 | 0.561 | 1.0 |
| P13F_PCA | PVE_R | -6.6 | 0.350 | 1.0 |
| P14M_UD | DC_BR | -3.0 | 0.480 | 1.0 |
| P14M_UD | DHE_B | 0.6 | 0.801 | 1.0 |
| P14M_UD | DHE_T | -1.9 | 0.289 | 1.0 |
| P14M_UD | PC_TR | -2.0 | 0.561 | 1.0 |
| P14M_UD | PVE_R | -2.3 | 0.740 | 1.0 |

These findings show that the two participants who were diagnosed with Posterior Cortical Atrophy, P12M_PCA and P13F_PCA, both looked significantly more at the bottom horizontal edge in the digital colour room images during the construct inference phase, compared to the neurologically healthy senior adults. I also observed this in P5M_svPPA, who had been diagnosed with Semantic Primary Progressive Aphasia. In P6M_nfPPA and P1M_tAD, I observed a

significantly higher proportional dwell time on the top horizontal edge in the digital colour room images, compared to the neurologically healthy senior adults.

During none of the three successive time windows did the social salience model predict the visual exploration patterns any better than the perceptual salience model, regardless of age or neurological health.

**Pupil dilation results**

I first performed paired sample t tests in which I compared the average baseline pupil dilations in the digital and the Print Colour Spaces condition with each other in each cohort.
The results showed that there was no difference between the average pupil dilations in the two presentation conditions in all three research cohorts,  confirming that the different light sources (monitor vs daylight lamp) had been of equal intensity.

I then compared the average baseline pupil dilations in the digital and print conditions between the neurologically healthy young and senior adults. The average baseline pupil dilation of young adults was 1343 mm² (SD=329 mm²) in the Digital Colour Spaces condition, compared to 922 mm² (SD=221 mm²) in senior adults. It was 745.8 times more likely that this difference in baseline dilation in the digital presentation condition was an effect of healthy ageing, with a two-sided p value <.001. The average baseline pupil dilation of young adults was 1432 mm² (SD=381 mm²) in the Print Colour Spaces condition, compared to 918 mm² (SD=254 mm²) in senior adults. It was 1549.1 times more likely that this difference in baseline dilation in the print presentation was an effect of healthy ageing, with a two-sided p value <.001. I did not observe  significant differences in baseline pupil dilations between the neurologically healthy senior adults and the senior adults living with dementia on a cohort level. However, there were a few notable individual differences, especially in P6M_nfPPA which Table 48 shows.

**Table 48:**
**Baseline average pupil dilations (mm²)**
**Senior adults living with dementia compared to control cohort**

| ID participant | Pupil Field | Mean diff mm² | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P1M_tAD | Digital | 545 | 0.026 | 3.8 |
| P1M_tAD | Print | NA | NA | NA |
| P2F_tAD | Digital | -3 | 0.989 | 1.0 |
| P2F_tAD | Print | -135 | 0.611 | 1.0 |
| P3F_tAD | Digital | -245 | 0.294 | 1.0 |
| P3F_tAD | Print | -221 | 0.406 | 1.0 |
| P4M_svPPA | Digital | -97 | 0.672 | 1.0 |
| P4M_svPPA | Print | NA | NA | NA |
| P5M_svPPA | Digital | -548 | 0.026 | 3.9 |
| P5M_svPPA | Print | -349 | 0.196 | 1.2 |
| P6M_nfPPA | Digital | 1133 | <.001 | 489.8 |
| P6M_nfPPA | Print | 1438 | <.001 | 1385.3 |
| P7M_nfPPA | Digital | -308 | 0.190 | 1.2 |
| P7M_nfPPA | Print | -272 | 0.310 | 1.0 |
| P8F_nfPPA | Digital | -89 | 0.697 | 1.0 |
| P8F_nfPPA | Print | -81 | 0.759 | 1.0 |
| P10M_bvFTD | Digital | 88 | 0.703 | 1.0 |
| P10M_bvFTD | Print | 89 | 0.736 | 1.0 |
| P11M_bvFTD | Digital | -180 | 0.436 | 1.0 |
| P11M_bvFTD | Print | -211 | 0.428 | 1.0 |
| P12M_PCA | Digital | -413 | 0.084 | 1.8 |
| P12M_PCA | Print | -426 | 0.118 | 1.5 |
| P13F_PCA | Digital | -160 | 0.488 | 1.0 |
| P13F_PCA | Print | -85 | 0.746 | 1.0 |
| P14M_UD | Digital | 12 | 0.957 | 1.0 |
| P14M_UD | Print | -206 | 0.438 | 1.0 |

The neurologically healthy young adults showed on average a significantly different pupil response to all the colour spaces, except the dark spaces, compared to the neurologically healthy senior adults. The pupil responses are reported as average differences in mm² over the 5 seconds viewing window per trial, compared to the pre-trial baseline pupil dilation.

The results are shown in Table 49. The abbreviation CF stands for colour field and the abbreviation CR stands for colour room.

**Table 49:**
**Colour spaces average pupil responses (mm²)**
**Neurologically healthy young adults compared to senior adults**

| Colour space | Mean diff mm² | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Dark Digital_CF | 58 | 0.270 | 1.0 |
| Light Digital_CF | -166 | 0.001 | 41.1 |
| Muted Digital_CF | NA | NA | NA |
| Saturated Digital_CF | -249 | < .001 | 1763.0 |
| Dark Digital_CR | 46 | 0.258 | 1.1 |
| Light Digital_CR | -163 | < .001 | 676.2 |
| Muted Digital_CR | -25 | 0.452 | 1.0 |
| Saturated Digital_CR | -194 | < .001 | 2278.0 |
| Dark Print_CF | 19 | 0.771 | 1.0 |
| Light Print_CF | -180 | < .001 | 104.0 |
| Muted Print_CF | -86 | 0.015 | 5.9 |
| Saturated Print_CF | -224 | < .001 | 2343.9 |
| Dark Print_CR | -59 | 0.122 | 1.4 |
| Light Print_CR | -290 | < .001 | 251.4 |
| Muted Print_CR | -177 | < .001 | 96.7 |
| Saturated Print_CR | -210 | < .001 | 1473.5 |

As these findings show, the largest difference in pupil responses between the young and senior adults occurred in response to light and saturated colour spaces, whereby the pupils of the young adults contracted on average significantly more than the pupils of the senior adults. This was the case for both the digital and the Print Colour Spaces and independent of spatial context.

The luminance level of the light colour spaces was higher than the saturated colours spaces (see the L values in Table 42), while the pupil contraction difference between the young and senior adults was the largest in the saturated colour spaces conditions. To investigate this finding further, I analysed the differences in pupil responses to light and saturated colour spaces within each cohort. This could possibly further elucidate the driving factor(s) behind the differences in pupil contraction to light and saturated colour spaces.

The results of this analyses are shown in Tables 50 and 51. The pupil responses are reported as average differences in mm² over the 5 seconds viewing window per trial, compared to the pre-trial baseline pupil dilation. The abbreviation CF stands for colour field and the abbreviation CR stands for colour room.

**Table 50:**
**Light vs saturated colour spaces**
**Average pupil responses (mm²)**
**Neurologically healthy young adults**

| Colour space | Mean diff mm² | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Light_Digital_CF vs Light_Digital_CR | -16 | 0.531 | 1 |
| Saturated_Digital_CF vs Saturated_Digital_CR | -73 | 0.091 | 1.7 |
| Light_Print_CF vs Light_Print_CR | 138 | 0.026 | 3.8 |
| Saturated_Print_CF vs Saturated_Print_CR | 16 | 0.513 | 1 |
| Light_Digital_CF vs Saturated_Digital_CF | -19 | 0.489 | 1 |
| Light_Digital_CR vs Saturated_Digital_CR | -76 | 0.043 | 2.7 |
| Light_Print_CF vs Saturated_Print_CF | -13 | 0.822 | 1 |
| Light_Print_CR vs Saturated_Print_CR | -154 | 0.008 | 16.2 |

**Table 51:**
**Light vs saturated colour spaces**
**Average pupil responses (mm²)**
**Neurologically healthy senior adults**

| Colour space | Mean diff mm² | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Light_Digital_CF vs Light_Digital_CR | -13 | 0.283 | 1 |
| Saturated_Digital_CF vs Saturated_Digital_CR | -18 | 0.334 | 1 |
| Light_Print_CF vs Light_Print_CR | 29 | 0.288 | 1 |
| Saturated_Print_CF vs Saturated_Print_CR | 7 | 0.765 | 1 |
| Light_Digital_CF vs Saturated_Digital_CF | -102 | <.001 | 830.5 |
| Light_Digital_CR vs Saturated_Digital_CR | -107 | <.001 | 1391 |
| Light_Print_CF vs Saturated_Print_CF | -54 | 0.040 | 2.9 |
| Light_Print_CR vs Saturated_Print_CR | -74 | <.001 | 91.2 |

These findings show that in young adults, the effect of depicted spatial dimension had a (moderate) significant effect on the pupil response in the print condition, whereby the light colour rooms prints triggered a greater pupil constriction than the light colour rooms fields. Significantly greater pupil constrictions were also observed in response to saturated colour rooms in both the digital and print conditions, compared to the light colour rooms.

In senior adults, only variations in luminance had an effect on the pupil constrictions in both the digital and print colour spaces conditions, and not the depicted spatial context.

On a cohort level, the senior adults living with dementia only showed a significantly different pupil response to the light colour rooms prints, showing on average 83 mm² less pupil constriction compared to the neurologically healthy adults. It was 12.8 times more likely that this was a general effect of dementia, with a two-sided p value of 0.006. Analysed on an individual level, all senior adults living with dementia showed less pupil constriction in response to the light colour rooms prints, compared to neurologically healthy senior adults, but these differences were not significant.

**Internal state evaluation results**

In this section I have described the internal state evaluations that the participants gave in response to the colour spaces.

I first looked at whether there was a global effect of spatial context and/or colour medium of the colour space images on people's affective responses. I observed that young adults responded on average more positive to the print colour fields than the digital colour fields. It was 3.3 times more likely that this difference was an effect of material presentation, with a two-sided p value of 0.033.

Neurologically healthy senior adults responded on average less positive to the colour rooms than the colour fields. The effect of depicted spatial context on the affective responses was in the digital colour image presentations 4.1 times more likely, with a two-sided p value of 0.024. In the print colour image presentations this was 16.3 times more likely, with a two-sided p value of 0.004. There was no significant effect of either colour medium or depicted spatial context on the affective responses of senior adults living with dementia to the colour space images. There was no significant difference between the global affective responses to the colour space images of the participants on a cohort level.

After grouping the colour space images according to depicted spatial context and colour axis, I found that in the digital presentations, there was no difference between the young and senior adults in their average affective responses, regardless of colour axis (saturated, muted, light, dark) or depicted spatial context (field or room).

In the print presentations, I observed that young adults rated the saturated yellow colour field image on average more positive, compared to the neurologically healthy senior adults.
The young adults indicated on average that this colour made them feel positive to very positive (μ=1.5, SD=0.87), whereas the senior adults indicated on average that this colour made them feel neutral to positive (μ=2.2, SD=1.0). It was 4.3 times more likely that a different preference for the saturated yellow colour field print was an effect of healthy ageing, with a two-sided p value of 0.022.

In contrast, I found that senior adults rated the saturated red field print higher than young adults. The young adults indicated on average that this colour made them feel neutral (μ=3, SD=1.3), whereas the senior adults indicated on average that this colour made them feel neutral to positive (μ=2.1, SD=1.3). It was 3.5 times more likely that a different preference for the saturated red field print was an effect of healthy ageing, with a two-sided p value of 0.03.

