Eye-movement studies of visual face perception

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Declaration

I, Joseph Arizpe, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

This thesis investigates factors influencing eye-movement patterns during face perception, the relationship of eye-movement patterns to facial recognition performance, and methodological considerations impacting the detection of differences in eye-movement patterns. In particular, in the first study (chapter 2), in which the basis of the other-race effect was investigated, differences in eye-movement patterns during recognition of own- versus other-race (African, Chinese) faces were found for Caucasian participants. However, these eye-movement differences were subtle and analysis-dependent, indicating that the discrepancy in prior reports regarding the presence or absence of such differences are due to variability in statistical sensitivity of analysis methods across studies. The second and third studies (chapters 3 and 4) characterized visuomotor factors, specifically pre-stimulus start position and distance, which strongly influence subsequent eye-movement patterns during face perception. An overall bias in fixation patterns to the opposite side of the face induced by start position and an increasing undershoot of the first ordinal fixation with increasing start distance were found. These visuomotor influences were not specific to faces and did not depend on the predictability of the location of the upcoming stimulus. These findings highlight the relevance, not only of stimulus and task factors, but also robust and characteristic visuomotor factors, in the interpretation of eye-movements as indices of visual attention. The final study (chapter 5) investigated individual differences as a factor in eye-movements to faces. The prevalence of different kinds of patterns and the impact of various stimulus, task, and visuomotor factors on the discriminability and consistency of individual eye-movement patterns were measured. The methodological strengths and limitations of the use of discrimination index and discrimination accuracy measures of the similarity of eye-movement patterns were also examined. Together these findings uncover neglected factors important to the interpretation of eye-movement patterns in studies of visual cognition.

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Chapter 1 - Introduction

1.1.1 - Brief overview of eye-movements

This section provides a very concise overview of eye-movements, their function in visual perception, and putative mechanisms underlying these functions. Open questions regarding eye-movement mechanisms are also described.

During human embryonic development, the eyes begin to form when the neural tube bulges outward, producing optic vesicles (O'Rahilly, 1983). Because the neural tube ultimately gives rise to the central nervous system (Detrait et al., 2005), the eyes, and in particular the retinae which contain the light-responsive neurons necessary for visual perception, are the only part of the central nervous system ordinarily visible from the outside of the body. Indeed, the retinae are considered brain tissue (Hubel, 1995). Measurement of eye-movements is thus a means of non-invasively investigating the interface at which visual information is transduced into neural representations, and for gaining unique and invaluable information relating objective visual input with the neural processes giving rise to subjective perception.

The light-responsive neurons lining the retina, onto which the light entering into the eye is focused, are mainly cells called rods or cones. Rods are neurons that enable achromatic low-acuity vision in dim light, while cones are those that enable high acuity color vision in brighter light (Cohen, 1972). The central portion of the retina, corresponding to about 5 degrees of perceived visual angle (Wandell, 1995), called the fovea, is specialized for high acuity color vision as it contains predominantly cones (Hendrickson, 1992). The neurons of the retina beyond the fovea, however, are mostly rods. Therefore, visual acuity and color perception is poorer in peripheral vision than in central (foveal) vision (Cohen, 1972).

For this reason, eye-movements are adaptive for bringing visual information of interest into the reception of the fovea for higher acuity chromatic perception, without

the necessity of head or body movement. Further, eye-movements that accommodate for head, body, environment, and/or object motion enable a stable image to fall onto the retina to allow for detailed perception despite the motion, which could otherwise blur the percept of interest. Eye-movements are additionally necessary because an entirely stationary image landing onto the retina would quickly lead to neural adaptation, and thus lead to perceptual fading; therefore, the position of the eyes is never entirely fixed (Martinez-Conde, Macknik, & Hubel, 2004). Lastly, the right half of the retinas (left visual field) project to the right hemisphere of visual cortex and likewise the left retinas (right visual field) project to the left hemisphere (Hubel, 1995). Because different cortical hemispheres (Warrington & James, 1967, 1986), or even different receptive field regions (Ahissar & Hochstein, 1997), are specialized or relatively selective for processing different kinds of visual information, eye-movements may be functional in bringing visual information into the reception of the cortical region specialized for a given kind of visual perceptual processing.

Six muscles (three pairs) act to move the eyeballs. The different muscles can each induce different kinds of motion, but for brevity only the major motions of each will be reviewed. The medial rectus muscle rotates the eyes medially when contracted, whereas its complement, the lateral rectus rotates the eyes laterally. The inferior rectus rotates the eyes downward, while its complement, the superior rectus rotates the eyes upward. Finally the superior oblique and inferior oblique create torsional motion of the eyes in opposite directions. These muscles are innervated by cranial nerves. The oculomotor nerve (cranial nerve III) innervates the superior, inferior, and medial recti, as well as the inferior oblique. The abducens nerve (cranial nerve VI) innervates the lateral rectus, and the Trochlear nerve (cranial nerve IV) innervates the superior oblique (Spencer & Porter, 1988). The neural circuits that control cognitively guided eye-movements still require much fundamental elucidation, though several cortical and subcortical regions implicated in eye-movements, such as the frontal eye fields (FEF), supplementary eye fields (SEF), the lateral intraparietal (LIP) area, and the superior colliculus, have been discovered (Hall & Colby, 2011; Schlag & Schlag-Rey, 1987).

There are several kinds of eye-movements, each with a different function. Very broadly, eye-movements can be categorized as vergence movements, in which the eyes move in different directions, or as version movements, in which the eyes move in the same direction. Vergence usually functions to align images falling on the retinae such that the resulting representations can be fused together in downstream cortical processing of the binocular visual input. This is necessary when shifting ones gaze between different depths. In contrast, version functions to move the eyes to another location typically while maintaining their alignment (Schor, 2004).

More specifically, five kinds of eye-movements are of particular importance for active visual perception. First, the vestibulo-ocular reflex occurs unconsciously to accommodate for head motion to maintain a stable image on the retina. Second, the optokinetic reflex occurs unconsciously when a moving tracked object moves out of the field of vision and the eyes then return to a starting position. An example of this reflex is when one is riding on a speeding train and looking at a cow outside of the window. As the cow leaves ones field of view with the motion of the train, the eyes return to their starting location, perhaps to look at another cow or a now passing telephone pole. Third, smooth pursuit eye-movements are employed unconsciously while a moving object is being tracked so as to keep the image of the object projected on the retina stable (Steinman, 2004). Though smooth pursuit typically requires a moving stimulus in order to be employed, it is also possible to be employed when stimulus motion is not visible, but is predictable or anticipated, suggesting that this kind of eye-movement is not reflexive, but rather has a cognitive mechanism (Barnes, 2008; Joiner & Shelhamer, 2006).

The last two kinds of eye-movements to be reviewed, namely saccades and fixations, are those particularly focused upon in this thesis. Saccades are eye-movements, employed consciously or unconsciously, to shift one's gaze. The speed and duration of a saccade is proportional to distance traveled. Despite saccades at up to about 500 degrees per second, visual perception remains stable and blurring is

not perceived during saccades. This lack of perceived blurring despite saccades is called saccadic suppression (Matin, 1974), and the mechanisms likely involves visual masking from the stable images on each side of a saccade and inhibitory neural mechanisms (Riggs, Merton, & Morton, 1974; Wurtz, 2008).

Fixations are employed to maintain one's gaze toward a specific spatial point. Despite the nomenclature however, fixations, though relatively stable, involve characteristic types of eye motion, and so are classified as genuine eye-movements (Martinez-Conde et al., 2004). Specifically, fixations contain three types of eye-movements: tremors, drifts, and microsaccades. The precise function, if any, of these types of movements are unclear and are still under investigation, though all may enable prevention of adaptation of the retinal neurons to the visual image to prevent perceptual fading. Tremors are the most minute of the fixational eye-movements and are irregular, high-frequency (approximately 90 Hz) oscillatory movements of low amplitude. Drifts are less minute, slower motions. Microsaccades are short (about 25 ms 41), small jerking motions, and seem to be attempts to correct drifts that shift the image too far away from center of the retina in addition to it probable role in preventing neural adaption in the retina Microsaccades may share at least some of the same neural circuits as saccades (Martinez-Conde et al., 2004; McCamy et al., 2012)..

Though we are able to shift spatial attention without eye movement (Posner, 1980), attention is improved with eye-movements (Peiyuan & Kowler, 1992; Schlingensiepen, Campbell, Legge, & Walker, 1986). This may be because attention and eye-movement brain areas functionally overlap (Corbetta et al., 1998; Kustov & Robinson, 1996), and so may be functionally related as suggested by reports that attention precedes a saccade to a given location in space (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; K Rayner, McConkie, & Ehrlich, 1978).

In addition to the visual stimulus, cognitive processes can influence the execution of eye-movements (Deubel, 1995; Hallett & Kalesnykas, 1995; Hallett, 1978; Yarbus,

1965; Zingale & Kowler, 1987), and task difficulty modulates the duration, and number of fixations and saccades (Findlay & Kapoula, 1992; Phillips, 1981; Keith Rayner & Fisher, 1987; Williams, Reingold, Moscovitch, & Behrmann, 1997; Zelinsky & Sheinberg, 1997). Further, visual preprocessing in the periphery occurs such that saccades will often terminate at a position intermediate to two discrete, spatially proximate stimuli. This phenomenon is called the center of gravity effect (Deuble, Wolf, & Hauske, 1984; Findlay, 1982; Ottes, Van Gisbergen, & Eggermont, 1985), and can be manipulated such that if one of the stimuli is more salient, then the saccade tends toward the more salient target.

Though our eyes are constantly changing position, thus constantly changing the image on the retina, perception of the visual environment does not seem very discontinuous, indicating that neural representations are modified to accommodate for eye-movements. The details of the mechanisms and circuits through which this is accomplished are still under investigation; however, converging evidence indicates a fundamental mechanism of spatial remapping of neural representations that is coordinated by neural signals related to the execution of eye-movements (Hall & Colby, 2011). In cortical areas V3A, LIP, and FEF of monkeys immediately before a saccade, the receptive field of neurons can have a dual responsiveness for both the current location of a stimulus as well as the location where the stimulus will be after the upcoming saccade (Kusunoki & Goldberg, 2003; Nakamura & Colby, 2002; Sommer & Wurtz, 2006), but this dual responsiveness ends beyond the time the saccade starts to be executed. Thus a predictive mechanism or some temporary expansion of the receptive fields of neurons may be at least one aspect of what accomplishes such remapping. It is assumed that some corollary discharge signals result from decisions to execute upcoming eye-movement plans. Precisely how such signals originate, propagate to, and bring about remapping in specific brain regions is not well understood (Wurtz, Joiner, & Berman, 2011); however, work in primates has uncovered neural signals propagating from the superior colliculus through the thalamic medialdorsal nucleus to the FEF that partially affect remapping, at least within the FEF (Sommer & Wurtz, 2002).

Because this thesis focuses principally on the employment of fixations and saccades during the perception of faces, the remaining introductory sections will review in depth a particular topic within the study of face perception, namely the Other-Race Effect. Because research on the Other-Race Effect has produced a body of findings which encapsulate and elucidate the perceptual mechanisms of face perception more generally, the following sections not only provide context to the first empirical chapter, which explicitly investigates the Other-Race Effect, but also introduces many key mechanistic concepts relevant to face perception in other contexts.

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1.2.1 - The Other-Race Effect

The Other Race Effect (ORE, also referred to as the Cross Race Effect, Own Race Advantage, Same Race Advantage, Own Race Bias, or similar phrases) is the robust and well-established finding that people are generally poorer at facial recognition of individuals of another race than of one's own race (Bothwell, Brigham, & Malpass, 1989; J. Brigham, Bennett, Meissner, & Mitchell, 2007; John C. Brigham & Malpass, 1985; Chance & Goldstein, 1996; Cross, Cross, & Daly, 1971; Lindsay, Jack, & Christian, 1991; Malpass & Kravitz, 1969; Meissner & Brigham, 2001; O'Toole, Deffenbacher, Valentin, & Abdi, 1994; Platz & Hosch, 1988; Shapiro & Penrod, 1986; Shepherd, Deregowski, & Ellis, 1974). The ORE can also be characterized by the subjective perception that faces of another race seem much more homogeneous than those of ones own race, (Feingold, 1914; Malpass & Kravitz, 1969)). For example, anecdotally it is often said that to Caucasians, Chinese often "all look alike", and vice versa.

The ORE has important real-world implications. The unreliability of cross-race eyewitness testimony due to the ORE has profound implications in the courtroom and for legal policy (J. Brigham et al., 2007; John C. Brigham & Malpass, 1985; Feingold, 1914; Leippe, 1995; Shapiro & Penrod, 1986). The ORE can create difficulties in social interactions between persons of different races, and this has additionally been suggested to be a factor in the formation of racial prejudice (John C. Brigham & Malpass, 1985; Lebrecht, Pierce, Tarr, & Tanaka, 2009). For these reasons, there can be some practical utility in understanding the mechanisms underlying the ORE, so as to possibly reduce its effect. Additionally, an understanding of the factors that produce the ORE may provide insight into the fundamental cognitive and neural mechanisms of face processing more generally, and have important theoretical and practical implications beyond the problems of cross race recognition.

Though the ORE has been studied for over 40 years, a definitive account of its basis has not yet been established. Many viable cognitive and social mechanisms have been proposed, and not all are necessarily mutually exclusive. In the following literature review, important considerations informing theories of the ORE and the main theories of the cognitive and perceptual mechanisms of the ORE will be reviewed.

Factors that Inform Theories of the ORE

Before reviewing theories of cognitive and perceptual mechanisms that have been proposed as bases for the ORE, I will first address important considerations that must factor into such theories of the ORE. Specifically, I will consider the definition of race in the ORE literature, the relationship between other-race experience and the ORE, ethnic differences in facial physiognomy, and the diagnostic value of different facial features for facial identification.

In-Groups and Out-Groups

Racial differences can be said to have an objective genetic basis, though it is not possible to delineate racial boundaries with precision (Rossion & Michel, 2012). For this reason, many studies of the ORE, including the present study, make reference to race as largely socially and culturally defined, rather than as purely biologically defined (e.g. Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Lindsay et al., 1991). It has been proposed that the investigation of the mechanisms underlying the ORE should not be discussed in terms of race as such, but in more general terms of in-groups and out-groups (P. M. Chiroro, Tredoux, Radaelli, & Meissner, 2008; Sporer, 2001). Support for this notion comes from evidence that an ORE-like effect also occurs among different age groups (Cross et al., 1971; Wright & Stroud, 2002), and between the sexes (Cross et al., 1971; Rehnman & Herlitz, 2006). Additionally, within a nominal race, one ethnic subgroup may have a deficit in recognizing individuals from different ethnic subgroups (P. M. Chiroro et al., 2008; McKone et al.,

2011). For example, one study found that White South Africans recognized White South Africans better than White Americans. Likewise, Black South Africans recognized Black South Africans better than Black Americans (P. M. Chiroro et al., 2008). From these results, it was concluded that race is a concept that needs to be retired from the ORE literature, so as to avoid misleading conclusions. Indeed, race *per se* is not the most fundamental conceptual level at which to investigate the ultimate basis for the ORE. Thus, the ORE may be considered a special case of a broader class of out-group face recognition deficits (e.g. other-race, other-ethnicity, other-age, other-sex, etc), which could all share mechanistic bases that are similar in principal.