I found different significant affective responses to the print colour room images. Young adults rated on average the white room print more positive than the senior adults. The young adults indicated on average that the white room print made them feel positive (μ=2, SD=1.1), whereas the senior adults indicated on average that it made them feel neutral to positive (μ=2.7, SD=1.1). It was 2.9 times more likely that a different preference for the white room print was an effect of healthy ageing, with a two-sided p value of 0.039. Young adults also rated on average the saturated yellow room print more positive than the senior adults. The young adults indicated on average that the saturated yellow room print made them feel positive to very positive (μ=1.9, SD=1.2), whereas the senior adults indicated on average that it made them feel neutral to positive (μ=2.9, SD=1.3). It was 3.4 times more likely that a different preference for the saturated yellow room print was an effect of healthy ageing, with a two-sided p value of 0.031.

When I compared the average affective responses to the colour images – grouped by colour axis and spatial context – of the senior adults living with dementia to the neurologically healthy senior adults I found overall no significant differences. The only colour image that senior adults living with dementia responded on average more positive to compared to, was the print version of the colour room painted in Pantone 448C, the supposedly most unpleasant colour in the world ('Pantone 448C', Wikipedia. Retrieved 11 January 2020). The emotional ratings were not normally distributed among the senior adults living with dementia however, so I only analysed this on an individual level. In Table 52 I have detailed these findings.
The affect rating range ranked from 1 (strongly positive) to 5 (strongly negative). A negative affect response difference therefore indicated a comparatively *more positive* response.

**Table 52:**
**Pantone 448C room print affective response difference**
**Senior adults living with dementia compared to control cohort**

| ID participant | Affect response difference | Two-sided p value | Odds of true effect |
|---|---|---|---|
| P2F_tAD | 0 | 0.968 | 1.0 |
| P3F_tAD | -3 | 0.026 | 3.9 |
| P5M_svPPA | 0 | 0.968 | 1.0 |
| P6M_nfPPA | -3 | 0.026 | 3.9 |
| P7M_nfPPA | 1 | 0.400 | 1.0 |
| P8F_nfPPA | -1 | 0.446 | 1.0 |
| P10M_bvFTD | -3 | 0.026 | 3.9 |
| P11M_bvFTD | -2 | 0.127 | 1.4 |
| P12M_PCA | 0 | 0.968 | 1.0 |
| P13F_PCA | -3 | 0.026 | 3.9 |
| P14M_UD | 1 | 0.400 | 1.0 |

The results show that senior adults living with various forms of dementia responded more positive to the print room picture in the colour Pantone 448C than the neurologically healthy senior adults did on average. This might mean that the more positive response could be a general effect of dementia.

When I ranked the average affect ratings of the young and senior adults from most positive to most negative, the degree of brightness appeared to play a key role, with saturated and light colours ranking mostly positive and muted and dark colours ranking mostly negative, which is shown in Figure 78. In the young adults, saturated yellow was the most positively rated colour in most colour image conditions, regardless of the material presentation. Only in the digital colour rooms condition this was not the case and was saturated orange rated most positively instead. Young adults rated Pantone 448C as the most negative colour in both the digital and print conditions, regardless of the depicted spatial context.

Senior adults rated saturated yellow as the most positive colour among the digital colour field images and saturated green was most positively rated among the digital colour room images. They rated saturated orange as the most positive colour in the print colour images, regardless of the depicted spatial context. Senior adults rated black as the most negative colour in most colour image conditions, regardless of depicted spatial context. Only in the print colour fields condition this was not the case and was Pantone 448C rated most negatively instead. Since my earlier analyses showed that senior adults living with dementia gave on average similar affective ratings to all colour space images but one as the neurologically healthy senior adults, I did not rank the colour images for this cohort separately.

Tables 53 and 54 show the average highest and lowest affect ratings for the different colour spaces in the young and senior adults.

**Table 53:**
**Young adults rankings of colour space images**

**1=strongly positive; 5=strongly negative**

| Colour space | Affect rank | Mean rating | Standard deviation |
|---|---|---|---|
| Digital saturated yellow field | Top | 1.82 | 0.99 |
| Digital Pantone 448C field | Bottom | 3.94 | 0.64 |
| Digital saturated orange room | Top | 1.88 | 0.90 |
| Digital Pantone 448C room | Bottom | 3.88 | 1.02 |
| Print saturated yellow field | Top | 1.53 | 0.85 |
| Print Pantone 448C field | Bottom | 4.18 | 0.86 |
| Print saturated yellow room | Top | 1.94 | 1.16 |
| Print Pantone 448C room | Bottom | 4.29 | 0.67 |

**Table 54:**
**Senior adults rankings of colour space images**

**1=strongly positive; 5=strongly negative**

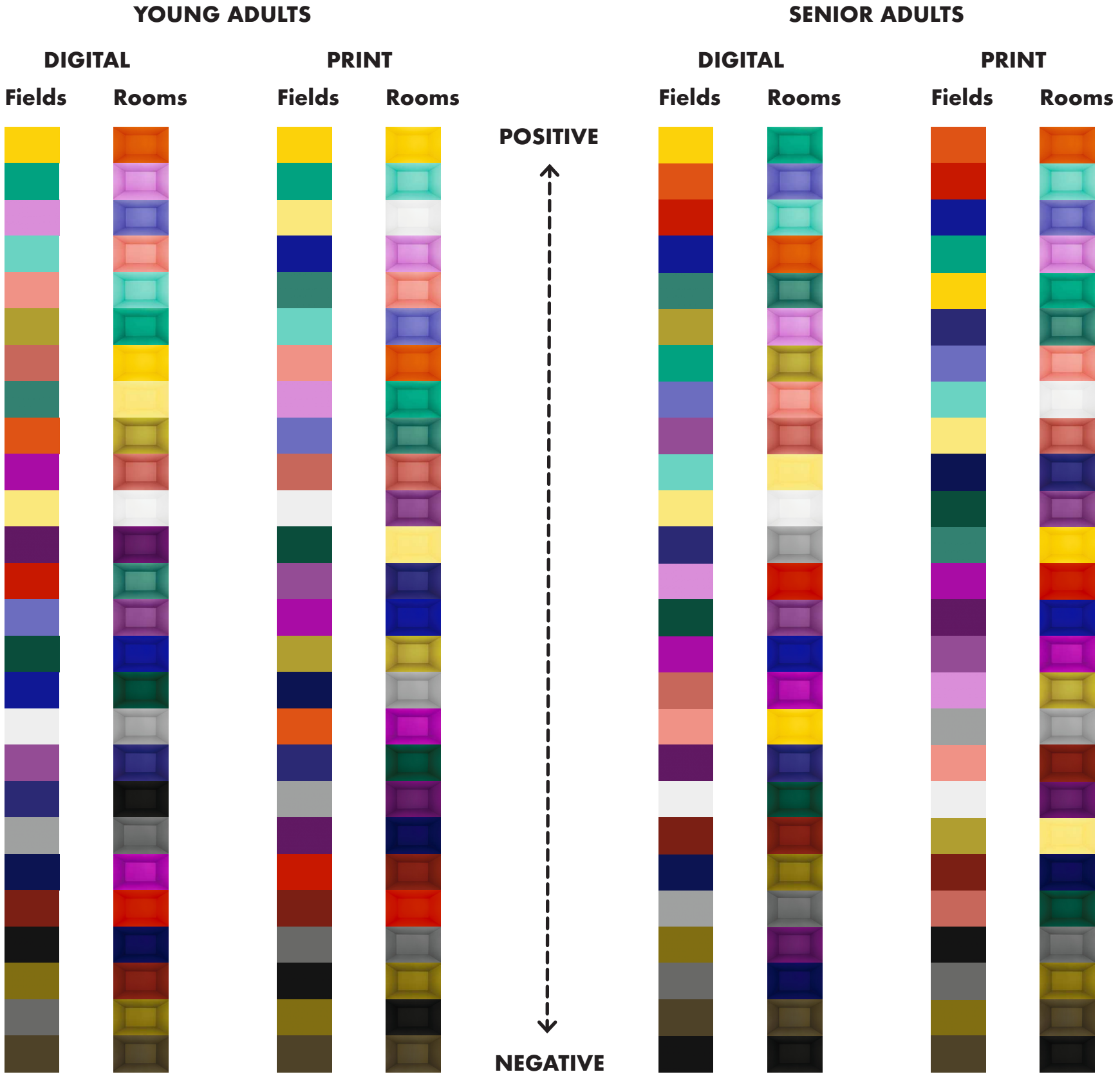
| Colour space | Affect rank | Mean rating | Standard deviation |
|---|---|---|---|
| Digital saturated yellow field | Top | 2.00 | 1.06 |
| Digital black field | Bottom | 4.10 | 0.89 |
| Digital saturated green room | Top | 2.20 | 0.87 |
| Digital black room | Bottom | 4.15 | 1.01 |
| Print saturated orange field | Top | 2.05 | 0.93 |
| Print Pantone 448C field | Bottom | 3.55 | 1.17 |
| Print saturated orange room | Top | 2.30 | 1.38 |
| Print black room | Bottom | 4.10 | 0.89 |

In the feedback they gave after the colour spaces experiments, many participants reported that they responded differently to colours when their spatial dimensions varied. Senior adults reported more often they responded to the nuances in space and contrast, which also aligned with the fixation patterns which showed that they looked more on the corners and shaded areas around the back wall edges of the rooms compared to the younger adults.

Figure 78

# AFFECTIVE RESPONSES TO COLOUR SPACE IMAGES

## NEUROLOGICALLY HEALTHY ADULTS



Some participants also mentioned that the way they felt about certain colours in the rooms was dependent on the time of day or their state of mind. Several participants, mostly senior adults, also reported that the order in which the colours were presented influenced their affective responses. They all gave similar accounts, saying that when a strongly negative colour was directly followed by a slightly negative, neutral or positive colour, they felt more positive towards these colours than otherwise. Which colours had this modifying effect was again highly personal however.

At the end of the two colour spaces experiments I also asked the participants if they had a preference for looking at the colour spaces as digital or print images. When given a choice, the vast majority of the neurologically healthy young adults indicated they preferred the colour spaces in print form over the monitor images. The majority of the neurologically healthy senior adults and those living with a dementia also preferred looking at the colours on the prints. However, more than a third of the neurologically healthy senior adults had no medium preference and among senior adults living with dementia, more than a quarter preferred the digital colour presentations. When asked to motivate their preference, participants who preferred the colours on the prints said they were easier on the eye, more pleasant to look at, more natural, immersive or vibrant, had more depth, texture or felt more tangible. Interestingly, participants who preferred the colours on the monitor gave similar reasons, saying that they found the digital colours flowed more easily, were more vibrant, or immersive, especially the room images.

Figure 79 shows the proportional distributions of colour medium preference in each research cohort.

**Electrodermal activity results**

The following tables detail the electrodermal activity (EDA) flux (%) patterns of the neurologically healthy participants.