Though the ORE may be discussed in terms of in-groups and out-groups, this is not to suggest that the ORE is exclusively, or even principally, explained by social mechanisms. For example, racial attitude may influence how one establishes in-groups and out-groups, but racial attitude by itself does not explain the ORE. In one early study, White undergraduate students enrolled in black studies showed a trend toward recognizing Black faces better than own-race faces, while students enrolled in psychology showed the expected ORE (Galper, 1973). It was suggested that it was the attitude of allegiance to black individuals that could have driven an elimination of the ORE. However, a lack of evidence from other studies that directly tested a relationship between measures of racial attitude and recognition ability (J. C. Brigham & Barkowitz, 1978; Lavrakas, Buri, & Mayzner, 1976; Platz & Hosch, 1988; Slone, Brigham, & Meissner, 2000; Yarmey, 1979) suggests that a strong connection is likely absent. However, a response bias to more frequently label other-race faces as recognized (Slone et al., 2000), may be related to prejudiced racial attitude (D. N. Elliott & Wittenberg, 1955; Meissner & Brigham, 2001; Yarmey, 1979). Further, some role of racial attitude in the ORE cannot be ruled out, as racial prejudice is negatively correlated with the degree of other-race experience (J. C. Brigham & Barkowitz, 1978; John C. Brigham & Ready, 1985; John C. Brigham, 1993; Meissner & Brigham, 2001; Slone et al., 2000), which, as I discuss below, is known to strongly relate to the ORE.

Other-Race Experience

It is clear that experience with other races relates to the ORE and that finding the fundamental social, cognitive, and perceptual mechanisms underpinning the ORE lies precisely in adequately explaining this relationship. Early studies of the ORE found little or no evidence of a relation between amount of contact with another race and the ORE (Cross et al., 1971; Malpass & Kravitz, 1969); however, evidence later emerged that it was the quality of contact with another race which influenced the ORE. In one study, White individuals who had Black friends had better Black face recognition, than did White individuals merely living in a racially integrated community (Lavrakas et al., 1976). Later studies further corroborated a relationship between self-reported racial contact and other-race recognition (J. C. Brigham, Maass, Snyder, & Spaulding, 1982; P. Chiroro & Valentine, 1995; MacLin, Van Sickler, MacLin, & Li, 2004; Slone et al., 2000; Wright, Boyd, & Tredoux, 2003). Further evidence suggested that experience can prevent the ORE (Walker & Hewstone, 2006), or even reverse it into an own-race recognition deficit (S Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2005; Wright et al., 2003).

Developmental studies have attempted to trace the emergence of the ORE in children and infants. A failure to detect an ORE has been reported in young children (Chance, Turner, & Goldstein, 1982; Pezdek, Blandon-Gitlin, & Moore, 2003; Sandy Sangrigoli & De Schonen, 2004) as old as 7 years (Goodman et al., 2007), though the increase in general face recognition ability with age makes the apparent equality of own- versus other-race recognition performance of very young children difficult to interpret owing to poor general performance at very young ages (Chance et al., 1982). Studies on the visual preferences of infants suggest that other-race faces are not perceived as different by newborns (Kelly et al., 2005), but are by older infants (Kelly, Quinn, et al., 2007), and that this phenomenon has emerged by 3 months (Bar-Haim, Ziv, Lamy, & Hodes, 2006; Hayden, Bhatt, Joseph, & Tanaka, 2007; Kelly et al., 2005; Kelly, Liu, et al., 2007; Sandy Sangrigoli & de Schonen, 2004),

depending on experience (Bar-Haim et al., 2006). This phenomenon may have a gradual development (Kelly, Quinn, et al., 2007), though it is unclear how periods of developmental plasticity and experience may interact during the formation or reversal of the ORE (Rhodes et al., 2009).

Perhaps the most compelling evidence that the ORE is experience-dependent and has a more fundamental attentional, perceptual, and/or motivational basis is that training to individuate other-race faces can rapidly reduce the ORE. White subjects who performed less than an hour of visual recognition training on Black and White faces showed greater performance improvement for Black faces (Malpass, Lavigueur, & Weldon, 1973). Improvement was greatest with electric shock feedback, indicating motivation influences performance. In addition, Black and White subjects who trained on a separate set of tasks involving verbal description of faces and recognition of faces from verbal descriptions did not show visual recognition improvement for faces of either race, suggesting that particular cognitive or perceptual processes must be engaged during experience with other race faces in order to reduce the ORE. Other studies have replicated the effect of individuation training on improved recognition of other race faces (E. S. Elliott, Wills, & Goldstein, 1973; Lebrecht et al., 2009; McGugin, Tanaka, Lebrecht, Tarr, & Gauthier, 2011). Effects five months after intensive training have been reported (Goldstein & Chance, 1985). Individuation training, but not racial categorization training, reduced the ORE and increased the face N250 ERP component (Tanaka & Pierce, 2009), thus further indicating that other-race individuation experience reduces the ORE through a change in the way other-race faces are processed. The locus of the most fundamental factors underlying the ORE is in the particular cognitive and perceptual processing differences for own- versus other-race faces, but the account of these factors is still very much incomplete.

To dissociate between the amount of exposure and the quality of experience with other race faces, which typically go together, Yovel and colleagues (Yovel et al., 2012) studied an impairment in newborn face recognition in neonatology nurses that

is analogous to the ORE. Critically, the neonatology nurses had massive perceptual experience with newborn faces but did not attempt to discriminate between them on an individual level. Performance on a newborn face recognition task was lower than adult recognition in neonatology nurses and no better than age and gender matched participants. These findings suggest that passive (even if massive) exposure alone does not contribute to face recognition and therefore may not account by itself for the ORE. The effect of individuation was shown with significantly increased face recognition ability for newborn faces after subjects who had no previous exposure to newborn faces learned to associate names to newborn faces. This suggests that individuation rather than perceptual exposure plays an important role in face recognition in general and recognition of other race faces in particular.

Ethnic Differences in Facial Physiognomy and Feature Heterogeneity

At least some of the cognitive and perceptual processing differences underlying the ORE may relate to objective physiognomic differences among races, so such physiognomic differences must be considered before any account can be given as to why and how other-race faces need to be processed differently for the ORE to be reduced or reversed. It is clear that facial physiognomy differs on average among ethnicities. For example, compared to Caucasians, Africans have relatively rounder, wider faces, thicker lips, and more bulbous noses (Shepherd & Deregowski, 1981). The average faces from my stimulus set illustrate these observations (Figure 1). In addition, many anthropometric measurement differences between Caucasians and Africans have been reported, with the greatest differences reported in the horizontal dimension (Porter & Olson, 2001). It must be that at least some of these physiognomic characteristics also have little overlap between given ethnicities, as people are able to distinguish an individual's race based on facial physiognomy alone, even when cues such as color and skin reflectance are absent (Hill, Bruce, & Akamatsu, 1995). An observer's lack of perceptual expertise with the physiognomy characteristic of a given ethnicity could provide a basis for the ORE; however, the physiognomic characteristics that differ on average among ethnicities, though likely

useful for discriminating race, are not necessarily useful for identification. Rather, the physiognomic characteristics that may differ in variability among ethnicities are likely to be more relevant to facial identification, and relevant differences could be either global or only feature-specific.

Figure 1. Mean Caucasian, African, and Chinese Faces. These images were produced by aligning and averaging several images of faces.

First, I will consider potential differences in global facial variability among races. Though not well studied, such global differences, if they exist at all, are unlikely to relate to the individuation and identification deficits of the ORE. Given the "all look alike" phenomenon, one could speculate that physiognomic characteristics objectively are globally more heterogeneous for faces of one ethnic group (one's own-race) than those of others (other-race). Contrary to this speculation though, ORE studies often report a race of face by race of observer interaction such that the recognition deficit for other race faces clearly goes both ways between races of observers. This crossover interaction of the ORE among races of observers is evidence to suggest that the ORE is not principally due to global differences in facial variability among different ethnicities (Meissner & Brigham, 2001; Sporer, 2001). To date, there is yet no evidence to support the hypothesis that the ORE has a basis in objective differences in global facial heterogeneity among ethnic groups. One study comparing variation in many anthropometric measures of Japanese, Caucasian, and African faces failed to find differences (Goldstein, 1979b). It should be noted,

however, that the measure of variation reported in that study was the coefficient of variance, which is variance expressed as a percent of the mean measurement. Thus, no absolute measure of facial feature variance among ethnicities was reported. Further, such simple distance and proportion measures provide little information regarding any potentially diagnostically important ethnic differences in the variability of the finer shapes of particular features.

In contrast, however, facial feature-specific (e.g eyes) variability differences among races would not be inconsistent with the crossover interaction of the ORE, assuming that the features an observer relies upon most for facial identification vary depending on the observer's previous experience with faces. Thus any such feature-specific variability differences may be important for understanding the ORE. There is evidence that for a given race, the relative heterogeneity among facial features differs. Specifically, in an INDSCAL analysis, the lower internal facial features explained approximately 75% of the variance for Black faces, but only 35% for White faces (Shepherd & Deregowski, 1981). Hair explained approximately 85% of variance in White faces, but only 35% for Black faces. Individual facial feature heterogeneities were not directly compared between races though, so no global differences in facial heterogeneity could be inferred, but these results do suggest facial feature-specific differences.

Diagnostic Facial Information

A separate, though possibly related, issue from the objective information contained in the physiognomic characteristics of faces is what diagnostic value particular facial features have for the observer. Particular facial features differ in behaviorally-determined diagnostic value for facial identification, though perhaps the hierarchy of diagnostic features differs by race of face and/or race of observer. Though conjunctions of facial features seem to provide more diagnostic value than any single internal facial feature by itself (Haig, 1986), a variety of experimental techniques and paradigms provide strongly converging evidence that the eyes are

the most important single internal facial feature for accurate (Caldara et al., 2005; Davies, Ellis, & Shepherd, 1977; Gosselin & Schyns, 2001; McKelvie, 1976; Sekuler, Gaspar, Gold, & Bennett, 2004) and rapid (Fraser, Craig, & Parker, 1990; Schyns, Bonnar, & Gosselin, 2002) facial recognition. The mouth is the next most diagnostic internal feature, and the nose apparently has very little diagnostic value (Davies et al., 1977; Fraser et al., 1990; Haig, 1986). It is clear though that external facial features, specifically hair alone or hair and outline of face combined, have diagnostic value (Gosselin & Schyns, 2001) which seem to greatly exceed the value of any single internal facial feature considered by itself (Davies et al., 1977; Fraser et al., 1990; Haig, 1986). It should be noted, however, that the studies that established this hierarchy of diagnostic value included experimental participants from Scotland, England, and Canada, and likely included few, if any, non-Caucasian participants. Additionally, the facial stimuli, when not schematic, were Caucasian faces. Therefore this hierarchy may not generalize to other races of observers or faces. Given evidence that variability in specific facial features of Caucasians differs compared to the same features of Africans (Shepherd & Deregowski, 1981), one could speculate that the diagnostic value of specific features differs between races. It is unknown whether there is a relationship between a given feature's variability across individuals, and its usefulness in facial identification (Goldstein, 1979a). Therefore an investigation into how the subjective diagnostic value of a feature relates to objective physiognomic variability among individuals, and whether the diagnostic hierarchy of features varies by race of face could provide critical insights into what underlies the ORE.

Cognitive and Perceptual Mechanisms of the ORE

The previous section reviewed important factors that must inform theories of the mechanisms that underlie the ORE, namely the definition of race, the role of other-race experience, the differences in objective racial physiognomy, and the relative differences in the diagnostic value among facial features. In the following section, I will review theories that attempt to explain the ORE with a focus on fundamental

cognitive and perceptual mechanisms. Though these theories will be treated separately, they are not necessarily mutually exclusive as they may be regarded as distinct mechanisms that possibly operate in sequence, in parallel, or interactively.

Racial Categorization Alters Face Processing

Caucasians have shown more rapid racial categorization of other-race faces than own-race faces (Levin, 1996; Valentine & Endo, 1992), and a visual search asymmetry such that other-race faces among own-race distracters are detected more rapidly than the reverse (Levin & Angelone, 2001; Levin, 1996, 2000; Valentine & Endo, 1992). From these observations, it has been proposed that other-race faces are rapidly perceived to have a feature that same-race faces lack, leading to an other-race categorization advantage (Levin, 1996, 2000). It has been further proposed that this rapid racial categorization takes attention away from the individuating information in other-race faces, thereby causing the well-known other-race recognition deficit. This "race as a visual feature" theory lacks specificity regarding what could constitute the race feature in other-race faces, why this feature necessarily distracts from individuating facial information, and how perception of this feature develops, though a social mechanism is suggested. More importantly, there was no evidence of a crossover of the categorization advantage (Valentine & Endo, 1992) or search asymmetry (Levin, 1996) when non-white observers were also tested. Rather, non-white participants from white-minority nations showed no categorization or detection advantage for either own- or other-race faces.