**Table 55:**
**Young adults Colour Spaces EDA flux (%)**

| Experiment | Wrist | EDA flux % | St Dev |
|---|---|---|---|
| Digital | Left | -15 | 45 |
| Digital | Right | -1 | 39 |
| Print | Left | -31 | 51 |
| Print | Right | -25 | 48 |

**Table 56:**
**Senior adults Colour Spaces EDA flux (%)**

| Experiment | Wrist | EDA flux % | St Dev |
|---|---|---|---|
| Digital | Left | -46 | 34 |
| Digital | Right | -15 | 45 |
| Print | Left | -53 | 37 |
| Print | Right | -23 | 58 |

**Table 57:**
**Young adults colour spaces left vs right EDA flux (%)**

| Experiment | Difference left/right % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Digital | -20 | 0.095 | 1.6 |
| Print | -10 | 0.253 | 1.1 |

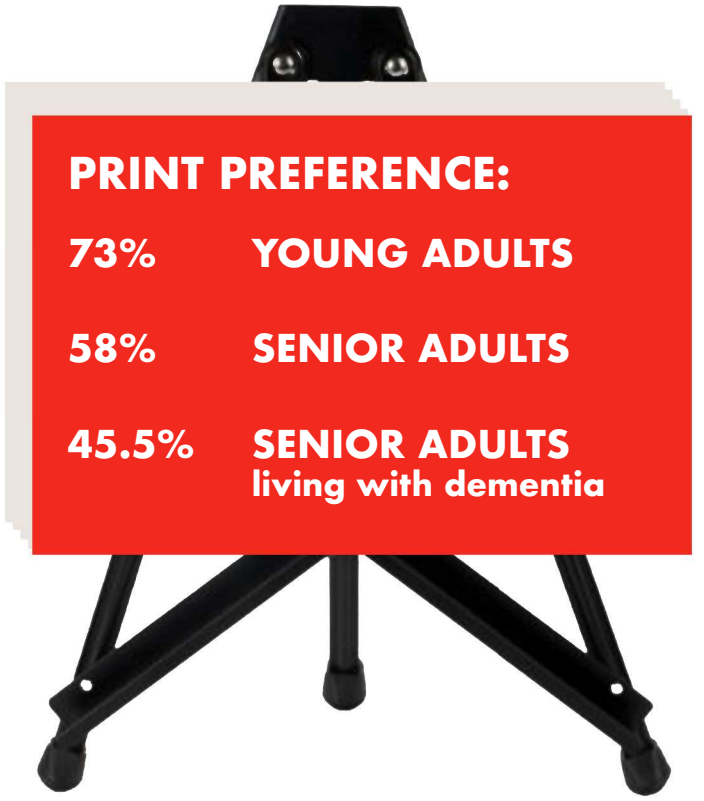
**Table 58:**
**Senior adults colour spaces left vs right EDA flux (%)**

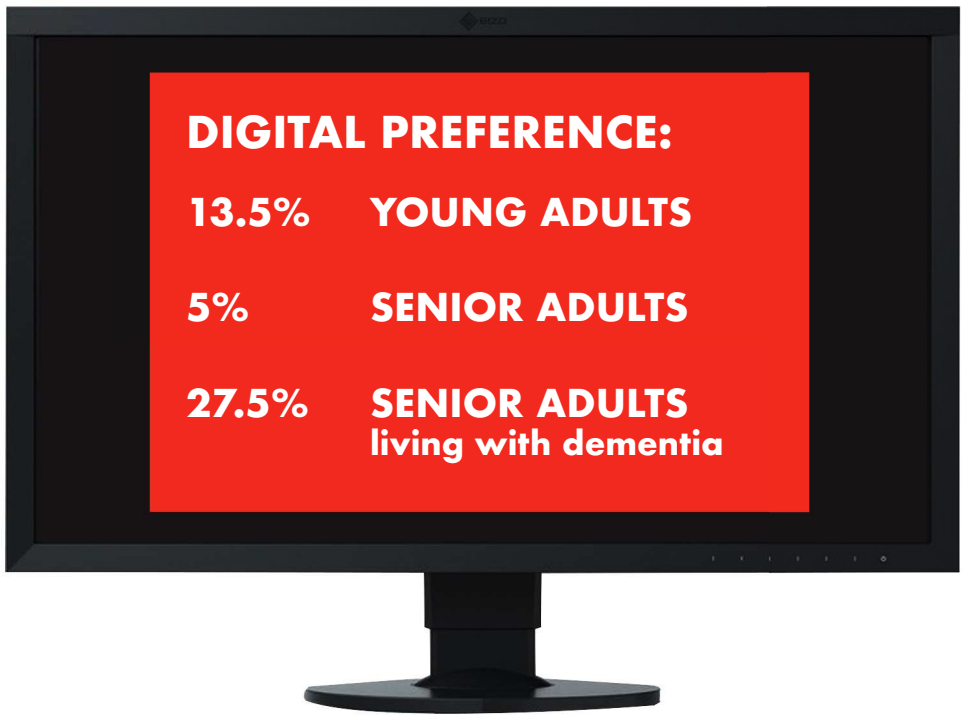
| Experiment | Difference left/right % | Two-sided p value | Odds of true effect |
|---|---|---|---|
| Digital | -33 | 0.036 | 3.1 |
| Print | -19 | 0.164 | 1.2 |

These findings show that during both Colour Spaces experiments, the average EDA flux of the young adults was lower than the personal average across all research sections, taking only active research time into account.

Figure 79

# MATERIAL PREFERENCES FOR COLOUR SPACE IMAGES
## IN HEALTHY AGEING AND DEMENTIA




**NO PREFERENCE:**

| | |
|---|---|
| 13.5% | YOUNG ADULTS |
| 37% | SENIOR ADULTS |
| 18% | SENIOR ADULTS living with dementia |

The results also indicate that there was no significant difference in EDA flux between the left and right wrist in both experiments. The EDA flux of the senior adults was also lower during both Colour Spaces experiments than the personal average across all research sections, taking only active research time into account. Comparing their left and right wrist EDA activity, I found a significant difference in flux of 33% during the Digital Colour Spaces experiment, whereby the right wrist showed the comparatively higher electrodermal activity.

When I compared the EDA responses of the young adults with the senior adults, I only found a significant difference in the left wrist EDA flux during the Digital Colour Spaces experiment, which is shown in Table 59.

**Table 59:**
**Healthy ageing effects on colour spaces EDA flux (%)**
**Young adults compared to senior adults**

| Experiment | Wrist | Location parameter % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| Digital | Left | 32 | 0.023 | 4.3 |
| Digital | Right | 14 | 0.342 | 1.0 |
| Print | Left | 22 | 0.157 | 1.3 |
| Print | Right | -2 | 0.896 | 1.0 |

There was on average an EDA flux difference of 32% between the left wrist of the young adults and the senior adults during the digital colour spaces experiment, with the young adults showing higher EDA activity. It was 4.3 times more likely that this difference was an effect of healthy ageing, with a two-sided p value of 0.023. This might indicate a stronger autonomic arousal in young adults.

Tables 60 and 61 show the EDA flux differences between the senior adults living with dementia and the control senior adults.

**Table 60:**
**Dementia effects on digital colour spaces EDA flux (%)**
**Senior adults living with dementia compared to control cohort**

| ID participant | Wrist | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P1M_tAD | Left | 14 | 0.694 | 1.0 |
| P1M_tAD | Right | -77 | 0.209 | 1.1 |
| P2F_tAD | Left | 99 | 0.010 | 7.8 |
| P2F_tAD | Right | -57 | 0.351 | 1.0 |
| P3F_tAD | Left | 47 | 0.193 | 1.2 |
| P3F_tAD | Right | 54 | 0.373 | 1.0 |
| P6M_nfPPA | Left | 90 | 0.017 | 5.2 |
| P6M_nfPPA | Right | 62 | 0.313 | 1.0 |
| P7M_nfPPA | Left | -52 | 0.147 | 1.3 |
| P7M_nfPPA | Right | 16 | 0.786 | 1.0 |
| P8F_nfPPA | Left | 95 | 0.013 | 6.4 |
| P8F_nfPPA | Right | -24 | 0.693 | 1.0 |
| P10M_bvFTD | Left | 259 | 0.000 | 55951.9 |
| P10M_bvFTD | Right | 16 | 0.791 | 1.0 |
| P11M_bvFTD | Left | 132 | 0.001 | 46.1 |
| P11M_bvFTD | Right | -6 | 0.922 | 1.0 |
| P12M_PCA | Left | -19 | 0.589 | 1.0 |
| P12M_PCA | Right | -49 | 0.420 | 1.0 |
| P13F_PCA | Left | -49 | 0.172 | 1.2 |
| P13F_PCA | Right | -58 | 0.340 | 1.0 |
| P14M_UD | Left | 100 | 0.010 | 8.3 |
| P14M_UD | Right | -38 | 0.531 | 1.0 |

**Table 61:**
**Dementia effects on print colour spaces EDA flux (%)**
**Senior adults living with dementia compared to control cohort**

| ID participant | Wrist | Mean difference % | Two-sided p value | Odds of true effect |
|---|---|---|---|---|
| P2F_tAD | Left | 21 | 0.592 | 1.0 |
| P2F_tAD | Right | -56 | 0.354 | 1.0 |
| P3F_tAD | Left | 82 | 0.044 | 2.7 |
| P3F_tAD | Right | 55 | 0.369 | 1.0 |
| P6M_nfPPA | Left | 67 | 0.095 | 1.6 |
| P6M_nfPPA | Right | 62 | 0.310 | 1.0 |
| P7M_nfPPA | Left | -43 | 0.269 | 1.0 |
| P7M_nfPPA | Right | 17 | 0.781 | 1.0 |
| P8F_nfPPA | Left | 112 | 0.008 | 9.3 |
| P8F_nfPPA | Right | -24 | 0.697 | 1.0 |
| P10M_bvFTD | Left | 26 | 0.509 | 1.0 |
| P10M_bvFTD | Right | 16 | 0.786 | 1.0 |
| P11M_bvFTD | Left | 82 | 0.043 | 2.7 |
| P11M_bvFTD | Right | -6 | 0.927 | 1.0 |
| P12M_PCA | Left | -24 | 0.533 | 1.0 |
| P12M_PCA | Right | -49 | 0.423 | 1.0 |
| P13F_PCA | Left | -43 | 0.270 | 1.0 |
| P13F_PCA | Right | -58 | 0.342 | 1.0 |
| P14M_UD | Left | 4 | 0.910 | 1.0 |
| P14M_UD | Right | -38 | 0.535 | 1.0 |

These results show that several senior adults living with dementia had a significantly higher EDA flux in their left wrist, during the Colour Spaces experiments -most prominently in the digital condition-, compared to the neurologically healthy senior adults. These findings might indicate that these senior adults living with dementia experienced a higher level of autonomic arousal during the Colour Spaces experiments, compared to the neurologically healthy senior adults.

## 4.3.4 DISCUSSION

In this section, I have reflected on how the experimental data of the Colour Spaces project elucidated my research questions and hypotheses.

### Visual exploration discussion

My first research question was (Q1):
'How does visual perception relate to visual imagination and other social functions?'

The findings from the Digital and Print Colour Spaces experiments showed that during the initial perceptual processing phase (0 – 250 ms) when looking at visual artworks and complex images, visual imagination was informed by the image elements that happen to fall in the central 5% of the visual field, which was in this study the centre of each image.

During the gist inference phase that followed (250 – 750 ms), top-down effects of perceived spatial context began to influence the visual exploration patterns. My research findings showed that during this phase, people would stay mostly fixated on the centre when viewing colour field images, but direct their foveal vision towards the edges of the back wall when looking at colour room images.

My research findings also showed that during the construct inference phase (>750 ms), the effects of perceived spatial context became more pronounced in the colour room image viewings, with people scanning the outlines of the back wall.

Looking at the pupil responses to the colour images, averaged over the 5 second viewing windows in each trial, I found effects of luminance, colour saturation and perceived spatial context on the pupil dilations. I also found several effects of healthy ageing and dementia, which I have elaborated further on below in relation to my other research questions and hypotheses.