More convincing support for the hypothesis that early racial out-group categorization influences subsequent facial perception comes from the ambiguous-race face illusion (MacLin & Malpass, 2001, 2003) and its apparent perceptual consequences (Figure 2). MacLin and Malpass (2001) constructed racially ambiguous artificial faces that had internal facial feature characteristics overlapping Black and Hispanic facial characteristics, but differing only in whether the hairstyle was typically Black or typically Hispanic. They tested Hispanic participants from a predominantly Hispanic

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region and found strong indications that the faces were processed differently depending on how the face was categorized, despite the facial physiognomies being objectively the same. Intriguingly, there was an "other-race" recognition deficit for faces with Black hairstyles. When asked to categorize the faces by race, participants tended make racial judgments corresponding to the hairstyle. Additionally, psychophysical measures revealed that subjectively Black faces were perceived to have darker complexion, wider mouths, less protruding eyes, and wider faces than subjectively Hispanic faces. A similar "other-race" recognition deficit with African-Caucasian ambiguous-race faces has been reported in Caucasian children (Shutts & Kinzler, 2007). A crossover between different race observers for ambiguous-race faces has not been tested. Though the ambiguous-race face illusion has been interpreted as inconsistent with the ORE being experience-dependent (Hugenberg, Miller, & Claypool, 2007; MacLin & Malpass, 2003; Shutts & Kinzler, 2007), one could speculate that it is other-race experience that either optimizes a race-specific face processing strategy or reverses reduced default processing of other-race faces. Thus, while there is some evidence for effects of racial categorization on subsequent identity processing, the nature of the influence remains to be elucidated.
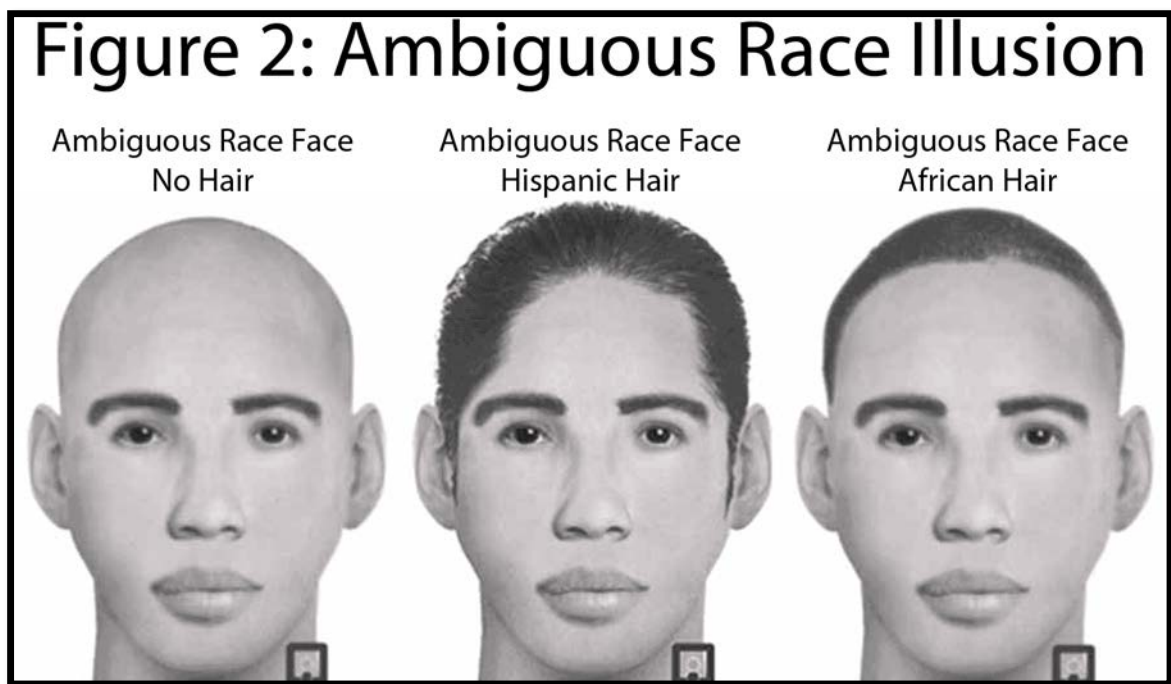
Figure 2. The Ambiguous Race Illusion. This is figure 1 from MacLin & Malpass, 2003, and illustrates the stimuli used to induce the Ambiguous Race Illusion.

Differences in Attention to Facial Features

Different race observers may employ different attention to facial features. In a study (Ellis, Deregowski, & Shepherd, 1975) comparing how Black Kenyans and White British teenagers verbally described Black and White faces, it was found that Black observers referred to face outline, eye size, eye-whites, eyebrows, ears, chin, and hair position more, and that White observers referred to eye color, hair color and texture more. Additionally, both races of observers described more features for black faces, though White observers tended to describe features that would not distinguish between Black individuals (e.g. color of skin, hair, and eyes). This is consistent with the hypothesis that the hierarchy of diagnostic facial features differs by race of face, and suggests that the ORE may be explained by a difference in degree and/or efficiency in employing attention to race-specific diagnostic facial features.

Indeed, manipulating attention to other-race features has been found to modulate the ORE. Training white American participants to discriminate artificial Black faces on eyes or on eye and mouth conjunctions was found to reduce the recognition deficit for Black faces (Lavrakas et al., 1976). Similarly, training White participants to discriminate artificial White faces using lower facial features eliminated the ORE for Black faces, while training on other features or mere exposure to the relevant training faces did not (Hills & Lewis, 2006). In that study, because the training that reduced the ORE utilized only own-race faces, it could be concluded that it was the change in allocation of attention, not increased expertise with the racial physiognomy, which eliminated the ORE. The effect of other-race experience observed in other studies may largely reflect learning to allocate attention efficiently for individuation of an other-race face.

It is believed that configural processing, not just individual feature processing, is important in face recognition, and that configural processing is enhanced with visual expertise (Diamond & Carey, 1986). Differences in the positions of the mouth, eyes, and nose, as well as spacing between the eyes, are examples of configural properties that are easily detected (Haig, 1984). It is thought that configural properties of a face are perceived as more than the sum of its parts (Sergent, 1984). It has been reported that recognition accuracy and reaction times were more affected for own- than other-race faces when faces were inverted (Rhodes, Brake, Taylor, & Tan, 1989). Because inversion (Yin, 1970) is believed to interfere with configural processing (Sergent, 1984), these results were interpreted as evidence that other-race faces are not processed configurally as well as own-race faces due to a lack of expertise with other-race faces. Attempts to replicate this finding have produced conflicting results however (Buckhout & Regan, 1988; Sandy Sangrigoli & De Schonen, 2004; Valentine & Bruce, 1986).

Face inversion is problematic in that it does not selectively disrupt configural processing, but also disrupts feature component processing (Rhodes, Hayward, & Winkler, 2006; for review, see McKone & Yovel, 2009). Thus other means of testing the possible configural processing basis of the ORE have been employed and provide evidence for this hypothesis. Australian and Chinese participants were tested on a task involving detection of feature and configural changes in own- and other-race faces that were manipulated through a featural and configural photomorphing technique (Rhodes et al., 2006). An own-race advantage was reported for both featural and configural change detection, suggesting that differences in both kinds of processing are implicated in the ORE. Similar results were obtained using a task in which study faces were unmodified whole faces, but test faces were either scrambled features (to isolate featural processing) or blurred whole faces (to isolate configural processing) (Hayward, Rhodes, & Schwaninger, 2008). The same scrambled/blurred face paradigm was used to test Chinese

participants who had been living in Australia for widely varying amounts of time (Rhodes et al., 2009). It was reported that time lived in Australia was correlated with reduced ORE for configural memory, but not for feature memory.

Differences in Holistic Facial Processing

Holistic processing is believed by some to be another level of face processing in which featural and configural information are integrated (Tanaka & Farah, 1993; Tanaka & Sengco, 1997). In the context of same- and other-race face processing, comparison of holistic and featural processing has been attempted using a paradigm called the "parts and wholes test" (Tanaka, Kiefer, & Bukach, 2004). Specifically, German nationals and Asians living for many years in Canada were shown photo-composite faces, each of which was composed of either Caucasian or Asian features. On each trial, participants were tested for immediate recognition with a two-alternative forced-choice between either two composite whole faces or two isolated feature exemplars. The German participants, who reported less experience with Asians than Caucasians, performed whole face recognition more accurately for own-race faces, but performed isolated feature recognition more accurately for other-race faces. Asian participants, who reported slightly more experience with Caucasians, performed whole face recognition with equivalent accuracy for own- and other-race faces. Results were interpreted as indicating that own-race faces are processed more holistically, and that other-race faces are processed more featurally, though experience with other-race faces can enable an equal degree of holistic processing of other- and own-race faces.

These results were replicated with Asians who had lived in Belgium for only about one year and Belgian Caucasians (Michel, Caldara, & Rossion, 2006). They noted that even only one-year of other-race experience may have enabled the Asian participants to holistically process own- and other-race faces equally well. However, unlike the prior study, the ORE itself was tested in these participants using the standard old-new recognition paradigm with a study phase and delayed test phase.

Despite apparently equal holistic own- and other-race face processing in the "part and wholes test" for the Asian participants, an ORE nonetheless persisted. It was concluded that holistic processing is not sufficient to eliminate the ORE. The possibility was also proposed that cognition is generally more holistic in Eastern cultures, and so Asians apply holistic processing to both own- and other-race faces by default, while Westerners may only apply holistic processing with experience. An equivalent result with Australian and Chinese participants was obtained by using a different measure of holistic processing (Michel, Rossion, Han, Chung, & Caldara, 2006), the face-composite paradigm (Young, Hellawell, & Hay, 1987), in which test faces have upper and lower halves of faces either aligned or misaligned. The finding was that there was an ORE crossover between races of participants and additionally that alignment of faces aided face recognition except for Australians observing Asian faces. Therefore, they similarly concluded that holistic processing is not sufficient to overcome the ORE. However, another research group tested Chinese and Caucasian participants on both the "parts and wholes test" and the face-composite test and failed to replicate the difference in holistic processing for own- and other-race faces (Mondloch et al., 2010).

Conclusion

The ORE and the theories of its basis have been reviewed. I initially addressed important considerations that must factor into such theories of the ORE, namely the definition of race in the ORE literature, the relationship between other-race experience and the ORE, ethnic differences in facial physiognomy, and the diagnostic value of different facial features for facial identification. With a focus on fundamental cognitive and perceptual mechanisms, I then reviewed evidence for different theories that attempt to explain the ORE, specifically racial categorization altering face processing, differences in attention to facial features, and differences in configural and holistic facial processing. Though these theories were treated separately, they are not necessarily mutually exclusive as they may be regarded as distinct mechanisms that possibly operate in sequence, in parallel, or interactively.

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1.3.1 - Eye-movement studies of the Other-Race Effect

Eye fixations are thought to reflect the allocation of visual attention to specific features of the world and eye movements appear to be functionally useful in visual recognition (Henderson, Williams, & Falk, 2005; Kealey, Sekuler, & Bennett, 2008). As such, analysis of eye fixations can potentially provide insight into cognitive processing and, in particular, the stimulus features used in a given task. Thus, eye-tracking may be a useful technique to study the basis of the Other-Race Effect (ORE) which is the robust and well-established finding that people are generally poorer at facial recognition of individuals of another race than of one's own race (Bothwell, Brigham, & Malpass, 1989; J. Brigham, Bennett, Meissner, & Mitchell, 2007; J. C. Brigham & Malpass, 1985; Chance & Goldstein, 1996; Cross, Cross, & Daly, 1971; Lindsay, Jack, & Christian, 1991; Malpass & Kravitz, 1969; Meissner & Brigham, 2001; O'Toole, Deffenbacher, Valentin, & Abdi, 1994; Platz & Hosch, 1988; Shapiro & Penrod, 1986; Shepherd, Deregowski, & Ellis, 1974). In particular, eye-tracking can potentially provide insight into the long unresolved questions of which specific facial features are attended during own- and other-race face processing and whether there are differences in the diagnostic value of facial features among races. Surprisingly, although the ORE has been studied for over forty years and the eye-tracking technique has been used to study face perception for even longer (Yarbus, 1965), few research groups to date have studied the ORE utilizing eye-tracking (Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Brielmann, Bülthoff, & Armann, 2014; Caldara, Zhou, & Miellet, 2010; Fu, Hu, Wang, Quinn, & Lee, 2012; Goldinger, He, & Papesh, 2009; Hills, Cooper, & Pake, 2013; Hills & Pake, 2013; Hu, Wang, Fu, Quinn, & Lee, 2014; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Miellet, Lao, Zhou, He, & Caldara, 2012; Miellet, Vizioli, He, Zhou, & Caldara, 2013; Nakabayashi, Lloyd-Jones, Butcher, & Liu, 2012; Rodger, Kelly, Blais, & Caldara, 2010; Tan, Stephen, Whitehead, & Sheppard, 2012).

While these prior studies have provided valuable data for advancing our understanding of the basis of the ORE, they present highly conflicting results from

which two competing views have emerged. The first view is that face processing depends on the culture of the observer, but is equivalent for different races of faces (Blais et al., 2008; Caldara et al., 2010; Hills et al., 2013; Hills & Pake, 2013; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Miellet et al., 2012, 2013; Rodger et al., 2010; Tan et al., 2012). The bulk of the evidence for this first view comes from a single research group, which used highly similar paradigms and analysis techniques across studies. The second view is that face processing differs by own- vs. other-race faces, but does not differ by race of observer (Goldinger et al., 2009). In accord with this second view, four more recent studies (Brielmann et al., 2014; Fu et al., 2012; Hu et al., 2014; Nakabayashi et al., 2012) provide further evidence that face processing differs between races of faces. Finally, a series of studies have additionally provided evidence that fixation pattern differences both by race of observer (Kelly, Liu, et al., 2011; Liu et al., 2011; Wheeler et al., 2011) and also by race of face (Hu et al., 2014; Liu et al., 2011; Wheeler et al., 2011; Xiao, Quinn, Pascalis, & Lee, 2014; Xiao, Xiao, Quinn, Anzures, & Lee, 2013) can be detected early and develop with age, though the mechanisms leading to the development of these eye movement differences are unclear (Kelly, Jack, et al., 2011).

Evidence that eye movement strategies for facial recognition differ by race of observer, but not race of face

Evidence for Western Caucasian foveal- and East Asian extrafoveal-sampling strategies

In the first eye-tracking study of the ORE (Blais et al., 2008), Western Caucasian and East Asian observers viewed Caucasian and East Asian faces during an old/new recognition task. As expected, the ORE was replicated in recognition performance for both groups of observers. Importantly though, in fixation patterns, differences based on race of observer, but not race of face stimulus, were reported. Specifically, during encoding Caucasian observers exhibited relatively more fixations to the eyes, and East Asians exhibited relatively more fixations to the nose.

Similarly, during recognition, Caucasians exhibited relatively more eye and mouth fixations and East Asians exhibited relatively more nose fixations. Additionally, an overall center-of-face tendency in fixation density was reported for East Asian observers, whereas the "classic" T-shape pattern, with peak density over the eyes, was reported for Caucasian observers. The results from this experiment were interpreted as showing that people from different cultures have different perceptual mechanisms that are applied to each face, regardless of the race of the face stimulus. A follow up study (Rodger et al., 2010) was conducted exactly like the original study but with inverted rather than upright faces. Though the ORE in recognition accuracy was not replicated for the inverted faces, fixation patterns specific to race of observer were reported, and these patterns were not significantly different to those seen for the upright faces in the original study. This was interpreted as further confirmation of culture-specific perceptual mechanisms for faces.