**My other research questions were:**

Q2. Does healthy ageing have an effect on visual imagination and other social brain functions?

Q3. Do different forms of dementia have general effects on visual imagination and other social brain functions?

Q4. Do different forms of dementia have specific effects on visual imagination and other social brain functions?

**Hypotheses:**
H1. Neurologically healthy young adults are likely to show more sensitive perceptual (bottom-up) and flexible cognitive (top-down) behavioural responses to visual artworks and complex images than neurologically healthy senior adults.

H2. Neurologically healthy senior adults are likely to rely more strongly on semantic knowledge in cognitive (top-down) responses to visual artworks and complex images than neurologically healthy young adults.

H3. The functional profiles of the dementia syndromes that I have mapped onto the Social Brain Atlas will align with the behavioural measurements.

H4. Given the prominence of semantic language in all dementia profiles in the Social Brain Atlas, it is likely that dementia is in general associated with decreased semantic language access in responses to visual artworks and complex images, compared to neurologically healthy senior adults.

The results from the 2 Colour Spaces experiments showed effects of healthy ageing and dementia on visual imagination during various temporal phases and behavioural modalities.

During the first 250 ms of each colour image presentation, corresponding with the perceptual processing phase, the vast majority of all participants' fixations were directed at the image centre, regardless of the colour medium or spatial context.

The senior adults focused on average 10% less at the centre of the colour images during this phase, compared to the neurologically healthy young adults, which was a significant difference. This effect was already visible during the 5 second presentations of a grey screen with a central fixation cross that preceded each colour image trial. In the earlier experiments of the research visit, the fixation patterns between neurologically healthy young and senior adults were similar during the perceptual processing phase of each image trial, which means that the lower central dwell times could possibly be an effect of fatigue. While this finding is perhaps not so much a reflection of perceptual sensitivity per se, it could be interpreted in support of my first hypothesis, based on the argument that perceptual processing is more energy consuming for senior adults.

Several senior adults living with dementia looked significantly less at the image centres of the colour images during the first 250 ms, compared to neurologically healthy senior adults.
This finding was observed in both participants who had been diagnosed with Posterior Cortical Atrophy, two out of three participants who had been diagnosed with Typical Alzheimer's Disease and one of the two participants who had been diagnosed with Behavioural Frontotemporal Dementia.
The majority of these participants had also looked less at the centres of images during the perceptual processing phase in the other experiments of the research visit. Their dwell time patterns during later temporal phases were often within or even sometimes above the normal variation however.
The lower central well times during the perceptual processing phase of each trial reflected for this reason more likely a difficulty to focus on the small central fixation cross that was shown directly before each image presentation.

This difficulty to fixate on a small, low contrast visual object could have various underlying causes however, of both physiological and attentional nature, which will have to be further elucidated in future research.

I observed very strong differences in proportional central dwell time between the digital and print conditions during the first 250 ms of viewing. This finding is likely related to the manual stimuli presentations in the Print Colour Spaces experiments, which meant there was a clear visual break between the presentation of the grey screen with the fixation cross that was shown before each colour print presentation. It is also likely that there was a lower measurement precision during the first 250 ms of each trial in the print condition, making the recorded eye tracking data during this time window less reliable.

During the gist inference phase (250 – 750 ms) all participants, independent of age or neurological health, fixated significantly less on the centres of digital room images, compared to the centres of digital field images. This finding suggests that during the gist evaluation phase, the spatial cues in the colour room images directed the visual attention more away from the image centre. Only in young adults however, did I also observe a significant difference between the average dwell times on image centres of the print colour field and room images. This finding could be interpreted as providing further support for my first hypothesis, as it appears to show that young adults responded more sensitively to depicted spatial cues in images during the gist evaluation phase than senior adults. However, the heat map patterns of visual exploration in Figures 76 and 77 showed that senior adults actually explored the spatial cues more explicitly and extensively than young adults across both the digital and the print presentations. A possible explanation for this could be that young adults processed the spatial cues in the colour images more effectively with their peripheral vision compared to the senior adults, as it has been shown that contrast sensitivity reduces with increasing age (Owsley et al., 1983). This interpretation of the finding would again be in support of the hypothesis that young adults were more sensitive to sensory information. The ranking of the measured proportional dwell times on the spatial elements in the colour rooms images contradicted my additional hypothesis that corners would be the most salient spatial cues during the visual explorations. Instead, in the digital presentations of the colour room images, the left vertical edge was on average fixated on the most during the gist inference phase by neurologically healthy adults – regardless of age – and the bottom horizontal line was on average fixated on the most by senior adults living with dementia. There were no significant differences between the cohorts in the proportional time spent looking at the spatial elements in the digital colour room images during the gist inference phase.

In the print presentations of the colour rooms images, the right vertical edge was on average fixated on the most during the gist inference phase by neurologically healthy young adults, whereas the bottom horizontal line was on average fixated on the most by senior adults, regardless of neurological health. The foveal interest areas that were placed on horizontal edges of the back wall in each colour room image had the closest absolute distance to the image centre. So the finding that the neurologically healthy adults were biased towards the left vertical edge in the digital colour room images during the gist inference phase can not easily be explained in terms of proximity to the initial gaze orientation. Senior adults living with dementia did focus most on the bottom horizontal edges in colour room images in both the digital and print presentations. In the print colour rooms condition, neurologically healthy senior adults also looked most at the bottom horizontal edge, but the young adults were more inclined to look at the right vertical edge. Research has found that the upward gaze becomes more restricted with increasing age (Chamberlain, 1971), which could help explain why the bottom horizontal edge of the back wall in the colour room images was looked at more by senior adults on average than the top horizontal edge, despite them being equally close to the image centre.

Another explanation for the greater proportional dwell time on the bottom horizontal edge of the back wall in the colour room image by senior adults might be related to the lighting conditions. The print colour room images were lit with a daylight lamp that was placed in a near 90 degrees angle directly above the prints. This created a subtle natural shadow gradient from the top to the bottom of each image, which meant that the bottom horizontal edge of the back wall in each colour room image appeared slightly darker, compared to the other edges of the back wall. The reason that senior adults explored the lower part of the rooms more in the prints compared to the young adults could therefore also be driven by a reduced contrast sensitivity and provide additional support for my first hypothesis.
During the construct inference phase, the neurologically healthy adults looked significantly more on almost all spatial elements in the colour room images, compared to the gist inference phase. The diagonal edges were barely looked at however across all three time windows however. I found no significant differences between the visual exploration patterns of the young and senior adults during this phase.

I found that several of the senior adults living with dementia looked significantly more at the horizontal edges of the digital colour room images during the construct inference phase, compared to neurologically healthy senior adults.
The two participants who were diagnosed with Posterior Cortical Atrophy, and also one of the two participants who had been diagnosed with Semantic Primary Progressive Aphasia, looked significantly more at the bottom horizontal edge. This finding could possibly be indicative of a more pronounced restriction of the upwards gaze and/or a more reduced contrast sensitivity compared to neurologically healthy senior adults. This finding is also congruent with the functional profiles in the Social Brain Atlas of these two dementia phenotypes, as are both associated with affected nodes in the Perception Network, which in turn supports my third hypothesis.

In contrast, one out of three of the participants who had been diagnosed with Nonfluent progressive Aphasia and one out of three of the participants diagnosed with Typical Alzheimer's Disease, looked significantly more at the top horizontal edge. The fixation heat maps of these participants showed that these participants, as well as the participants with Posterior Cortical Atrophy, demonstrated a limited exploration radius from the centre of the colour images, compared to the neurologically healthy senior adults. This finding added to the observation that Posterior Cortical Atrophy, Typical Alzheimer's Disease and Frontotemporal Dementia was associated with difficulty fixating the gaze on a small central fixation cross. Further research is needed however to be able to relate these findings to the Social Brain Atlas profiles of these various dementia syndromes.
In addition, another participant who had been diagnosed with Nonfluent Primary Progressive Aphasia showed a strong left-sided visual exploration bias, but upon further examination of a recent MRI scan by a consulted neurologist, no brain lesion was identified that could account for this apparent right-sided spatial neglect. However, Nonfluent Primary Progressive Aphasia is associated with an increased risk of a corticobasal disorder and the finding of a hemispatial neglect in the visual exploration of monochromatic colour images with minimal spatial cues could potentially be an early indication of a development in that direction.

During none of the 3 successive time windows in the image trials of the Colour Spaces experiments did the social salience model predict the visual exploration patterns any better than the perceptual salience model, regardless of age or neurological health. This finding suggests that the visual exploration patterns of participants during the Colour Spaces experiments were driven as much by perceptual factors as by social salience.

**Pupil responses discussion**

I also observed strong effects of perceptual factors, as well as effects of healthy ageing and dementia, on the pupil responses to the colour images. To begin with, the baseline pupil dilations of senior adults were significantly smaller than the young adults in both the digital and print conditions. Smaller pupil dilations is a known effect of ageing, especially in low luminance conditions (Guillon et al., 2016). Given that the research experiments took place in a blackout room, this effect will have likely been emphasised.

In addition to the smaller baseline pupil dilations in senior adults – regardless of neurological health – the research findings also showed that the pupils of senior adults showed a significantly smaller proportional pupil contraction in response to light and saturated colours, compared to young adults. I observed no differences between young and senior adults in pupil responses to the dark colours.

The finding of significant differences in constriction but not dilation responses of the pupils between young and senior adults point to a likely key role of the pupillary light reflex, which is part of the parasympathetic nervous system and regulated by the Edinger-Westphal nuclei in the midbrain. That there was a comparatively greater pupil constriction in response to the saturated colours in relation to the light colours in young adults, despite the fact the light colour had a higher luminance, could possibly be explained by the Helmholtz-Kohlrausch effect.

Von Helmholtz – the same scientist who was credited with the trichromatic theory of colour perception – first described the phenomenon that strongly saturated colours are perceived brighter by the human visual system, compared to colours with the same luminance but lower saturation (von Helmholtz, 1867/1924). Previous research has demonstrated the Helmholtz-Kohlrausch effect in observer judgements of perceived surface reflectance and colour brightness (Nayatani, 1998; Wyszecki, 1967), and a recent study found a correlation between perceived colour brightness and the magnitude of pupil contraction (Suzuki et al., 2019). Based on a Bayesian ideal observer model of the human visual ecology, combined with fMRI brain scans, Corney et al (2009) proposed that the anatomical base for the Helmholtz-Kohlrausch effect is likely to be situated in the primary visual cortex (V1) and not earlier in the visual processing trajectory. This could implicate that V1 is perhaps more sensitive to the brightness of colours in young adults than in senior adults, which would support my first hypothesis that young adults respond more sensitively to sensory information than senior adults.

When I analysed the pupil responses to light and saturated colours further, I found that young adults showed equally strong pupil contractions in response to saturated colours as to light colours, providing further evidence for an influence of the Helmholtz-Kohlrausch effect on pupil contractions in young adults. In addition, young adults showed significantly stronger pupil contractions in response to the colour room images, compared to the colour field images, with the exception of the light colours images in the print presentations. This finding is an indication that the imagined spatial dimensions of the colour room images, intensified the colour experience in young adults, leading in turn to a greater pupil constriction.

The fact that I did not observe this effect in the light colour prints condition, could possibly be explained by the lower contrast of the spatial elements in the light colour rooms due to the high luminance levels, meaning they might been perceived as less 3-dimensional. In senior adults – independent of neurological health – I only found significant effects of luminance on the pupil constrictions and no effects of colour saturation or imagined spatial dimensions. These findings are congruent with my first hypothesis, but I would have expected more divergent pupil responses in the participants living with dementia, especially in those who had been diagnosed with a form of dementia that is known to affect spatial perception and orientation such as Posterior Cortical Atrophy and Typical Alzheimer's Disease for instance.

**Internal state evaluation discussion**

While the depicted spatial dimensions of the colour images only had a significant effect on the pupil contractions in young adults, I found an opposite effect in the affective responses to the colour images.

On average, senior adults – independent of neurological health – rated the colour room images significantly more negative than the colour field images in both the digital and print presentations. Evidence that these were effects of imagined spatial dimensions of the colour room images, rather than visual perception, comes from the fact that the pupil responses of senior adults were the same for the colour field and room images.

The affective responses to colour images of young adults on the other hand, were not influenced by depicted spatial context, but they did significantly vary across the different material presentations of the colour images. Young adults rated the print colour field images significantly more positive than the digital colour field images. This finding was also reflected by a higher percentile of young adults having a preference for the print colour images over the digital versions, compared to the senior adults. Both findings provide further evidence of a greater sensory sensitivity in young adults, supporting my first hypothesis. The finding that the affective responses to colour images in senior adults were more influenced by depicted spatial context compared to young adults appears to contradict the findings of the pupil responses. An interpretation that could possibly align these findings however is that senior adults might have experienced stronger top-down effects of imagined spatial context in their affective responses to the colour images.
The mental operation Imagined Objects/Scenes in the Social Brain Atlas is associated with anterior hubs in the Animation and the Construction Network (Alcala-Lopez et al., 2017).
The stronger pupil contractions in response to the imagined spatial dimensions of the room images in young adults could be driven by the Animation Network (bottom-up effect).

The more negative affective responses to the imagined spatial dimensions of the rooms images in senior adults could in turn be driven by the Construction Network (top-down effect).
This interpretation would be in line with both my first and my second hypothesis, and show that young adults are more sensitive to sensory information and senior adults rely more on semantic information in their responses to visual artworks and complex images.

The affective responses of senior adults living with dementia were on average not significantly influenced by either material presentation or depicted spatial context, which is at odds with my third and fourth hypotheses given that many of the dementia profiles in the Social Brain Atlas involved anterior hubs in the Animation and the Construction Network, in particular Behavioural Frontotemporal Dementia.

I found several significant differences in responses to specific colour images across the 3 research cohorts. Young adults rated saturated yellow most positively, except in the digital room images, where they preferred saturated orange the most. They responded most negatively to Pantone 448C in both the digital and print condition, independently of depicted spatial context. This finding replicates the outcomes of the survey that was commissioned by the Australian government in 2012 among 1000 smokers, which found that Pantone 448C was the most unpleasant colour.

Senior adults also gave saturated yellow the most positive rating on average in the digital colour field presentations, but in the digital room presentations they rated saturated green most positively. In the print presentations, they rated saturated orange most positively, independently of depicted spatial context.
Senior adults rated black as the most negative colour in the digital colour presentations and the print colour rooms images, but they rated Pantone 448C most negatively in the print colour fields condition.

While not as unanimous as in young adults, this finding provides further support for the claim that Pantone 448C might truly be a universally disliked colour (at least among Western populations).

In this light, it was a salient finding that 36% of the senior adults living with dementia rated the Pantone 448C print room images significantly more positive than the neurologically healthy senior adults did on average. There was no particular type of dementia more strongly associated with this finding, suggesting it might be a general effect of dementia. The ecological valence theory of human colour preferences (Palmer and Schloss, 2010) could offer a possible explanation for this effect. The ecological valence theory proposes that people's colour preferences result from their average responses to colours over the course of their lives. Certain colours such as dark yellow are generally more disliked by adults than children, because they have learned to associate the colour with aversive visual stimuli (such as faeces and decay for instance). A similar learned negative response could also well apply to the sluggish brown of Pantone 448C.
The finding that people living with dementia often found this colour to be less aversive than neurologically healthy senior adults, might therefore indicate that their affective responses to colours were less informed by semantic knowledge and perhaps more akin to the instinctive colour preferences of young children before they learn ecological colour associations.
This interpretation would be congruent with my fourth hypothesis which stated that senior adults living with dementia have in general a reduced access to their semantic knowledge base.

I should note however, that those senior adults living with dementia who rated Pantone 448C significantly more positively, rated all the colours in general very positively. This does not necessarily undermine the argument I made earlier, but it does suggest that a potentially smaller influence of semantic knowledge on their colour preferences is likely not specifically focused on this particular colour. It's more likely the case that the difference in their affective response to Pantone 448C, compared to the average affective response of the neurologically senior adult was the most pronounced. Apart from Pantone 448C, I found no significant differences in the colour preferences of the senior adults living with dementia, compared to the neurologically healthy senior adults across both material presentations and depicted spatial contexts.

The increased autonomic arousal that I measured in several senior adults living with dementia during the Colour Spaces experiments should also be taken into consideration in relation to their affective responses to colours, as it could be a sign of heightened sensitivity to colour stimulation. The increased autonomic arousal in particularly the left wrist could reflect that the colour stimulations were experienced as pleasant, but it could also be an indication of over-stimulation. It could well be that both explanations apply simultaneously, which signals that colours should be used with careful consideration in environmental designs for senior adults living with dementia.

I also found an overall congruence between the affective responses to the colour images between young and senior adults, but young adults rated saturated yellow more positive, whereas the senior adults rated the saturated red more positive. Perhaps this finding can be explained by the Helmholtz-Kohlrausch effect. The observed reduced sensitivity to colour saturation in senior adults might have meant that the intense brightness of the saturated red that was modelled on Barnett Newman's painting series 'Who's Afraid of Red Yellow and Blue' was a more pleasant experience for them, than for the young adults who were perhaps more likely to be overwhelmed by this colour.
Young adults rated the white and the saturated yellow room prints more positive than senior adults, but saturated yellow was also perceived a strongly positive colour by senior adults.
Both young and senior adults rated saturated orange as strongly positive. Bright yellow and orange are colours that are widely used in social environments to draw people's attention. My research findings show that this effect is also driven by their affective influence, in addition to their perceptual properties.

Pantone 448C, as well as dark yellow were rated very negatively on average by the neurologically healthy adults, whereas saturated orange and yellow were rated very positive on average. Since Pantone 448C and the saturated orange hue, as well as the dark and saturated yellow were on the same chroma axis, separated only by a degree of lightness, this suggests that lightness and specifically brightness, plays a crucial role in people's affective responses to colours. This suggestion of a strong link between colour brightness and affective response is supported by the ranking order of the affective ratings that young and senior adults gave to the colour spaces, which showed a colours gradient from bright to dark that corresponded with affective ratings from positive to negative (Figure 78).

**Electrodermal activity discussion**

During the Colour Spaces experiments, the electrodermal activity (EDA) flux was lower than the personal average for all the neurologically healthy participants. This finding suggest that the Colour Spaces research sections triggered less autonomic arousal, compared to the other research sections in this study.
The neurologically healthy senior adults showed significantly asymmetric EDA flux patterns, but only during the Digital Colour Spaces experiment, with comparatively higher electrodermal activity in the right wrist. During this experiment, there was also a significant difference in the EDA flux in the left wrist between young and senior adults, with higher electrodermal activity in the left wrist of young adults. Based on previous research that found that an asymmetric increase in left-sided electrodermal activity had a 50% change of being associated with positive emotional arousal (Lanteaume et al., 2007), these findings could suggest that young adults experienced a higher positive emotional arousal during the digital colour presentations, compared to senior adults. Alternatively, this finding could possibly also be indicative of a greater sensory response to colours in young adults, especially brightness, which I reflected on in the previous sections. Both interpretations could be aligned with my first hypothesis, which stated that young adults respond more sensitively to sensory visual information.
Several senior adults living with dementia showed a higher EDA flux in the left wrist during the Colour Spaces experiments, compared to the neurologically healthy senior adults. The left wrist EDA flux difference was the greatest in the two participants diagnosed with Frontotemporal dementia, but I also observed significant differences in a participant living with Typical Alzheimer's Disease and a participants living with Nonfluent Primary Progressive Aphasia. A participant who was diagnosed with an unspecified form of dementia with suspected subcortical involvement also had an elevated EDA flux in the left wrist.
In these participants, the left wrist EDA during the Colour Spaces experiments was higher than the personal average across all research sections. None of these participants had shown significantly different pupillary responses to the colour images, compared to the neurologically healthy adults, suggesting it was less likely that this finding was caused by an increased sensory sensitivity to colours and more likely that the increased electrodermal activity in the left wrist reflected a positive emotional arousal. However, it can not be ruled out that the pupillary and electrodermal responses to the sensory properties of colours might be dissociated and future research will have to further elucidate this. When relating this finding to the functional profiles of these dementia syndromes, an increased autonomic arousal response to colours would be most likely driven by the altered network dynamics in the anterior Animation Network, which includes core hubs of the limbic system that is thought to drive emotional autonomic arousal (Boucsein, 2012).

Follow-up research with larger cohorts will have to be conducted to refine and validate the Colour Spaces experiments as reliable instruments to assess visual imagination and other social brain functions in healthy ageing and dementia.

## 4.4 SUMMARY AND CONCLUSIONS

In this study I set out to study multi-modal aspects of visual imagination in healthy ageing and dementia, focusing on visual art and complex images in the context of the social brain.
In this section I have summarised the key research findings of the Thinking Eyes and Colour Spaces projects and reflected on how they complemented each other in elucidating the research questions and hypotheses. In addition, I have also elaborated on the limitations of this study, as well as directions for future research.

**Key findings Thinking Eyes experiments**

- The visual exploration patterns of visual artworks and complex images showed temporal changes that could be aligned with different processing phases in the human brain.

- During the initial perceptual processing phase (0 – 250 ms), the gaze of neurologically healthy adults stayed mostly fixated on the image centres, where participants had been prompted to look beforehand.

- During the initial perceptual processing phase (0 – 250 ms), the gaze of senior adults living Posterior Cortical Atrophy stayed significantly less fixated on the image centres, compared to neurologically healthy senior adults. This effect was also observed to a lesser extend in senior adults living with Typical Alzheimer's Disease.

- During the gist inference phase (250 – 750 ms), top-down effects of social salience significantly influenced the visual exploration of figurative visual artworks and complex images, but not the distorted versions of the images.

- During the construct inference phase (>750 ms), in addition to social salience, auditory processing and different viewing strategies also had significant top-down effects on the visual exploration of figurative visual artworks and complex images.

- A novel social salience model of visual exploration, based on the principles of foveal vision and the functional profiles of the Social Brain Atlas, predicted the visual exploration patterns of figurative visual artworks and complex images significantly better than an alternative model that only took perceptual factors into account.

- Looking at visual artworks and complex images with the Visual Thinking Strategies (VTS) method made all participants – independent of age and neurological health – explore the images in general significantly more compared to when they listened to contextual information, and made them focus especially on animate elements (human and animal faces, hand actions and other body elements).

- Looking at visual artworks and complex images while listening to contextual information from a museum catalogue made all participants – independent of age and neurological health – explore the images in general significantly less compared to the VTS method, but made them focus slightly more on inanimate elements (human made objects, built environment, natural, text and number elements).

- In young adults, looking at visual artworks and complex images with the Visual Thinking Strategies (VTS) method from their personal perspective significantly increased their resonance with the images, while listening to contextual information decreased their resonance with the images significantly.