A series of other follow-up studies coming from the same research group (Caldara et al., 2010; Miellet et al., 2012, 2013), with variations on the original experimental paradigm (Blais et al., 2008) all largely replicated the initial results, but suggested further potential differences in how different race observers extract the same information during facial recognition. One of these studies (Caldara et al., 2010) restricted extrafoveal vision through variably-sized gaze-contingent Gaussian apertures, and while they mostly replicated the original results with larger apertures, they found that highly restricted extrafoveal vision induced East Asian observers to fixate the eyes as much as Caucasian observers. Based on these results it was suggested that different race observers extract the same facial information while employing different culturally dependent strategies to do so. The authors argued that only when East Asian participants' extrafoveal vision could not include the eyes were the eyes directly fixated. As additional evidence consistent with this account of identical information extracted through different strategies, an additional analysis on the face stimuli failed to find significant differences in image variance between races of face stimuli, and it was suggested that individual features do not differ in

diagnostic value between the races. A similar study, this time with expanding gaze-contingent apertures and a retinal spatial frequency filter model (Miellet et al., 2013), again replicated the original result, but also suggested that Westerners use local high spatial frequency information while Easterners use global low spatial frequency information. A final complementary study (Miellet et al., 2012) employed virtual gaze-contingent scotomas, rather than apertures, to mask central vision while conducting the same task as the other studies. With larger virtual scotomas, the Western Caucasian observers' eye movement patterns more closely resembled the center-of-face biased eye movement patterns of the East Asian observers, whereas the scotomas largely did not affect East Asian observers' eye movement patterns. This was interpreted as providing supporting evidence to the prior aperture study (Caldara et al., 2010) that both Western Caucasian and East Asian observers utilize the same facial information (i.e. principally the eyes) for facial recognition, though Western Caucasian observers prefer to fixate the eyes and East Asian observers prefer to sample eye feature information with extrafoveal vision. Thus, when the virtual scotomas prevented the Western Caucasian observers from sampling facial information with the fovea, these observers were forced to change their eye movement patterns to sample this information in extrafoveal vision, just like the East Asian observers had by default. Overall, these five studies from the same research group suggest that differences in eye movements and local (foveal) versus global (extrafoveal) information use during face encoding and recognition depend on the race of the observer with no difference in fixations based on the race of the face stimulus being viewed. Specifically, for facial recognition, East Asian observers prefer to sample information on the eyes through their extrafoveal vision, whereas Western Caucasian observers prefer to directly fixate the eyes.

Evidence for optimized diagnostic feature sampling for own-race faces in White and Black observers

Two studies from an independent research group (Hills et al., 2013; Hills & Pake, 2013) suggest different conclusions with respect to the nature of information use

between different races of observers. Specifically, rather than different strategies to sample the same information (i.e. principally the eyes), this research group concluded that attention was allocated to the nose for 'Black' observers and to the eyes for 'White' observers because those features are where the diagnostic information is located for Black and White faces, respectively. In the first study (Hills et al., 2013), participants fixated at locations where either the region between the eyes or the tip of nose of the upcoming face stimulus would subsequently appear, or were not required to fixate anywhere in particular. Overall, White observers spent the most time fixating the eye regions, while Black observers spent the most time fixating the nose region; however, no influence of race of face stimulus was reported. Importantly though, the ORE was erased for White participants when they were forced to initially fixate at the location where the nose would appear, through an increase in recognition of Black faces. Likewise, the ORE was erased for Black participants when they were forced to initially fixate the location where the region between the eyes would appear. Further, under those conditions, the location of the first fixation (following the first saccade) resembled the opposite race observers' patterns compared to the no-forced fixation condition, suggesting that the fixation manipulation affected attention allocation. The second study (Hills & Pake, 2013), employing a similar paradigm but different analysis parameters (e.g. more AOIs) also found influences of the race of observer, but not race of face, on eye-movements and performance, consistent with the first study.

Despite differences in the proposed underlying mechanism, all the studies discussed so far seem to provide strong evidence both for an influence of the race of observer on fixation patterns to faces, and also for the lack of influence of the race of face on eye-movement patterns.

Evidence that eye movement strategies for facial recognition differ by race of face, but not race of observer

In stark contrast to the studies described above, another group (Goldinger et al., 2009) concluded exactly the opposite, namely that it is the race of the face stimulus that influences eye-movements and not the race of the observer. Specifically, eye-movement and pupillometric differences depended on whether the race of face was own- or other-race, but not on the race of the observer, in Caucasian and East Asian participants observing Caucasian and Japanese faces. As in most of the previously discussed studies, the ORE was replicated in recognition performance. Importantly, regardless of the race of the observer, own-race faces elicited a relatively greater proportion of fixations to the eyes and hair, while other-race faces elicited a relatively greater proportion of fixations to the nose and mouth. This was true for both Caucasian and East Asian observers. Other measures revealed that on average, other-race faces elicited significantly fewer fixations, longer duration fixations, fewer unique Areas of Interests (AOIs) fixated, and less total distance traveled by the eyes than own-race faces. Evidence for more regressions (number of returns to previously visited AOIs) was also reported for other-race faces. Thus, for both races of observers, similar patterns of differences in the spatial and temporal dynamics of eye-movements were reported between own- and other-race faces. Pupil dilation measurements, used as an index of mental processing load, additionally revealed that other-race faces elicited larger pupil dilations than own-race faces, thus suggesting that they were more difficult to process. Further, participants whose performance was below the median value on other-race recognition showed decreasing pupil dilation over time only to other-race faces, while participants with performance above the median value showed similar pupil dilation to both own- and other-race faces across trials. There was evidence that between races of faces, the top half performers also exhibited eye-movements equivalent in total fixation number and total distance traveled. The authors concluded that, compared to own-race, other-race face encoding elicits attention to different facial features, and also requires greater effort, which may, in their view, be related to less vigorous eye-

movements. It was further concluded that other-race face processing differences occur early during encoding, and that some people's encoding efforts can wane in response to processing difficulty.

An additional eye-tracking study from another research group (Tan et al., 2012) testing Malaysian Chinese observers on recognition of East Asian, Western Caucasian, and African faces found an ORE for African face recognition only. No differences in eye-movement patterns were detected for the different race faces, providing further suggestion that the race of face does not modulate eye-movement patterns for a given race observer.

Further, though inconsistent, evidence that eye movement strategies for facial recognition differ by race of face

Four additional studies (Brielmann et al., 2014; Fu et al., 2012; Hu et al., 2014; Nakabayashi et al., 2012) provide further, but limited, evidence for fixation pattern differences between races of face stimuli. The first reported such differences in a study of White Caucasian observers looking at White and Black faces (Nakabayashi et al., 2012), but the study produced results which partially replicate and partially diverge from the study by Goldinger and colleagues just described. In partial agreement with the study by Goldinger and colleagues, own-race faces elicited longer total dwell times to the left eye, and other-race faces elicited longer total dwell time to the mouth; however, such differences were seen during recognition, and no differences were found during encoding as previously reported. When investigating in more detail, analyses by ordinal fixation number suggested possible fixation pattern differences between races of face stimuli for both first and second fixation Additionally, in contrast to Goldinger and colleagues' findings, more fixations were reported to other- than own-race faces.

While the second and third studies (both from the same research group) also provide evidence that eye movement strategies for facial recognition differ by race of face,

they also provide contradictory evidence to that of the study by Goldinger and colleagues with respect to the nature of these differences. Though the first of these two studies notably did not replicate the ORE in performance, it reported that Chinese participants spent relatively more time fixating the eyes of other-race Caucasian faces, and spent relatively more time fixating the nose and mouth of own-race Chinese faces (Fu et al., 2012). An additional analysis on the stimuli failed to find differences in model-defined salience in the internal facial features between the races of faces. The second of these two studies (Hu et al., 2014), employed a similar paradigm but included Chinese children in addition to adults, and replicated the observer race-specific patterns in both children and adults, and further found that saccade length was shorter for own- than other-race faces. The results, however, also failed to replicate the ORE in performance for both the children and adults. Overall, the results of these two studies contradict the study by Goldinger and colleagues, which rather reported that for East Asian observers, own-race faces elicited relatively more fixations to the eyes, relatively fewer fixations to the nose, and more total saccade distance traveled than other-race faces.

The fourth study (Brielmann et al., 2014) investigated fixation patterns of European observers categorizing Caucasian and Asian faces by race when faces were presented in frontal- , half-profile-, and profile-view. A race categorization task was used rather than the commonly used identification task, because racial categorization was hypothesized to implicitly occur before facial identification in the three studies described above. Thus it was thought to be a potentially useful task to address the ambiguities of those studies if the same fixations pattern differences were to be seen between races of faces as that could then suggest that the differential patterns are due to race *per se*, and not due to a modulation of fixation strategy to more efficiently carry out the identification task. Indeed it was reported that regardless of the view of the faces, Caucasian faces received relatively more fixations to the eyes and relatively fewer fixations to the nose than Asian faces. View of the faces modulated fixation patterns largely in a manner corresponding to the size changes of the features caused by change in view and did not interact with

race of face. Additionally, for the first fixation, and also for subsequent fixations, no bias for the geometric center of faces was detected, but rather fixations to specific facial features, even for profile-views where the features were away from the midlines of the stimuli. From these results it was concluded that race of face did not change the general spatial fixation patterns, but rather the fixation distribution across features.

Evidence that own-race eye-movement patterns begin early and develop with age

Several studies have provided evidence both that fixation pattern differences by race of observer (Kelly, Liu, et al., 2011; Liu et al., 2011; Wheeler et al., 2011) and also by race of face (Hu et al., 2014; Liu et al., 2011; Wheeler et al., 2011; Xiao et al., 2014, 2013) can be detected early and develop with age, though the mechanisms leading to the development of these eye-movement differences are unclear (Kelly, Jack, et al., 2011).

A study (Kelly, Liu, et al., 2011) of children aged 7-12 who were either Western Caucasian children from the UK or East Asian from China reported that Western Caucasian children observers tended to look relatively more at eyes, and East Asian children observers looked relatively more at the nose/center of face revealing that eye-movement patterns differ by race of observer even from and early age. Also, comparing each child's eye movement patterns against the adult eye-movement patterns corresponding to their race (patterns from Blais et al., 2008), a non-significant trend that with age children's' fixation patterns correlated more with adult patterns, suggesting that over that 7-12 year old age range, these patterns may develop to more closely resemble the adult fixation patterns of their own race.

Looking slightly earlier in development, another study (Hu et al., 2014), this time with Chinese children in a younger 4-7 year old range, reported relatively greater fixation time to the eyes of other-race Caucasian faces and relatively more fixation time to

the nose of own-race Chinese faces, as well as shorter distance saccades over the Chinese face. Compared to adult observers, children spent relatively less time fixating the nose. These results reveal that fixation pattern differences by race of face could be observed in these young children, and that Chinese children in this 4-7 year old age group have not yet developed fully adult fixation patterns.

Investigating earlier still in development, a series of studies on infants indicate that development of fixation pattern differences by race of face begin even within the first few months of life. Chinese infants aged 4-9 months viewing Chinese and Caucasian faces showed with increasing age a decrease in looking time at internal facial features, particularly the noses, of other-race Caucasian faces (Liu et al., 2011). Caucasian infants 6-10 months old viewing dynamic Caucasian and African faces in contrast exhibited more own-race eye and less other-race mouth fixation time with increasing age (Wheeler et al., 2011). Along with that data, the study presented a reanalysis of the prior study (i.e. Liu et al., 2011) and found that when only including those Chinese infants 6 months and older, own-race nose fixations increased with age, and other-race nose fixations decreased with age, but that all other features maintained the same between own- and other-race faces. Consistent with this, another study (Xiao et al., 2013) on a group of Caucasian 6- and 9-month old infants viewing dynamic Caucasian and African faces revealed that 6-month olds fixated left eye and mouth more for own race faces, while 9-month olds fixated eyes more for own race, and mouth more for other race. Finally, a study (Xiao et al., 2014) on Caucasian infants 6-9 months old, this time viewing dynamic Caucasian and Chin faces, reported that with increased age the infants exhibited increased looking time to eyes for both races. The findings from this final infant study suggest that Caucasian infants fixation patterns vary for different races of other-race faces (i.e., Chinese vs. African), and the authors suggested that this may be due to the physiognomic differences between the races of faces. Together these infant studies reveal that development of fixation pattern differences by race of face, and possibly also by race of observer, begin even within the first few months of life

Lastly, a study (Kelly, Jack, et al., 2011) on British born Chinese adults viewing East Asian and Western Caucasian faces was conducted to determine if patterns were developed due to culture or due to genetics. No difference in recognition accuracy was found, as would be expected given the participants' experience with both races faces. Even though most of the participants grew up in the UK, they still employed East Asian fixation patterns as determined by a classifier that compared each participant's pattern to the group Eastern and Western patterns from a prior study (Blais et al., 2008). Nevertheless, about 25% showed Western Caucasian pattern. While these data may suggest that culture alone cannot account for the differences in eye movement patterns for different observers, a major limitation of this study was that most of the subjects attended the same activity center at which they engaged with their Chinese cultural heritage. Thus even if eye-movement patterns are modulated by culture as those authors originally hypothesized, this maintained connection with their cultural heritage potentially explains the largely Eastern fixation patterns in the study's participants.

Summary

In summary, the existing eye-tracking studies of the ORE present highly conflicting results, and two general competing views have emerged. The first view is that face processing depends on the culture of the observer, but is equivalent for race of face stimulus (Blais et al., 2008; Caldara et al., 2010; Hills et al., 2013; Hills & Pake, 2013; Miellet et al., 2013; Rodger et al., 2010). The second view is that face processing differs by own- vs. other-race face stimulus, but does not differ by race of observer (Goldinger et al., 2009), and four recent studies (Brielmann et al., 2014; Fu et al., 2012; Hu et al., 2014; Nakabayashi et al., 2012) provide corroborating evidence that face processing differs between races of faces. Finally, though the mechanisms leading to the development of these eye movement differences remain unlcear (Kelly, Jack, et al., 2011), a series of studies have additionally provided evidence both that eye movement pattern differences by race of observer (Kelly, Liu, et al., 2011; Liu et al., 2011; Wheeler et al., 2011) and also by race of face (Hu et al.,

2014; Liu et al., 2011; Wheeler et al., 2011; Xiao et al., 2014, 2013) can be detected early and develop with age.

1.3.2 - References

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Chapter 2 - Differences in looking at own- and other-race faces are subtle and analysis-dependent: An account of discrepant reports

2.1 - Introduction

Fixations are thought to reflect the allocation of visual attention to specific features of the world and eye movements appear to be functionally useful in visual recognition (Henderson, Williams, & Falk, 2005; Kealey, Sekuler, & Bennett, 2008). As such, analysis of eye fixations can potentially provide insight into cognitive processing and, in particular, the stimulus features used in a given task. Thus, eye-tracking is a useful technique to study the basis of the Other-Race Effect (ORE) which is the robust and well-established finding that people are generally poorer at facial recognition of individuals of another race than of one's own race (Bothwell, Brigham, & Malpass, 1989; J. Brigham, Bennett, Meissner, & Mitchell, 2007; John C. Brigham & Malpass, 1985; Chance & Goldstein, 1996; Cross, Cross, & Daly, 1971; Lindsay, Jack, & Christian, 1991; Malpass & Kravitz, 1969; Meissner & Brigham, 2001; O'Toole, Deffenbacher, Valentin, & Abdi, 1994; Platz & Hosch, 1988; Shapiro & Penrod, 1986; Shepherd, Deregowski, & Ellis, 1974). In particular, eye-tracking can potentially provide insight into the long unresolved questions of which specific facial features are attended during own- and other-race face processing and whether there are differences in the diagnostic value of facial features among races. Surprisingly, although the ORE has been studied for over forty years and the eye-tracking technique has been used to study face perception for even longer (Yarbus, 1965), only a handful of studies of the ORE to date have utilized eye-tracking (Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Brielmann, Bülthoff, & Armann, 2014; Caldara, Zhou, & Miellet, 2010; Fu, Hu, Wang, Quinn, & Lee, 2012; Goldinger, He, & Papesh, 2009; Hills, Cooper, & Pake, 2013; Hills & Pake, 2013; C. Hu, Wang, Fu, Quinn, & Lee, 2014; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet, Lao, Zhou, He, & Caldara, 2012; Sébastien Miellet, Vizioli, He, Zhou, & Caldara, 2013;

Nakabayashi, Lloyd-Jones, Butcher, & Liu, 2012; Rodger, Kelly, Blais, & Caldara, 2010; Tan, Stephen, Whitehead, & Sheppard, 2012).

While such prior studies have provided valuable data for advancing our understanding of the basis of the ORE, they present highly conflicting results from which two competing views have emerged with respect to own- and other-race face identification mechanisms. The first view is that facial identification processing depends on the culture of the observer, but is equivalent for different races of faces (Blais et al., 2008; Caldara et al., 2010; Hills et al., 2013; Hills & Pake, 2013; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet et al., 2012, 2013; Rodger et al., 2010; Tan et al., 2012). The bulk of the evidence for this first view comes from one research group, which used variations on a paradigm and highly similar analysis techniques across studies. The second view is that face identification processing does not depend on the race of observer but does differ for own- vs. other-race faces (Goldinger et al., 2009; Or, Peterson, & Eckstein, 2013). In accord with this second view, three recent studies (Fu et al., 2012; C. Hu et al., 2014; Nakabayashi et al., 2012) provide further evidence that facial identification processing differs between races of faces. In light of these conflicting reports, the aim of the current study is to address the fundamental question of whether eye-movement patterns from a given observer differ for same- versus other-race face identification and to understand the basis for the conflicting reports.

Although the eye-tracking studies described above utilize different paradigms (e.g. 2, 5, and 10 second encoding, different pre-stimulus fixation locations, etc), stimuli (neutral vs. emotional faces, frontal vs. half-profile, Asian vs. African faces, etc), measures (relative frequencies vs. durations, etc), and analyses (maps vs. Areas of Interest, etc), it is astonishing that such fundamentally different results and interpretations have emerged among studies with essentially the same task, namely to encode and recognize same- and other-race faces. My study has advantages for both comparing with prior research and for potentially finding novel results. First, I used two other-race face categories (African and Chinese), in contrast to prior

studies, which typically only used one. Second, I employed multiple analytic approaches, including the use of both AOI (Area of Interest) and heatmap analyses. Third, I controlled and systematically varied the fixation location prior to stimulus onset to detect differences in fixations to other race faces independent of visuomotor factors such as those investigated in chapters 3 and 4 (J. Arizpe, Kravitz, Yovel, & Baker, 2012; J. M. Arizpe, Walsh, & Baker, 2015). Finally, I obtained eye-tracking data during both the encoding and recognition phases of the study. By adopting these approaches, the present study aims to bridge the gaps between prior studies, test for replication of results, and identify any factors that may account for the disagreement among prior studies.

I found that for Caucasian observers, recognition for Chinese faces was impaired relative to Caucasian and African faces. Further I found evidence for significantly increased fixations to the eyes in own- (Caucasian) versus other-race (African and Chinese) faces, and significantly increased fixations to the mouth for other- than own-race faces. Compared to Caucasian faces, Chinese faces also elicited significantly more fixations in the nose region. Thus, I conclude that other-race faces elicit different fixation patterns compared to own-race faces. These differences between face races were relatively small, however, thus potentially explaining the conflicting reports in prior studies regarding the influence of race of face on eye-movement patterns. I suggest that differences in paradigm and limitations of the analyses in prior studies may have led to a lack of sensitivity for this effect in some studies (Blais et al., 2008; Caldara et al., 2010; Hills et al., 2013; Hills & Pake, 2013; Sébastien Miellet et al., 2013; Rodger et al., 2010; Tan et al., 2012), and a detection of this effect in others (Fu et al., 2012; Goldinger et al., 2009; C. Hu et al., 2014; Nakabayashi et al., 2012).

2.2 - Methods

Ethics Statement

All participants gave written informed consent and were compensated for their participation. The study was approved by the Institutional Review Board of the National Institutes of Health, Bethesda, Maryland, USA.

Participants

30 Caucasian participants (11 male), living in the Washington D.C. area. One participant's data was excluded from analyses of test phase eye-movements due to partial data corruption.

Eye-tracking

I used an EyeLink II headmounted eye-tracker (SR Research, Mississauga, ON, Canada), and sampled pupil centroid at 500 Hz. The default nine point calibration and validation sequences were repeated throughout the experiment. Both eyes were calibrated and validated, but only the eye with the lowest maximum error was recorded for the trials following a particular calibration. Calibration was repeated when maximum error at validation was more than 1° of visual angle. Before each trial, a drift correction was performed. Default criteria for fixations, blinks, and saccades as implemented in the Eyelink system were used.

Stimuli

I collected 32 Caucasian-American, 32 African-American, and 32 Chinese face images (16 male and 16 female for each race), for a total of 96 grayscale neutral expression frontal-view face images (see Figure 1a for examples). All Caucasian faces were taken from the neutral expression 18 to 29 age group of the Productive

Aging Lab Face Database established by the University of Texas at Dallas (http://vitallongevity.utdallas.edu/stimuli/facedb/categories/neutral-faces.html) (Minear & Park, 2004). African-American faces were taken from the neutral expression 18 to 29 age group of the Productive Aging Lab Face Database, from the MacBrain ("NimStim") Face Stimulus Set made by the MacArthur Foundation Research Network on Early Experience and Brain Development (http://www.macbrain.org/resources.htm), and from the Color FERET Database (http://www.nist.gov/itl/iad/ig/colorferet.cfm) (Phillips, Moon, Rizvi, & Rauss, 2000; Phillips, Wechsler, Huang, & Rauss, 1998) established by the United States Department of Defense (DOD) Counterdrug Technology Program. All Chinese faces were taken from the CAS-PEAL Face Database (http://www.jdl.ac.cn/peal/index.html) (Gao et al., 2008) established by the ICT-ISVISION Joint Research and Development Laboratory (JDL) for Face Recognition. Each face was scaled to have a forehead width subtending 10 degrees of visual angle at presentation and was rotated to correct for any tilt of the head. Images were cropped to remove most of the background, but not the hair or other external features, and all images were equated for overall luminance. At presentation, images were centered on a black background. To eliminate any possible stimulus bias as the source of any laterality effects, half of the faces were randomly left-right flipped across the vertical midline of the image for each participant.

The website of the Productive Aging Lab Face Database states: "This [database] contains a range of face of all ages which are suitable for use as stimuli in face processing studies. Releases have been signed by the participants we photographed and the faces may be included in publications or in media events." Development of the MacBrain Face Stimulus Set was overseen by Nim Tottenham and supported by the John D. and Catherine T. MacArthur Foundation Research Network on Early Experience and Brain Development. Please contact Nim Tottenham at tott0006@tc.umn.edu for more information concerning the stimulus set. Portions of the research in this paper use the FERET database of facial images collected under the FERET program, sponsored by the DOD Counterdrug

Technology Development Program Office. The research in this paper use the CAS-PEAL-R1 face database collected under the sponsor of the Chinese National Hi-Tech Program and ISVISION Tech. Co. Ltd.

Areas of Interest (AOIs)

For the purposes of analysis and for aspects of my experimental design, rectangular areas-of-interest (AOIs) were manually drawn prior to the experiment for each face around the right and left eyes, bridge of nose (i.e. middle of eye region), right and left half of nose, and right and left half of mouth (Figure 1b, for example) using EyeLink Data Viewer software. These AOIs were never visible to participants during the experiment.

Design

I varied race of face stimulus (Caucasian, African, Chinese) and pre-stimulus fixation location ("start position") across the trials of the experiment comprised of two phases: study and test. I systematically varied start position because fixation patterns are affected by visuo-motor factors (e.g. start position, as revealed in chapters 3 and 4) (J. Arizpe et al., 2012; J. M. Arizpe et al., 2015) in addition to stimulus factors (face). During the study phase, participants observed 48 faces (16 of each race, 8 male for each race) in a self-paced manner (up to 10 seconds, self-terminating trials with a button press). At test, participants observed 96 faces (the 48 study phase faces plus 48 new faces) for a limited duration (one second only) and indicated whether or not they recognized each face as one observed during study (old/new task) with a button press. Participants were instructed to respond within two seconds following stimulus onset, as soon as they thought they knew the answer (Figure 1c). The experiment was programmed in Python and interfaced with the eye-tracker.

Start positions were either above, below, right of, or left of the internal features of the

upcoming face stimulus (see Figure 1b for examples). Coordinates for a given start position were calculated uniquely for each face stimulus to be equidistant from all of the nearest internal facial features. Specifically, for right and left start positions, the unique coordinate that was equidistant from the centers of the nearest eye, nearest half-nose, and nearest half-mouth AOI was calculated numerically for each face. Upper start positions were equidistant from the center of the two eye AOIs, and the lower start positions were equidistant from the two half-mouth AOIs. Distances from the upper and lower start positions to their respective AOI centers were constrained to be the mean of the right and left start position distances from their respective AOI centers.

Before stimulus onset, participants fixated at the start position, indicated by a standard Eyelink II calibration target (0.17° diameter black circle overlaid on a 0.75° diameter white circle) on the black screen. Participants initiated the trial by pressing a button while looking at the fixation target. In this period, a drift correction was performed. A colored dot (0.5° diameter) remained after drift correction, and the stimulus appeared only after a participant had fixated at the dot for an accumulated total of 1500 ms. This ensured that drift correction and fixation were stable prior to stimulus onset. If more than 1500 ms of fixation away from the start position accumulated before the trial could be initiated, drift correction was repeated. A fixation was considered off the start position if it landed more than 0.5° from the center of the dot. Dot color changed successively from red to yellow to green in order to signal to the participant that a maintained fixation was successfully detected at the start position.

In both the study and test phases, there were equal proportions of trials for each combination of levels of the factors of face race, face gender, and start position. When a given face was presented in both the study and test phases, the face images were identical across study and test phases. This practice had the advantage of making analysis more straightforward and easily interpreted since changes in viewpoint, emotional expression, lighting, etc. would not serve as

confounds for eye-movement differences; however, this practice also has the limitation of potentially allowing simple image matching mechanisms, in addition to the more abstract facial identification mechanisms of interest. The particular subset of faces used in the study phase was randomized across participants. Of the faces presented in both study and test phase, half of the faces were presented with the same start position at study and test and for the other half, the start position on the other side of the face was used (e.g. left to right start position between study and test; upper to lower between study and test).
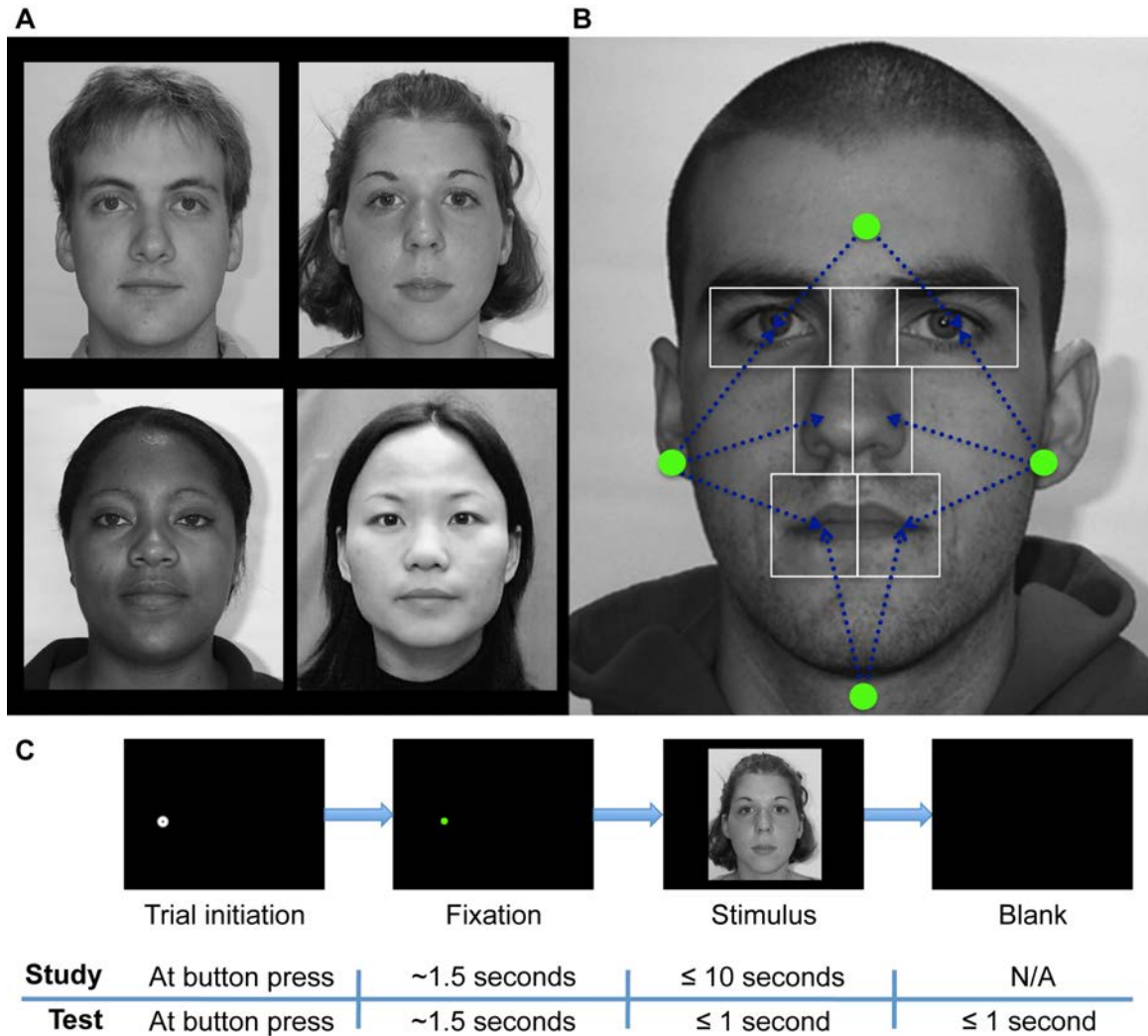
Figure 1. Study design. (A) *Four example face stimuli.* **(B)** *AOIs for one face showing the calculation of start positions, which were determined separately for each face and defined relative to that face. Green dots schematically illustrate the potential start positions relative to the upcoming face. Left and right start positions were equidistant from centers of the nearest eye, nose and mouth AOIs. Upper and lower start positions were equidistant from the centers of the two eye or two mouth AOIs, respectively. Dotted blue lines schematically illustrate that the start positions were equidistant from the centers of the indicated AOIs.* **(C)** *Trial sequences in study and test phases. A face was only presented if the participant successfully maintained fixation for a total of 1.5 seconds. After face onset in the study phase, participants were free to study the face for up to 10 seconds and pressed a button to begin the next trial. In the test phase, faces were presented for one second only and participants responded with button presses to indicate whether the face was 'old' or 'new'.*

Analyses

Software

Fixation and AOI data were obtained through EyeLink Data Viewer software by SR Research. Subsequent analyses on these data and behavioral data from the test phase were performed with custom Matlab (The MathWorks, Inc., Natick, MA, USA) code. ANOVAs were performed in SPSS (IBM, Somers, NY).