- In senior adults, looking at visual artworks and complex images with different viewing strategies did not significantly affect their resonance with the images.

- In senior adults living with dementia, looking at visual artworks and complex images while listening to contextual information decreased their resonance with the images significantly.

- Auditory processing had specific top-down effects on the visual exploration patterns of visual artworks and complex images in senior adults living with various forms of dementia during the silent viewing phase that followed an audio recording.

- A novel quantitative analysis method for VTS speech samples showed that individual speech profiles were stable in healthy ageing, but showed both general and specific effects of dementia. The most likely speech parameters to be affected were the content words and semantic words ratios.

- Electrodermal activity, indicative of autonomic arousal, was considerably lower during the Thinking Eyes experiments in senior adults living with dementia, compared to the standard neuropsychometric test section of the research.

**Key findings Colour Spaces experiments**

- The visual exploration patterns of monochromatic colour space images showed temporal changes that could be aligned with different processing phases in the human brain.

- During the initial perceptual processing phase (0 – 250 ms), the gaze of neurologically healthy adults stayed mostly fixated on the image centres, where participants had been prompted to look beforehand.

- During the initial perceptual processing phase (0 – 250 ms), the gaze of senior adults living Posterior Cortical Atrophy stayed significantly less fixated on the image centres, compared to neurologically healthy senior adults. This effect was also observed to a lesser extend in senior adults living with Typical Alzheimer's Disease or Behavioural Frontotemporal Dementia.

- During the gist inference phase (250 – 750 ms), depicted spatial context significantly influenced the visual exploration of colour space images.

- During the construct inference phase (>750 ms), the effects of depicted spatial context significantly on the visual exploration of colour space images became more pronounced.

- A novel social salience model of visual exploration, based on the principles of foveal vision and the functional profiles of the Social Brain Atlas, predicted the visual exploration patterns of colour space images no better than an alternative model that only took perceptual factors into account.

- The visual exploration patterns of colour room images showed significant effects of healthy ageing and dementia, which might be related to a reduced contrast sensitivity in healthy ageing and both physiological and attentional impairments in various forms of dementia.

- Young adults showed significantly stronger pupil contractions to light and saturated colours, compared to senior adults. The results showed no significant differences in the pupil responses to dark colours.

- The equally strong pupil response to light and saturated colours in young adults, despite a higher luminance of the light colours could be explained by the Helmholtz-Kohlrausch effect which describes that strongly saturated colours have a higher perceived brightness than colours with the same luminance but a lower saturation.

- The finding that the Helmholtz-Kohlrausch effect was only observed in the pupil contractions of young adults, suggests a reduced sensitivity to colour saturation in senior adults, independent of neurological health.

- The affective responses to monochromatic colour spaces were broadly aligned with the brightness of the colours, with brighter colours on average evoking more positive feelings in participants regardless of age and neurological health.

- The affective responses of neurologically healthy young and senior adults to the colour space images replicated a 2012 survey under 1000 smokers commissioned by the government of Australia that found that Pantone 448C was generally experienced as the most unpleasant colour.

- In contrast, the Pantone 448C colour field print was rated significantly more positively by 36% of the senior adults living with dementia, compared to neurologically healthy adults.

- The affective responses of young adults to monochromatic colour space images were only significantly affected by material presentation, whereby they preferred the print versions over the digital colour images.

- The affective responses to monochromatic colour space images of senior adults, independent of neurological health, were only significantly affected by depicted spatial context, whereby the colour rooms were rated more negatively.

- The majority of all participants, independent of age and neurological health, preferred the colour prints over the digital colour presentations. The neurologically healthy senior adults  had more often no preference than the young adults and the senior adults with dementia more often preferred the digital colours than the neurologically healthy senior adults.

- Young adults and various senior adults living with dementia had a significantly higher electrodermal activity in the left wrist during the Digital Colour Spaces experiment, compared to the neurologically healthy senior adults. This could perhaps be indicative of a more positive emotional arousal in young adults and senior adults living with dementia in response to digital colours, but it could also reflect a stronger autonomic response to the sensory colour stimulations.

The Thinking Eyes and Colour Spaces projects complemented each other by exploring different aspects of multi-modal responses to colours, visual artworks and complex images, contextualised in the framework of the Social Brain Atlas. The research findings from the two projects were congruent with each other and provided support for most of my hypotheses. Before summarising how each project elucidated the research questions and hypotheses that I set out to investigate in this study, I have described them once more on the next page.

**Research questions:**

Q1. How does visual perception relate to visual imagination and other social brain functions?

Q2. Does healthy ageing have an effect on visual imagination and other social brain functions?

Q3. Do different forms of dementia have general effects on visual imagination and other social brain functions?

Q4. Do different forms of dementia have specific effects on visual imagination and other social brain functions?

**Hypotheses:**

H1. Neurologically healthy young adults are likely to show more sensitive perceptual (bottom-up) and flexible cognitive (top-down) behavioural responses to visual artworks and complex images than neurologically healthy senior adults.

H2. Neurologically healthy senior adults are likely to rely more strongly on semantic knowledge in cognitive (top-down) responses to visual artworks and complex images than neurologically healthy young adults.

H3. The functional profiles of the dementia syndromes that I have mapped onto the Social Brain Atlas will align with the behavioural measurements.

H4. Given the prominence of semantic language in all dementia profiles in the Social Brain Atlas, it is likely that dementia is in general associated with decreased semantic language access in responses to visual artworks and complex images, compared to neurologically healthy senior adults.

The combined findings of the Thinking Eyes and Colour Spaces experiments showed that visual perception informs visual imagination and other social brain functions in various ways, with measurable effects of healthy ageing and dementia from the gist inference phase (250 – 750 ms) onwards.

The Thinking Eyes experiments showed the strongest affects of healthy ageing and dementia on auditory processing, viewing strategies and speech production (top-down responses) in the visual exploration of and resonance with visual artworks and complex images. The findings provided the most convincing support for my first two hypotheses as well as my fourth hypothesis are likely to be related to functional dynamics of the two highest processing levels of the Social Brain Atlas: the Interaction and the Construction Network. The results of the thinking Eyes also showed cautious support for my third hypothesis, but further research with a larger cohort of senior adults living with various forms of dementia will have to be conducted to be able to make more substantial inferences.

The Colour Spaces experiments showed strong effects of healthy ageing and dementia on both sensory processing (bottom-up) and internal representations (top-down) of monochromatic colour images. The findings also provided the most convincing support for my first two hypotheses as well as my fourth hypothesis and indicated a differentiated involvement of all four hierarchical processing levels of the Social Brain Atlas. The results of the Colour Spaces experiments also showed cautious support for my third hypothesis, but again, further research with a larger cohort of senior adults living with various forms of dementia will have to be conducted to be able to make more substantial inferences.

## 4.5 LIMITATIONS

This study inevitably also faced limitations, which were both of conceptual and practical nature. In my introduction of the Social Brain Atlas, I already mentioned several limitations in its scope and underlying research methods. A limitation of my own visual representations of the Social Brain Atlas, was that due to the sheer volume of information, the word clouds that I placed around the brain maps were necessarily in a very small font. I have attempted to mitigate this limitation by enlarging the word clouds in the separate network figures as much a possible, and in addition I have designed a magnifying instrument to further improve their legibility.

One of the major limitations of the neuroscientific experimental research were the small cohorts sizes, which impacted on the statistical power of the quantitative data analyses. Especially the group of senior adults living with dementia was very small with 11 – 14 participants in each experiment, who also had different dementia diagnoses. Recruitment had proven to be a substantial hurdle, which was also related to the fact that participants had to donate a minimum of 3 hours of their time, which was a big ask. The upside was that 11 out of the 14 participants living with dementia and all of the neurologically healthy adults took part in all 6 research sections, which resulted in a uniquely comprehensive overview of the multi-modal dynamics of visual imagination in relation to visual art and complex images, placed in the context of the social brain.

The research cohorts were mostly well-balanced with respect to education and visual art experiences, but the majority of the research participants in my neuroscientific experiments had a white ethnicity. I had explicitly set out to recruit people from diverse ethnic and cultural backgrounds, but unfortunately I did not succeed in fulfilling the ambition I had set for myself in this respect. Ideally I would have also included more female senior adults living with dementia in my research, but within the time limits of the experimental research this was not feasible.

In designing the neuroscientific experiments, I had to find a balance between the expansive qualities of visual art and colour experiences and the constraints of carefully controlled experimental conditions. This meant that the research participants had to engage with the colour and visual art images in the two neuroscientific experiments in artificial viewing conditions. They were sat in a chair at the narrow end of a small Table, with their heads immobilised so that the eye tracking camera that was placed in front of them on the Table could make accurate measurements. The Table mounted eye tracking technology also required a minimal distance of 75 cm between the eyes and the image display, which was much further away than people usually view images of approximately A3 paper-size proportions. This also meant that participants, especially those with poorer eye sight, likely struggled to properly see the finer details in the images.

Another limitation was the range of visual artworks and complex images I could select for my experimental stimuli. My research took place within the context of a 2-years research residency at the Wellcome Collection in London which has strong medical history focus, which is reflected in their art collections.

## 4.6 FUTURE DIRECTIONS

Following on from this study, I will strive to develop a fully interactive online version of the Social Brain Atlas, which would eliminate the obstacle of the very small font in the word clouds, as it would be able to zoom in and out as desired. An digital Social Brain Atlas would also enable the use of animations, which could show the dynamics between the different network levels.

An important focus of future research will be to replicate and extend my research findings in larger cohorts of senior adults living with dementia, with well defined diagnoses that include biomarker and genetic information where possible. Functional neuroimaging experiments, using fMRI or MEG, will provide valuable insights into the neural correlates of the multi-modal social brain dynamics of visual imagination in relation to visual art and complex images.

This could also be a very important test of the Social Brain Atlas framework, particularly by linking art processing to other social, emotional and autonomic functions in healthy ageing and various dementia syndromes. Dementia syndromes are much better models intrinsically than other lesion models (e.g., stroke) to probe the hypothesis that brain diseases are network based disorders. Future research will also focus on validation of the novel visual rating scales that I developed for this study.

Beyond academia, I will use the findings of this study to create programmes for art museums and other cultural institutions with my company The Thinking Eye, that aim to strengthen social engagement, careful observation, divergent thinking and communication skills, through visual art interactions.

Informed by the effects of healthy ageing and dementia that I observed, I will tailor the design of these programmes to age and neurological health. Furthermore, the connections I made between my experimental research and the Social Brain Atlas have been only of a theoretical nature in this study.

I will also develop new art experiments which will allow the general public to freely explore their sensory, emotional and conceptual responses to visual artworks and complex images. In parallel, I will further develop the Perspectacles (see under the Appendices 5.3) and other optical instruments that I designed as part of the artistic research of this study with the aim to make them commercially available. In future research, I will also investigate whether their perceptual effects could potentially be of benefit to people who have neurological conditions that lead to altered visual perceptions, such as the rare form of dementia Posterior Cortical Atrophy, but also more common neurological conditions as migraine for instance.
In collaboration with the co-founder of the Visual Thinking Strategies (VTS) method Philip Yenawine, I will work towards developing a socially engaging digital platform for senior adults which creates personal speech profiles based on verbal responses to visual artworks. If people engage with this platform over the course of years, it could be possible to pick up on early signs of dementia, based on subtle changes in speech construction.
Yenawine's company Inq has already developed a digital platform for desktop and mobile devices that engages audiences with visual artworks using the VTS method and this existing infrastructure will be further modified to enable the collection, transcription and automated analysis of high-quality speech recordings.