Behavior

I assessed participants' discrimination performance, response bias, and reaction time on the old/new recognition task in the test phase. d' (d' = z(hit rate) - z(false alarm rate)) and criterion c (c = -[z(hit rate) + z(false alarm rate)]/2) were computed for discrimination performance for each participant, broken down by race of face and start position. Reaction times were analyzed for correct trials only. Reaction time values more extreme than 2.5 standard deviations from the median within each condition and participant were excluded from analysis. Reaction time analyses were broken down by Race of Face and Start Position conditions with analysis being performed on the medians calculated for each subject. Greenhouse-Geisser correction was applied if any of the factors or interactions of a given ANOVA violated sphericity.

AOI Analyses

I assessed the relative frequencies of fixations across the AOIs as a function of my experimental manipulations. The AOIs used were left eye, bridge, right eye, nose (left and right sides combined to be comparable with prior studies), mouth (left and right sides combined), and other (outside the defined AOI regions). Given the variable numbers of fixations across trials and across participants, only the first five fixations of each trial were included in the analyses of the study phase. Participants

rarely made fewer than five fixations in study phase trials and, further, the first few fixations are likely to be the most essential for the task, as indicated in prior research (Hsiao & Cottrell, 2008). For the test analysis phase, all fixations within the entire stimulus viewing time (limit of one second per trial) were included. Relative frequency was calculated for each AOI as the number of actual fixations divided by the total number of possible fixations across all trials of the given condition for each subject (e.g. 16 study phase trials with Chinese faces multiplied by 4 fixations per trial = 64 total possible fixations across all Chinese face study phase trials). ANOVAs on relative frequencies excluded the relative frequency value for the region outside of the AOIs.   Greenhouse-Geisser correction was also applied if any of the factors or interactions of a given ANOVA violated sphericity

Spatial Density Analyses

I mapped the spatial density of fixations during the study phase as a function of my experimental manipulations. Each fixation was plotted with equal density and spatial extent, and fixations were not weighted by the fixation duration (essentially the same qualitative pattern of results was obtained when this weighting function was applied). Fixations beyond the fifth fixation were excluded from the analysis to ensure an equal amount of data across trials. The first fixation was also excluded (See Results for motivation). To ensure that summation of fixation maps across different face trials produced spatially meaningful density maps, fixation maps for individual faces were first aligned to a common reference frame using simple translations only. This reference frame was defined by the internal facial features. Specifically, the alignment minimized the sum of the squared differences between the center of the AOIs for each face and the average centers of the AOIs across all 96 faces. Within this common reference frame, fixations were then plotted as Gaussian densities with a mean of 0 and a standard deviation of 0.3° of visual angle in both the x and y dimensions. These density plots were then averaged across trials and across participants. A small proportion of analyzed fixations (< 2% during study, < 1% during test) fell outside of the bounds of the stimulus image region (i.e. onto the

black background outside the square frame of the face stimulus). These fixations were not excluded from the analyses, but are simply not visible in plots. The resulting maps show the spatial fixation densities, using a color scale from zero to the maximum density value observed, with values approaching zero being deep blue. All maps within a single figure contain the same total number of fixations and so are scaled the same to allow for direct comparison.

Spatial Density Contrasts

Difference Maps. In order to view differences in the spatial fixation density between two conditions, a pixel-wise subtraction between two spatial density maps was performed for each participant and then averaged across participants.

Statistical Maps. In order to produce maps of statistically significant differences in the spatial density map contrasts, a Monte Carlo permutation test was performed on fixation locations between the contrasted conditions. A Monte Carlo permutation test (also called an approximate permutation test or a random permutation test) is a standard, accurate and robust method of performing a significance test on data that is not known to have a parametric (e.g. normal) distribution of values, such as my data. I have used this type of statistical analysis method on eye-tracking data in a prior study (J. Arizpe et al., 2012) detailed in chapter 3, based on methods applied to the analysis of functional brain imaging data (Nichols & Holmes, 2002) and similar to that used in a prior study of eye tracking (Leonards et al., 2007).

The null hypothesis in the Monte Carlo permutation tests was that the distributions of fixation locations of each ordinal fixation (i.e. fixation 2, fixation 3 etc.) were the same between the contrasted conditions (e.g. fixation 2 in Caucasian versus Chinese trials, or fixation 3 in right start position versus left). Thus, exchangeability of fixation locations between the given contrasted conditions was assumed only for fixations of the same ordinal value in the sequence of five fixations per trial. Only the first five fixations were analyzed for the same reasons that only the first five fixations were

analyzed in the AOI analyses. 104,000 resampling iterations were performed for each statistical map. For each iteration, locations of fixations were resampled for each individual participant according to the assumed exchangeability, then a new resampled spatial density contrast was produced. These resampled maps were then averaged across participants to produce 104,000 group difference maps, the distribution of which was used to determine significance. Maps of p-values were computed pixel-wise based on the number of corresponding pixels in the resampling iterations that were greater than a given positively valued pixel (i.e. where condition 1 had a greater density) in the true spatial density contrast and that were less than a given negatively valued pixel (i.e. condition 2 greater) in the true spatial density contrast. The maps were thresholded at a pixel significance of $p < 0.01$ (equivalent to two-tailed $p < 0.02$).

For eye-tracking data, my statistical analysis has advantages over other methods of performing significance tests on contrasted fixation maps. A pixel-wise t-test is inappropriate because fixation density data across participants does not approximate a normal distribution at each pixel of a heatmap. Pixel-wise non-parametric tests could create a large multiple comparisons problem, which grows as the pixel resolution of heatmaps grow. In my analysis, fixation locations are exchanged rather than pixels; therefore, increasing the resolution at which heatmaps are displayed does not exacerbate the multiple comparisons problem. My analysis is an alternative to a another approach, which has been implemented by Caldara and colleagues in a free Matlab toolbox called iMap (Caldara & Miellet, 2011).

Correction for Multiple Comparisons on Statistical Maps. In order to reduce the chance of false positives in my statistical maps due to multiple comparisons, I utilized False Discovery Rate (FDR) control, which enables setting the statistical thresholds to those at which a given estimated rate of false positives can be attained. The AFNI (http://afni.nimh.nih.gov) function 3dFDR was applied to each of the statistical maps. Because approximately half of the pixels in the statistical maps did not correspond to face stimulus pixels and because my aim was to detect fixation

differences over internal facial features, the same non-face region mask was applied to all statistical maps before FDR correction so that those pixels would be ignored in the 3dFDR algorithm. My FDR threshold was set to $q < 0.05$, at which it would be estimated that 5% of surviving pixels are false positives. Cluster size correction is an alternative method to FDR control for multiple comparisons correction, though in the context of this study, where fine-grained mapping of highly significant regions is preferred to detection of larger area regions, I chose to employ FDR control.

Profile Density Analyses

Because AOI analyses can be criticized for requiring a highly subjective *a priori* segmentation of visual features (Caldara & Miellet, 2011), but spatial statistical maps can be criticized for lacking sensitivity, I conducted additional exploratory analyses that were meant to increase sensitivity without subjective segmentation. In particular, I calculated profile densities (i.e. densities summed along a single dimension of a heatmap) for the different conditions during the study phase. The y-profile plots were the result of summing along the horizontal dimension (x-axis) of a spatial density heatmap. The y-profile plots visualize fixation density over specific facial features without respect to laterality or fine differences in horizontal position. Since the primary effects of interest here focused on which facial features were fixated (eyes, nose, mouth), I report only y-profile plots.

Profile Density Contrasts

Difference Plots. In order to visualize potential differences in profile density between two conditions, spatial density difference maps were summed along the vertical dimension to produce x-profile density difference plots and summed along the horizontal dimension to produce y-profile density difference plots. X-profile density difference plots visualize potential differences in left-right face laterality between contrasted conditions, and y-profile density difference plots visualize potential differences in density over specific facial features.

Profile Statistical Maps. To find regions of statistically significant difference in the profile density difference plots, I re-used the 104,000 resampled iterations from the spatial density contrast statistical map analyses to perform a Monte Carlo permutation test on the contrasted profile plots. All resampled iterations from the relevant spatial density Monte Carlo permutation test were summed along the vertical dimension to produce the resampled iterations of the x-profile Monte Carlo permutation test, and were summed along the horizontal dimension to produce the resampled iterations of the y-profile Monte Carlo permutation test. P-values were computed pixel-wise (i.e. at each pixel along the relevant dimension) based on the number of corresponding pixels in the resampling iterations that were greater than a given positively valued pixel (i.e. where condition 1 had a greater profile density) in the true profile density difference plot and that were less than a given negatively valued pixel (i.e. condition 2 greater) in the true profile density difference plot. Maps visualizing the results were thresholded at a pixel significance of $p < 0.025$ (equivalent to two-tailed $p < 0.05$). In these maps, pixels along the entire orthogonal dimension were highlighted where the dimension of interest had a significantly different profile density between contrasted conditions.

Correction for Multiple Comparisons on Profile Statistical Maps. FDR control with threshold of $q < 0.05$ was again employed, but this time utilizing all pixels for each profile statistical map.

2.3 - Results

Discrimination, Criterion, and Reaction Time
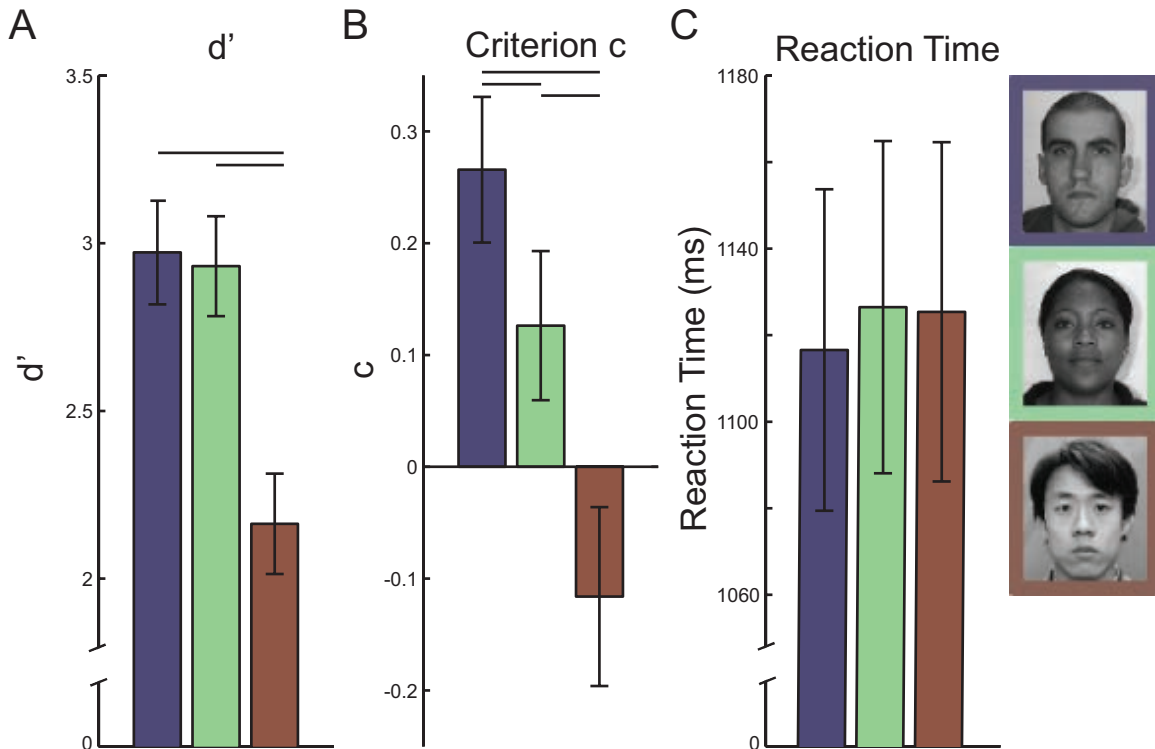
***Figure 2. Effects of race of face on recognition performance. (A)** Face recognition performance, measured by d', was significantly lower for Chinese compared to Caucasian and African faces. **(B)** Criterion scores for Caucasian faces were higher (stricter) than African and Chinese faces. Also criterion scores for African faces were higher than for Chinese faces. **(C)** Reaction times did not differ among different race faces. Error bars indicate the between-subjects standard error.*

Reduced Discrimination for Chinese Faces, Conservative Bias for Caucasian Faces

Consistent with prior reports, I observed evidence for an Other-Race Effect in the discrimination scores (d') and criterion scores (c) of my Caucasian participants, particularly for Chinese faces (Figure 2). A two-way ANOVA on discrimination scores (Figure 2a), with Race (Caucasian, African, Chinese) and Start Position (left, right, up, down) as within-subject factors revealed a significant main effect of Race ($F(2,58) > 29.20$, $p < 0.001$, $\eta_p^2 = 0.50$), but no main effect or interactions involving Start Position ($p > 0.19$, $\eta_p^2 < 0.053$). Pairwise Race comparisons, pooling across

Start Position, revealed significantly better discrimination performance for Caucasian ($t(29) > 5.99$, $p < 0.001$, one-tailed, bias corrected $G_{Hedges} = 0.94$) and African ($t(29) > 5.36$, $p < 0.001$, two-tailed, bias corrected $G_{Hedges} = 0.31$) faces than Chinese faces. No significant difference was found between Caucasian and African discrimination ($p > 0.33$, one-tailed, bias corrected $G_{Hedges} = 0.048$). Thus an other-race discrimination deficit was observed for Chinese faces only.

Criterion (c) scores estimated bias in responding that a face was recognized, where a higher criterion score indicates a stricter criterion or more reluctance to respond that a face was recognized. A two-way ANOVA on criterion scores (Figure 2b), with Race and Start Position as within-subject factors revealed a significant main effect of Race ($F(1.42,41.06) > 7.84$, $p < 0.005$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.213$), but no main effect or interactions involving Start Position (both $p > 0.27$, Greenhouse-Geisser corrected, $\eta_p^2 < 0.044$). Pairwise Race comparisons, pooling across Start Position, revealed significantly higher criterion scores for Caucasian faces than African faces ($t(29) > 2.24$, $p < 0.017$, one-tailed, bias corrected $G_{Hedges} = 0.37$) and Chinese faces ($t(29) > 3.60$, $p < 0.0008$, one-tailed, bias corrected $G_{Hedges} = 0.93$). Also criterion scores were higher for African faces ($t(29) > 2.39$, $p < 0.024$, two-tailed, bias corrected $G_{Hedges} = 0.58$) than Chinese faces. One-sampled t-tests on criterion scores for each race revealed that only scores for Caucasian faces significantly differed from zero (Caucasian: $p < 0.0005$, two-tailed, Other Races: $p > 0.072$, two-tailed). Together these results reveal that other-race faces elicited a less conservative criterion to report that a face was recognized, with Chinese faces eliciting the least conservative.

There were no differences in viewing time in the study phase (mean study viewing time was 7023 ms with a 418 ms standard error for Caucasian faces, 7112ms with a 450 ms standard error for African faces, and 6933ms with a 415 ms standard error for Chinese faces) or reaction time during the test phase (Figure 2c). A two-way ANOVA on study viewing time did not yield any significant main effects of Race or Start Position or any interaction (all $p > 0.51$). Similarly, a two-way ANOVA on

reaction time data did not yield any significant main effects of Race or Start Position or any interaction (all p > 0.26).

Temporal Dynamics of Fixations

In my prior studies of facial fixation patterns (J. Arizpe et al., 2012; J. M. Arizpe et al., 2015) detailed in chapters 3 and 4, I found that the first ordinal fixation was shorter in duration than subsequent fixations, suggesting that facial information for individuation was not deeply processed during the first fixation (see also Hsiao & Cottrell, 2008), and focused my analyses on the subsequent fixations only. The same effect was observed in the current data (see S1 Supplementary Material for full details), and so I excluded the first ordinal fixation in my analyses of the spatial distribution of fixations below, though qualitatively the same results were observed when it was included (reported in S1 Supplementary Material). Importantly, Race of Face did not significantly influence the temporal dynamics of eye-movements (Figures S1 and S2 in S1 Supplementary Material). Additionally though, I found an influence of Phase (Study, Test) on the temporal dynamics of fixations (Figure S4 in S1 Supplementary Material), which may reflect the influence of the time restriction in the test phase. Therefore, my main analyses focus on data from the Study Phase during which eye-movements were unrestricted.

Spatial Patterns of Fixations

AOIs

Independent Influences of Race of Face and Start Position

I next focused on the specific pattern of fixations with the first fixation excluded (Figure 3). Area of Interest (AOI) analyses revealed that Race and Start Position both influence fixation patterns, but also indicate that their influences are independent. A three-way ANOVA on the relative frequency of fixations in the study

phase with AOI (left eye, bridge, right eye, nose, and mouth), Race (Caucasian, African, Chinese) and Start Position (left, right, up, down) as within-subject factors, revealed a significant main effect of AOI ($F(2.81,81.55) > 5.24$, $p < 0.004$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.15$), indicating that not all AOIs were fixated with equal frequency. There were no other main effects, neither for Start Position ($F(2.78,80.61)>2.61$, $p>0.060$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.083$) nor for Race ($F(1.96,56.78)>2.75$, $p>0.070$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.087$), but both of these factors interacted separately with AOI. Critically, the significant interaction between Race and AOI ($F(6.31, 183.00) > 2.43$, $p < 0.025$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.077$) indicates that fixation patterns varied by Race. The significant interaction between Start Position and AOI ($F(7.24, 209.84) > 17.51$, $p < 0.001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.38$) replicates my prior work (J. Arizpe et al., 2012; J. M. Arizpe et al., 2015) reported in chapters 3 and 4, demonstrating that fixation patterns vary by Start Position. There was no interaction between Start Position and Race ($F(4.77, 138.40) < 0.79$, $p > 0.54$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.027$) and no significant three-way interaction among AOI, Race, and Start Position ($F(12.60, 365.53) < 1.44$, $p > 0.14$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.047$), suggesting that the influences of Race and Start Position on fixation pattern are independent. The effect size of the AOI x Start Position interaction ($\eta_p^2 = 0.38$) was greater than that of the AOI x Race interaction ($\eta_p^2 = 0.077$), indicating that the independent effect of Start Position on the spatial pattern of eye-movements was greater than that of Race.

These patterns in the study phase were replicated in the test phase (Supplemental Figure 3) in a similar three-way ANOVA on the relative frequency of fixations in the test phase with AOI, Race, and Start Position as within-subject factors. This revealed a significant main effect of AOI ($F(2.29,64.02) > 5.05$, $p < 0.008$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.15$) in the test phase, again indicating that not all AOIs were fixated with equal frequency. Again, there were no other main effects, neither for Start Position ($F(2.19,61.41)>1.90$, $p>0.13$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.064$) nor for Race ($F(1.89,52.82)>1.92$, $p>0.15$, Greenhouse-

Geisser corrected, $\eta_p^2 = 0.064$), but both of these factors interacted separately with AOI. The significant interaction between Race and AOI ($F(5.43, 152.01) > 3.58$, $p < 0.004$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.11$) again critically indicates that fixation patterns varied by Race. The significant interaction between Start Position and AOI ($F(6.36, 177.96) > 11.96$, $p < 0.001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.30$) additionally replicates that fixation patterns vary by Start Position. There was no interaction between Start Position and Race ($F(4.67, 130.86) < 1.31$, $p > 0.25$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.045$) and no significant three-way interaction among AOI, Race, and Start Position ($F(12.53, 350.75) < 1.46$, $p > 0.13$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.049$), suggesting again that the influences of Race and Start Position on fixation pattern are independent. The effect size of the AOI x Start Position interaction ($\eta_p^2 = 0.30$) in the test phase was greater than that of the AOI x Race interaction ($\eta_p^2 = 0.11$), further indicating that the independent effect of Start Position on the spatial pattern of eye-movements was greater than that of Race. Given the independence of the effects of Start Position and Race and because the influence of Start Position has been thoroughly investigated in two prior studies (J. Arizpe et al., 2012; J. M. Arizpe et al., 2015) detailed in in chapters 3 and 4, the following analyses will mainly focus on the influence of Race of face stimulus on eye-movements.

Small but Systematic Influences of Race of Face Stimulus

The preceding analyses suggest an effect of Race of face on fixation patterns. Relative frequencies of fixations in my AOIs for Caucasian and Chinese faces (Figure 3a) highly resembles the analogous plot in the prior study (Figure 2 in Goldinger et al., 2009, which is the data for Caucasian observers looking at Caucasian and Asian faces with five second encoding duration), even though the precise way my AOIs were drawn differs slightly and my data utilizes only the second through fifth fixations. Notably, as previously indicated, relative frequency differences between own- and other-race faces (Figure 3a for study phase, Supplemental Figure 3a for test phase) in the left eye, right eye, nose, and mouth

AOIs all, without exception, tended in the same direction as the prior study, specifically reflecting a relatively greater proportion of fixations over both eyes in own-race faces and relatively greater proportion of mouth and nose fixations for other-race faces. To test more rigorously for replication of this prior study (Goldinger et al., 2009), I conducted planned pairwise comparisons testing the hypotheses of relatively greater proportion of fixations for own- (Caucasian) versus other-race (African or Chinese) faces in each eye AOI and relatively greater proportion of fixations for other- versus own-race faces in the nose and mouth.

For the study phase (Figure 3), the tests for each of the two eye AOIs revealed significant differences in the hypothesized direction only for Caucasian versus Chinese faces (both eyes $t(29) > 1.76$, $p < 0.044$, one-tailed; bias corrected $G_{Hedges} = 0.17$ and 0.26, for left and right eyes, respectively) and not for Caucasian versus African faces (both eyes $t(29) < 1.23$, $p > 0.11$, one-tailed, though both tended in the hypothesized direction, bias corrected $G_{Hedges} < 0.16$). Additionally, the tests for the nose and mouth AOIs in the study phase yielded significant differences in three of the four comparisons (nose own- versus both other-race and mouth own-race versus African all $t(29) > 2.15$, $p < 0.021$, one-tailed, bias corrected $G_{Hedges} = 0.20\text{-}0.26$), where the mouth for Chinese versus Caucasian faces ($t(29) > 1.33$, $p > 0.095$, one-tailed, bias corrected $G_{Hedges} = 0.17$) did not reach significance.
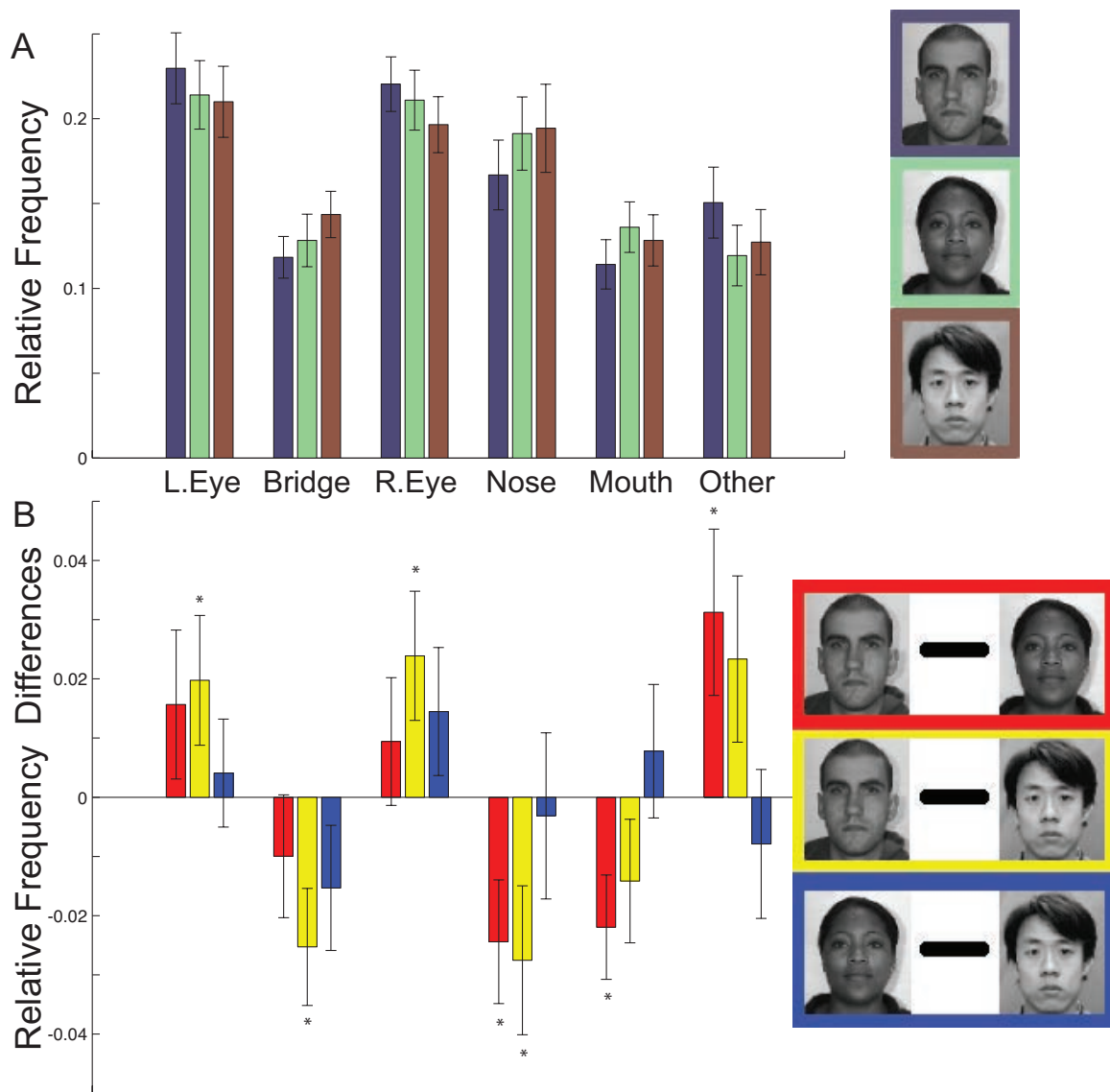
Figure 3. Distribution of fixations across AOIs for own- and other-race faces during the study phase. (A) *Relative frequencies of fixations for each race of face across AOIs for the second through fifth fixations pooled.* ***(B)*** *Within-subject differences among race of face conditions from (A) reveal significantly more eye fixations for Caucasian than Chinese faces, significantly fewer nose fixations for own- than other-race faces, and significantly fewer mouth fixations for Caucasian than African faces. Error bars indicate the between-subjects standard error.*

For the test phase data (Supplemental Figure 3), the same set of pairwise tests on relative frequency data from the entire period the test stimulus was visible revealed significant differences in the hypothesized direction for Caucasian versus Chinese for both eye AOIs (both $t(28) > 2.70$, $p < 0.007$, one-tailed; bias corrected $G_{Hedges} = 0.21$ and 0.20, for left and right eyes, respectively) and for Caucasian versus African for the right eye ($t(28) > 2.07$, $p < 0.024$, one-tailed, bias corrected $G_{Hedges} = 0.17$),

but not for the left (t(28) < 0.43, p > 0.33, one-tailed, bias corrected G_{Hedges} = 0.034). For the nose AOI, they revealed marginally more fixations for Chinese (t(28) > 1.68, p < 0.052, one-tailed, bias corrected G_{Hedges} = 0.14), but not for African (t(28) < 0.36, p > 0.36, one-tailed, bias corrected G_{Hedges} = 0.026), than Caucasian faces. They also revealed significantly more fixations to the mouth for African (t(28) > 2.22, p < 0.018, one-tailed, bias corrected G_{Hedges} = 0.23), but not Chinese (t(28) < 0.26, p > 0.40, one-tailed, bias corrected G_{Hedges} = 0.026), than Caucasian faces.

Together these data show that I largely replicated in AOI analyses the prior study that reported a relatively greater proportion of fixations over both eyes for own-race faces and a relatively greater proportion of mouth and nose fixations for other-race faces.

Spatial Density Maps

The AOI analyses suggested a small effect of Race of face on fixation patterns. Because AOI analyses can be criticized for requiring a highly subjective *a priori* segmentation of visual features (Caldara & Miellet, 2011), I further investigated the influence of Race of face on fixation patterns through spatial density map analyses (see Methods). Because the AOI analyses suggested that the influence of Start Position on fixation patterns does not interact with Race, I pooled all Start Positions together for my spatial density map analyses to find effects of Race.

Spatial Density Maps: Spatial Tendencies of Fixations Differ by Race of Face

Spatial density maps on study phase data for each Race of face with all Start Positions pooled revealed fixation patterns which are consistent with the AOI relative frequency plots, but also showed more fine-grained spatial patterns in the fixations (Figure 4). The average faces for each race underlie the spatial density maps in the figure. The general shapes of the envelopes of fixation density over the faces were qualitatively similar for the different races, though some differences were apparent.