# 5. APPENDICES

## APPENDIX 5.1
### THINKING EYES QUESTIONNAIRE

This questionnaire is about how you relate to visual art. It doesn't matter how much you know about visual art or how much you like it, we're interested in your personal responses and there are no right or wrong answers.

* = required answer

I. Please enter your Participant Code in capital letters:

### A. Background Questions

II. What is your age?*

III. What is your gender identity?*
1. Female
2. Inter
3. Male
4. Rather not say

IV. Which hand do you use to write with?*
1. Left
2. Right
3. Both

V. Where you born in the United Kingdom?*
1. Yes
2. No

VI. If not, where were you born?

VII. Did you ever live in a different country?*
1. Yes
2. No

VIII. If yes, where was this and for how long?

IX. What is the highest level of education you have completed?*
1. School Leaver: Did not complete GCSEs/O-Levels
2. GCSEs/O-levels
3. AS Levels
4. A-levels
5. University Degree (e.g. BA, BSc)
6. Master's Degree (e.g. MA, MSc)
7. PHD/Doctorate

X. Is English your first language?*
1. Yes
2. No

XI. If no, are you fluent in English?*
1. Yes
2. No

### B. Health Questions

XII. Do you have a visual impairment?*
1. Yes
2. No

XIII. If you said 'yes' to having a visual impairment (e.g. colour blindness), please describe it here:*

XIV. Do you have a hearing impairment?*
1. Yes
2. No

XV. If you said 'yes' to having a hearing impairment, please describe the impairment here:*

XVI. Do you consider yourself to have dyslexia?*
1. Yes
2. No

XVII. How claustrophobic are you?*
1. Not at all
2. Slightly
3. Severely

XVIII. Do you have a neurological condition?*
1. Yes
2. No

XIX. If you said 'yes' to having a neurological condition (e.g. autism, stroke, epilepsy or dementia), please describe it here:

XX. Does anyone in your family have a neurological condition?*
1. Yes
2. No

XXI. If you said 'yes' to a family member having a neurological condition, please mention the condition and your relationship to the person here:

**C. Visual Art Background Questions**

XXII. How often have you seen the visual artworks in the Reading Room of the Wellcome Collection?*
1. Never
2. Once
3. A few times
4. Many times

XXIII. How often do you look at visual art in general?*
1. Daily
2. Weekly
3. Monthly
4. A few times a year
5. Hardly ever

XXIV. What do you value about looking at visual art? (multiple answers possible)*
1. Visiting special spaces, such as museums and galleries
2. Experiencing a sense of beauty
3. Admiring artistic craftsmanship
4. Feeling an emotional connection
5. Recognising familiar artists and favourite artworks
6. Having new experiences and insights
7. Being transported into other worlds
8. Reflecting on my personal and cultural identity
9. Taking the time to look at things carefully
10. Other,.....
11. Nothing

XXV. What type of visual art do you appreciate?*
1. Figurative
2. Abstract
3. Both
4. Neither
5. Other

XXVI. What do you pay most attention to when looking at visual art?
(multiple answers possible)*
1. Colours
2. Use of light
3. Forms
4. Spaces
5. Movement
6. Patterns
7. Textures

8. People
9. Animals
10. Objects
11. Emotions
12. Narrative
13. Concept
14. Nothing

XXVII. How often do you make visual art yourself?*
1. Daily
2. Weekly
3. Monthly
4. A few times a year
5. Hardly ever

XXIII. What motivates you to make visual art? (multiple answers possible)*
1. I enjoy making things with my hands
2. Making visual art enhances my well-being
3. Making visual art allows me to give expression to my thoughts and feelings
4. I wish to connect to other people through my visual art
5. My aim is to make a living out of making visual art
6. Nothing
7. Other,

XXIX. What stops you from making visual art? (multiple answers possible)*
1. I do not enjoy making things with my hands
2. It puts too much strain on my well-being
3. I have a disabling physical or mental impairment
4. I lack the technical skills
5. I lack the imagination
6. I lack the confidence
7. I don't have the time
8. I don't have the space
9. Nothing
10. Other,

XXX. How much training have you had in making visual art?*
1. I completed a formal education to become a practicing visual artist
2. I have done a course or courses in making visual art
3. I taught myself how to make visual art
4. I have little to no experience in making visual art

XXXI. How much knowledge do you have of visual art history and theory?*
1. I completed a formal education in visual art history and/or theory
2. I have done a course or courses in visual art history and/or theory
3. I have taught myself about visual art history and/or theory
4. I have little to no knowledge of visual art history and theory

## APPENDIX 5.2
## ELECTRODERMAL ACTIVITY (EDA) ANALYSIS PROTOCOL

### Introduction
Every research participant wore where possible an Empatica E4 wristband on each wrist. The same set of 4 Empatica wristbands was used throughout the data collection phase to minimise noise variance.

### Data collection
For every participant the electrodermal activity (EDA) was measured continuously from both wrists during the research visit(s). The Empatica data was exported from a secured website as .csv files in which the electrodermal activity was expressed as microsiemens with a sample rate of 4 HZ and an Unix timestamp indicating the start of the recording session.

**Data segmentation**
To segment the recorded electrodermal activity, the data were imported into a custom-made Excel template whereby a separate file was created for each participant. Two separate templates were created for research participants who had completed all the activities within a single visit and those who had them spread over two visits to prevent strong fatigue effects.

The Empatica software recorded one Unix timestamp at the start of the recording session, which I copied into a cell in Excel and turned into an incremental timeline with the sampling rate of 4HZ. This meant that for each data row a value of 0.25 was added to the Unix timestamp. The data was then segmented in time windows for each wrist – including only values larger than zero – corresponding with the following Excel formula:

EDAtw_n=IF(AND(An>0, Bn>C$n,Bn<D$n), An," ")

Were An stands for a particular EDA recording, Bn stands for the Unix time code corresponding to An, C$n stands for the start time of the defined research section and D$n stands for the end time of the defined research section, both in Unix time code.

In my research, I defined 6 research time windows. Time window 1 consisted of the neuropsychometric section of the research visit and was defined by the time period between the start of the Empatica recording session and the start of the first eye tracking experiment of that research visit. For participants who took part over two visits, time window 1 during the first research visit consisted of the Thinking Eyes questionnaire and the Mood Shade Scale. Time window 1 during the second research visit consisted of the abbreviated WASI for neurologically healthy participants or the ACE-III for dementia participants, the Mood Shade Scale and the Matching Colours Scale.

Time windows (TW) 2-6 corresponded to the Thinking Eyes and Colour Spaces experiments in the following order:

TW2: Thinking Eyes Snapshots experiment
TW3: Thinking Eyes Perspectives experiment
TW4: Thinking Eyes Panoramas experiment
TW5: Digital Colour Spaces experiment
TW6: Print Colour Spaces experiment

These time windows were defined individually for each research participant based on the recorded start times by the Eyelink software of the first and last trial of the corresponding eye tracking experiment. These timestamps were obtained from the data source overview in the Data Viewer software that was used to pre-process the eye tracking data. The start and end times of each research time window were encoded as RFC 2822 timestamps in the format dd/mm/yyyy hh:mm:ss.

For each research participant the RFC 2822 timestamps of the start and end times of each experiment were converted to Unix timestamps using the following formula:

Unix timestamp = (TWx-DATE(1970,1,1))*86400

Where TWx stands for a RFC 2822 timestamp.

For most experiments the duration of the last trial was less than 1% of the total duration of the experiment and no extra time was added to the timestamps. However, the third Thinking Eye experiment ‘Panoramas’ only consisted of two trials of a minimum of 4.5 minutes each. Therefore, the timestamp that indicated the start of the 2nd trial in that experiment was a less accurate time marker for the end time of the experiment time window and a compensatory 4.5 minutes were added to the RFC 2822 timestamp of the 2nd (last) trial of that experiment.

**Data analysis**
From the resulting segmented data strings of recorded electrodermal activity, the mean value and standard deviation were calculated with standard Excel formulas: =AVERAGE(*data string*) and =STDEV(*data string*).

## APPENDIX 5.3
## VISUAL DOCUMENTATION ARTISTIC RESEARCH

### Introduction

My artistic research in the form of optical instruments and visual art objects and installations aimed to complement the neuroscientific projects by exploring the research questions and hypotheses in different dimensions than verbal language.

The resulting exhibition was presented during my PHD defence in my studio at the Limehouse Art Foundation, London. Building on the principles of the Visual Thinking Strategies (VTS) method, the viewer is invited to explore the visual documentation initially without any contextual information, guided by the questions:

"What is going in this image/installation?"
"What do you see that makes you say that?"
"What more can you find?"

On page 226 a brief contextual description is provided of the items that are documented in this appendix.

**Appendix 5.3.1**





**Appendix 5.3.2**

**Appendix 5.3.3A**



# Appendix 5.3.3B

**Appendix 5.3.4A**



# Appendix 5.3.4B

**Appendix 5.3.5A**



# Appendix 5.3.5B

**Appendix 5.3.6A**



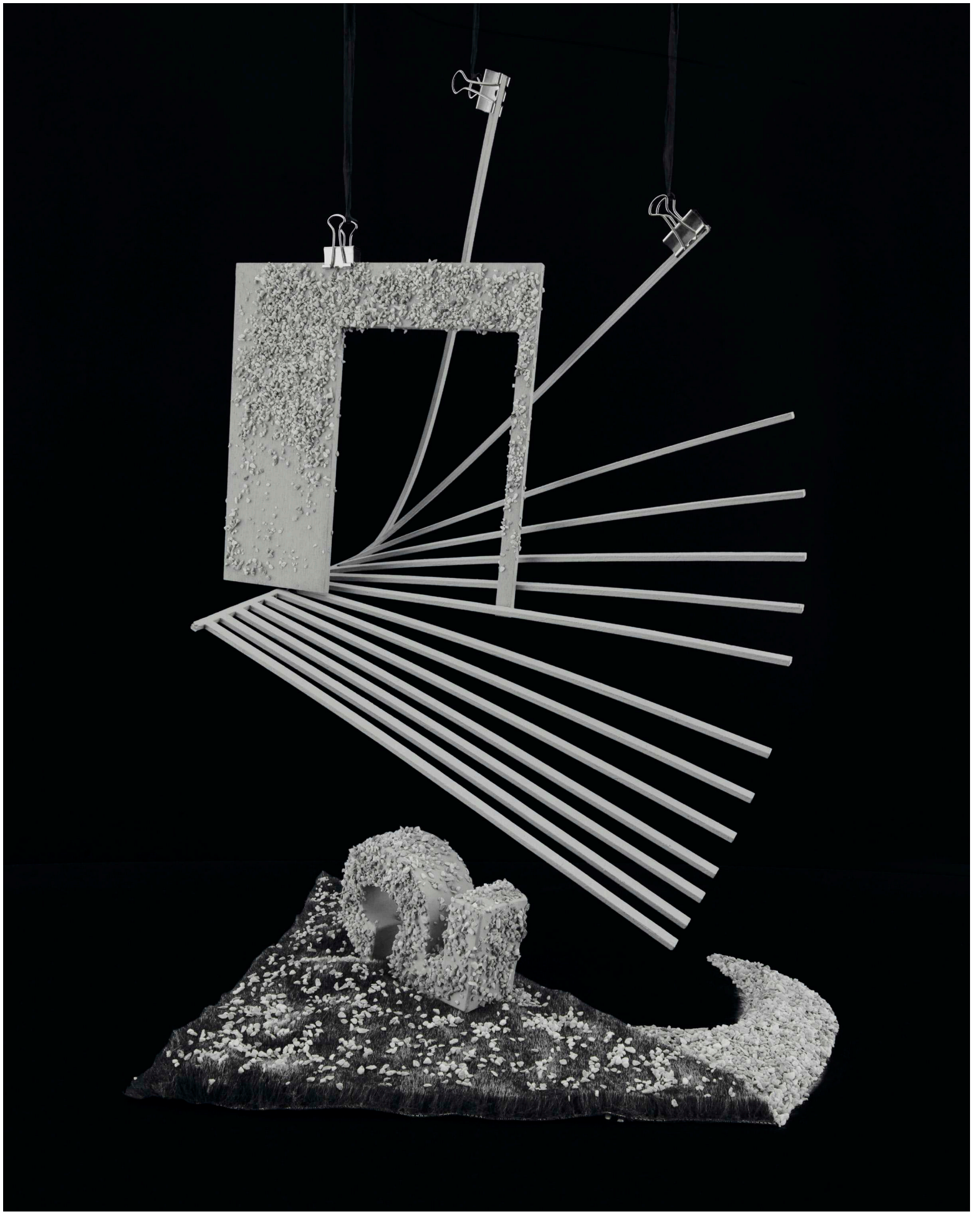
# Appendix 5.3.6B

**Appendix 5.3.7A**



# Appendix 5.3.7B

**Appendix 5.3.8A**



## Appendix 5.3.8B















**Appendix 5.3.10A**



**Appendix 5.3.10B**



**Appendix 5.3.10C**



**Appendix 5.3.10D**



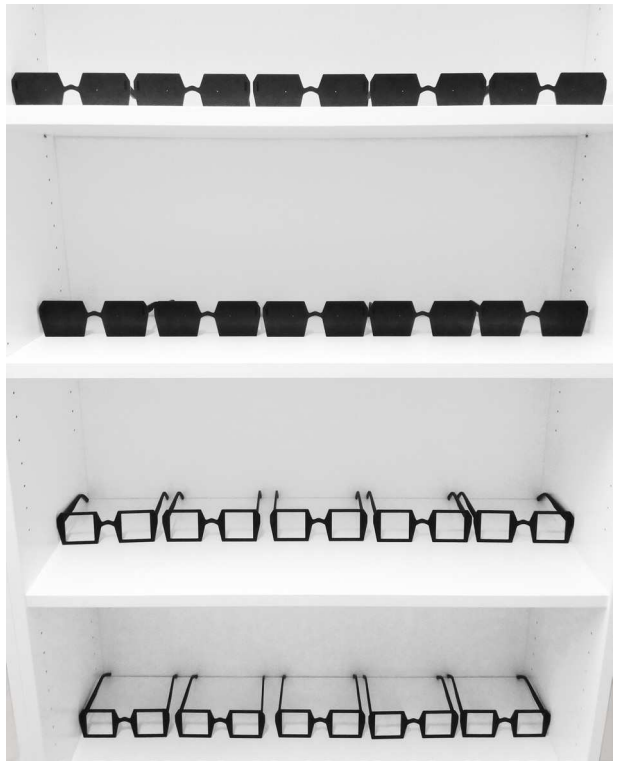
**Appendix 5.3.10E**



**Appendix 5.3.10F**



**Appendix 5.3.10G**



## CONTEXTUAL INFORMATION ARTISTIC RESEARCH

**Appendix 5.3.1**
Scalar: A magnifying glass that I designed to enlarge the word clouds of the Social Brain Atlas in this thesis (Figures 1 - 39).

**Appendix 5.3.2**
Mindmodels: Sculptural models I created for 6 photographic works (Appendix 5.3.3A – 5.3.10A) that aimed to explore the sensory, emotional and conceptual dimensions of the perceptual categories from the inanimate domain of the Social Salience Model of Visual Exploration (Figures 53, 59, 60):

- Human made objects
- Built environment elements
- Natural elements
- Text elements
- Number elements

The colour choices and scene compositions built further on the findings of the Thinking Eyes project (section 4.2) and the Colour Spaces project (section 4.3). The saturated blue, red and yellow wall panels were among the most positively rated colours.
The dark yellow, Pantone 448C and pure black were among the most negatively rated colours. The white and black backgrounds in the photographic works reflected on the influence of luminance in people's affective responses to colours (Figure 78).

**Appendix 5.3.3A – 5.3.8B: Installation dimensions**
Photographic works: Canson Baryta print in ash wooden box frame stained in white or black with standard glass, 508 x 635 mm. Wall panels: Plywood sheet 1220 x 2440 mm 18 mm thick.

**Appendix 5.3.3A – B: Art experiment # 01**
Photographic model of inanimate elements with ground colours International Klein Blue and Barnett Newman Red in a pure white context, paired with an International Klein Blue colour field. Wall panel angle: 45°.

**Appendix 5.3.4A – B: Art experiment # 02**
Photographic model of inanimate elements with ground colours Light Red, Barnett Newman Red and Muted Green in a pure white context, paired with a Barnett Newman Red colour field. Wall panel angle: 35°.

**Appendix 5.3.5A – B : Art experiment # 03**
Photographic model of inanimate elements with ground colours Saturated Yellow, Saturated Orange and International Klein Blue in a pure white context, paired with a Saturated Yellow colour field. Wall panel angle: 25°.

**Appendix 5.3.6A – B: Art experiment # 04**
Photographic model of inanimate elements with ground colours Muted Yellow, Dark Yellow and Saturated Yellow in a pure black context, paired with a Dark Yellow colour field.
Wall panel angle: 25°.

**Appendix 5.3.7A – B: Art experiment # 05**
Photographic model of inanimate elements with ground colours Muted Orange, Dark Green and Natural Wood in a pure black context, paired with a Pantone 448C colour field.
Wall panel angle: 35°.

**Appendix 5.3.8A – B: Art experiment # 06**
Photographic model of inanimate elements with ground colours Light and Dark Grey in a pure black context, paired with a pure black colour field. Wall panel angle: 45°.

**Appendix 5.3.9A – C**
Installation shots of the Art experiments #1 – #6 as described under Appendices 5.3.3A – 5.3.8B.

**Appendix 5.3.10A – G**
Perspectacles: A series of optical instruments that I designed with the aim to investigate how they might influence visual perception while engaging with the photographic works and colour wall panels.

I made the following different Perspectacle designs:

- Foveal Perspectacle; these glasses aim to isolate the foveal vision by only letting light from the central 5% of the visual field come though 1mm pinholes (Appendix 5.3.10A)

- Colour Field Perspectacles; an acrylic glass frame (Appendix 10.3.10G) filled with two different colours of transparent acrylic glass for each eye (Appendix 5.3.10B, Appendix 5.3.10F), aligning with the binocular nature of human vision.

- Hemifield Colour Perspectacles; an acrylic glass frame (Appendix 10.3.10G) filled with two or more different colours of transparent acrylic glass (Appendix 5.3.10C, Appendix 5.3.10F) on each side, aligning with the division of human vision in hemi-fields.

- Quadrant Field Colour Perspectacles; an acrylic glass frame (Appendix 10.3.10G) filled with two or more different colours of transparent acrylic glass (Appendix 5.3.10D, Appendix 5.3.10F) on each side, aligning with the division of human vision in quadrant fields.

- Colour Line Perspectacles; these glasses place combinations of straight, wavy and jagged line gratings of transparent acrylic in various colours combinations, aligned with the Colour Spaces project, between the eyes and the visual field (Appendix 5.3.10E, Appendix 5.3.10F).

**Appendix 5.3.10F**
Overview of selection of acrylic inlays for the Perspectacles. During the exhibition of the art experiments, visitors were free to experiment with making their own combinations and share their experiences on a form (voluntary).

**Appendix 5.3.10G**
Overview of Foveal Perspectacles frames (top)
and Inlay Perspectacle frames (bottom).

## APPENDIX 5.4
## LITERATURE


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## APPENDIX 5.5
## DIVISION OF LABOUR

**SUPERVISION**

**Primary supervisor neuroscientific research**

Prof Jason Warren
Neurodegenerative Diseases
UCL Queen Square Institute of Neurology
Faculty of Brain Sciences
London, United Kingdom

**Primary supervisor artistic research**
Prof Jeroen Boomgaard
Lectoraat Art & Public Space
Gerrit Rietveld Academie
Amsterdam, the Netherlands

**Principal Investigator EPSRC research grant**
**Secondary supervisor neuroscientific research**
Prof Seb Crutch
Neurodegenerative Diseases
UCL Queen Square Institute of Neurology
Faculty of Brain Sciences
London, United Kingdom

**Secondary supervisor neuroscientific research**
Dr Aida Suarez Gonzalez
Neurodegenerative Diseases
UCL Queen Square Institute of Neurology
Faculty of Brain Sciences
London, United Kingdom

**NEUROSCIENTIFIC RESEARCH**
**Experimental design assistance**
Dr Sam Hutton
Consultant for SR-Research
Brighton, United Kingdom

**Ethics and recruitment assistance**
Ms Emilie Brotherhood
Project manager Created Out of Mind
Wellcome Collection, London, United Kingdom

**Public communications assistance**
Ms Kailey Nolan
Communications Officer Created Out of Mind
Wellcome Collection, London, United Kingdom

**Narrators eye tracking experiments**
Ms Bridie Rollins
External partnerships assistant Created Out of Mind
Wellcome Collection, London, United Kingdom

Mr Julian West
Co-Director Created Out of Mind
Wellcome Collection, London, United Kingdom

Ms Janette Junghaus
Project manager Created Out of Mind
Wellcome Collection, London, United Kingdom

Prof Paul Camic
Co-Director Created Out of Mind
Wellcome Collection, London, United Kingdom

**Research sessions assistance**
Ms Ivanna Pavisic, UCL PHD researcher
Ms Adrienne Shum, UCL BA student
Ms Ferozan Sarfaraz, graduate work experience

**Statistical analysis assistance**
Dr Jennifer Nicholas
Associate Professor Department of Medical Statistics
LSHTM, London, United Kingdom

**ARTISTIC RESEARCH**
**Technical and production assistance**
Mr Romain Meunier
Mr Darren Ellis
Mr George Walker
UCL Institute of Making
London, United Kingdom

**Public engagement assistance**
Ms Necole Schmitz
Ms Sara Brouwer

Ms Beth Munro
UCL Institute of Making
London, United Kingdom

Mr Chris Lovejoy
Ms Heather Ging
UCL Queen Square Institute of Neurology
Faculty of Brain Sciences
London, United Kingdom

**THESIS PRODUCTION**
**Proofreading**
Ms Laurens Krüger

## APPENDIX 5.6
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Darren Ellis
Tamsin Fessey
Heather Ging
Aida Suarez Gonzalez
Noemie Goudal
John Greenwood
Una Hamilton Helle
Darren Harvey-Regan
Emma Harding
Chris Hardy
Elizabeth Holton
Sam Hutton
Jeremy Johnson
Janette Junghaus
Charlotte Kremers
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Dirk van Leeuwen
Gerrit van Leeuwen
Rien van Leeuwen
Ruth van Leeuwen
Chris Lovejoy
Charles Marshall
Janice McLaren
Erik Meideros
Romain Meunier
Jennifer Nicholas
Kailey Nolan
Anne Parnell
Ivanna Pavisic
Naja Rantorp
Lea R'Bibo
Mai Requena-Komuro
Bridie Rollins
Ferozan Sarfaraz
Harri Sivasathiaseelan
Necole Schmitz
Adrienne Shum
Sophie Tappeiner
Patricia Townsend
George Walker
Jason Warren
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Philip Yenawine
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