Specifically, for all races, I observed the commonly reported inverted triangle shape with a strong tendency toward eyes and an overall tendency for the left side of the face. Also consistent with the AOI analyses, the spatial density maps suggest that Caucasian faces may have elicited fewer fixations to the mouth and nose regions than African and Chinese faces. Additionally, there are hints of fine-scaled spatial differences between the races in the eye and bridge regions of the faces, in addition to possibly fewer fixations to the eye-region in African faces than Caucasian and Chinese. It is also notable that Caucasian fixation densities appear to have more focal peaks than the African and Chinese faces; therefore, perhaps fixation patterns are also more diffuse for other-race faces.
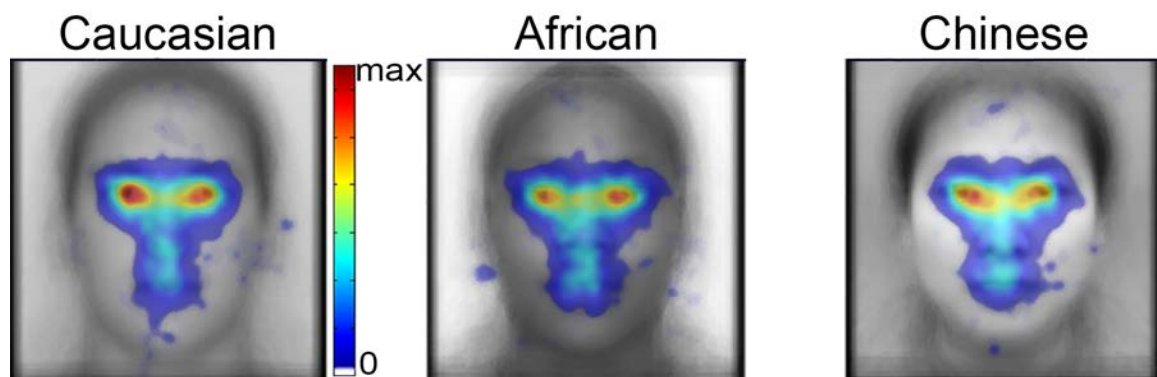
Figure 4. Spatial density of fixations for Caucasian, African, and Chinese faces during the study phase. *The faces plotted beneath the spatial density plots are the average of all faces of the given race after alignment. Fixations are plotted as Gaussian densities summed across trials and participants. Fixation density is indicated using a color scale from zero to the maximum density value observed, with zero being transparent.*

Contrast Maps

In order to visualize the differences in fixation density suggested by the spatial density maps, I subtracted spatial density maps (Figure 5a). The average face subtractions between races underlay the contrast maps in the figure. These contrasts show that Caucasian faces elicited fewer fixations to the mouth and nose regions than African and Chinese faces. Particularly striking is the relatively higher magnitude of fixation density over the left eye of Caucasian faces compared to African and Chinese faces, in addition to fewer fixations to the eye-region in African faces than Caucasian and Chinese.

In order to determine the statistical significance of these apparent differences in fixation patterns between races of face, I produced statistical maps (see Methods). Uncorrected maps at the $p < 0.01$ threshold for each tail of each contrast provide evidence for more fixations to the specific parts of the eyes and fewer fixations to parts of the mouth and nose regions of own-race (Caucasian) than other-race faces (Figure 5b). However, those specific differences did not survive a correction for multiple comparisons (Figure 5c) based on FDR control (see Methods). The differences also did not survive correction when an alternative method of multiple comparisons correction, cluster size correction, was applied.

A Difference Maps:

Caucasian - African   Caucasian - Chinese   African - Chinese
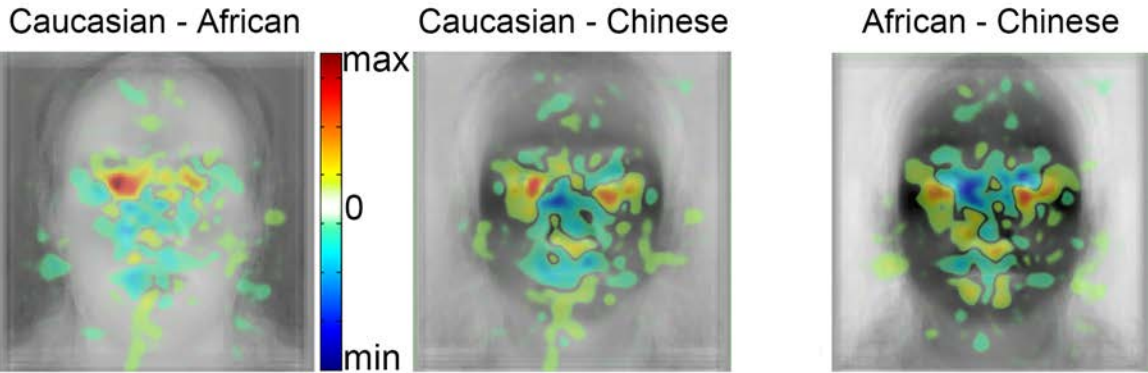
B Uncorrected Statistical (p < 0.01 Threshold) Maps:

Caucasian - African   Caucasian - Chinese   African - Chinese
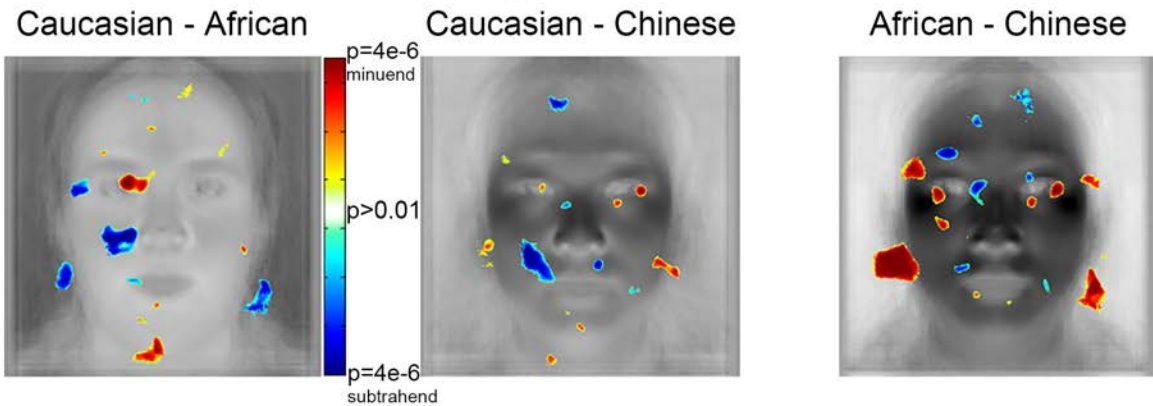
C FDR Corrected (q < 0.05, Face Area) Maps:

Caucasian - African   Caucasian - Chinese   African - Chinese
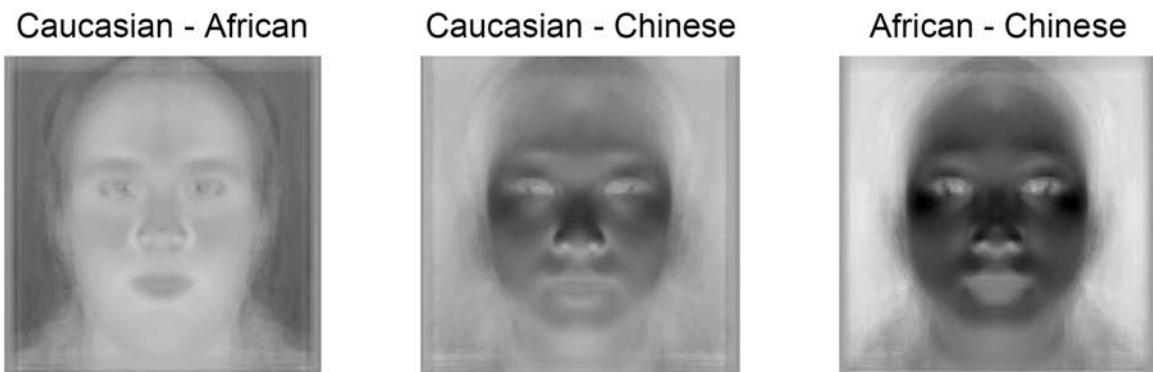
Figure 5. Spatial density contrast maps. (A) *Spatial density difference maps showing numerically greater fixation density over the eyes and numerically lesser fixation density over the nose and mouth of own- than other-race faces.* ***(B)*** *Statistical maps thresholded at p < 0.01, uncorrected, suggesting fine differences in fixation density for the features of own- and other-races faces and also evidence of greater diffusivity of the spatial extent of fixation patterns for other- compared to own-race faces.* ***(C)*** *The same statistical maps from (B) FDR corrected at q < 0.05 reveal that no differences survive the correction.*

Profile Analyses

Because AOI analyses can be criticized for requiring a highly subjective *a priori* segmentation of visual features (Caldara & Miellet, 2011), but spatial statistical maps can be criticized for lacking sensitivity, I conducted additional exploratory analyses that were meant to increase sensitivity without subjective segmentation. Specifically, profile plots and profile contrasts were also produced in order to detect differences in fixation patterns along individual dimensions (see Methods). The same data used for the statistical maps were collapsed along single dimensions (horizontal or vertical) to produce these profile plots and contrasts. Here I focus only on the profile plots in the y- (vertical) dimension because this dimension allows for comparing fixation densities in the eyes, nose, and mouth regions.

<u>Profile Plots</u>

The y-profile curves again suggest a higher density of fixations for in the eye regions and fewer fixations in the mouth regions for own- versus other-race (Figure 6a).

<u>Profile Contrasts: Own-Race Eye and Other-Race Mouth and Nose Fixations</u>

I produced profile statistical maps in order to test the significance of these differences in the profile plots. These maps (Figure 6b) suggest that relatively more eye-region fixations landed on Caucasian than African and Chinese faces. Also, compared to Caucasian faces, African faces had more mouth and nose fixations, and Chinese faces has more mouth fixations and fewer chin fixations. Contrasting African and Chinese faces revealed that Chinese faces received relatively more eye and forehead/hair fixations and Africans more lower lip fixations. However, when correction for multiple comparisons was applied according to FDR control (see Methods), only relatively more eye-region fixations landed on Caucasian than African were detected (Figure 6c).

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A Vertical Profile Density Plot
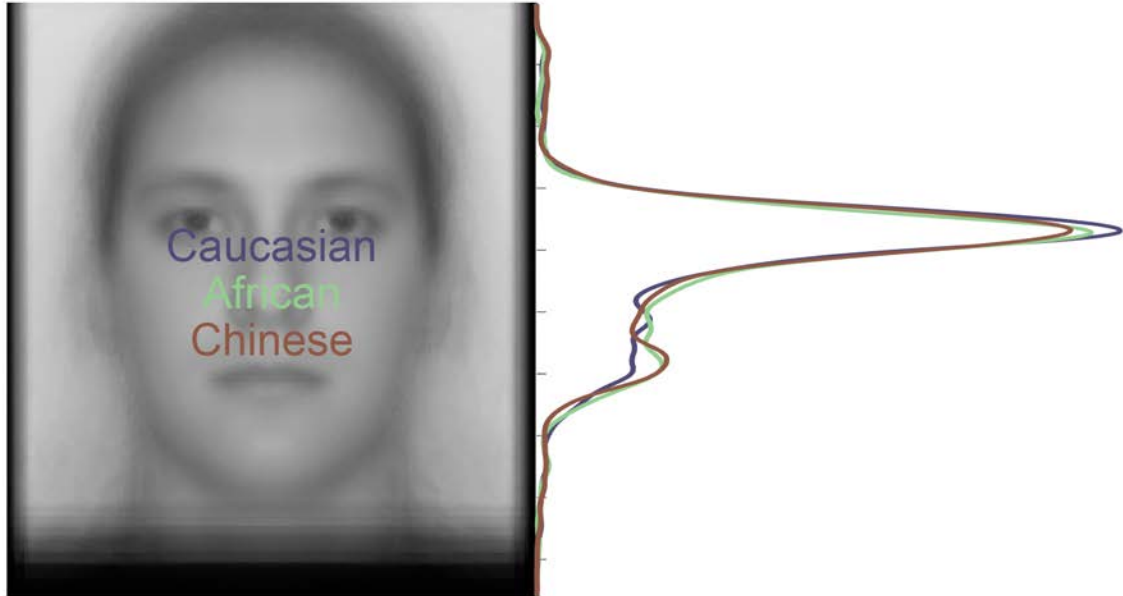
B Statistical Profile Plots p < 0.025

Caucasian - African   Caucasian - Chinese   African - Chinese
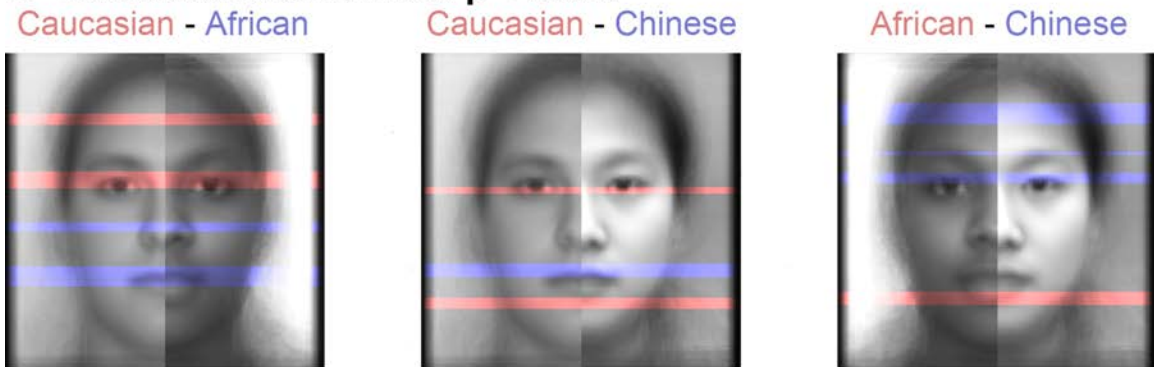
C FDR Corrected q < 0.05

Figure 6. Vertical profile density plots and profile contrast plots. (A) Vertical profile densities for Caucasian, African, and Chinese faces suggesting numerically greater fixations density over the eyes and numerically lesser fixation density over the mouth for own- than other-race faces. (B) Statistical profile plots thresholded at p < 0.025, uncorrected, suggesting significantly greater fixation density over the eyes and numerically lesser fixation density over the mouth for own- than other-race faces. (C) The same statistical profile plots from (B) FDR corrected at q < 0.05 reveal that a relatively greater fixation density over the eyes for Caucasian than African faces survives the correction.

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2.4 - Discussion

Differences in looking at other-race faces

Two highly conflicting views have emerged from prior eye-tracking studies of the other race effect, namely (i) that face recognition processing depends on the culture of the observer, but is equivalent by race of face observed (Blais et al., 2008; Caldara et al., 2010; Hills et al., 2013; Hills & Pake, 2013; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet et al., 2012, 2013; Rodger et al., 2010; Tan et al., 2012), and (ii) that face recognition processing differs by own- vs. other-race face (Fu et al., 2012; C. Hu et al., 2014; Nakabayashi et al., 2012), but does not differ by race of observer (Goldinger et al., 2009; Or et al., 2013). Here, I focused on the effect of race of face, not race of observer, and found evidence that fixations were indeed influenced by race of face in my Caucasian observers. Furthermore, my study clarifies why the discrepant reports regarding the influence of the race of face on eye-movements may exist, namely differences in the statistical sensitivity of different analysis methods employed across studies.

I investigated the effect of race of face on recognition performance and fixation patterns of Caucasian observers viewing Caucasian, African, and Chinese faces. Consistent with some previous eye-tracking studies (Fu et al., 2012; Goldinger et al., 2009; Nakabayashi et al., 2012), I found in Caucasian observers impairment for discriminating Chinese faces, less conservative criterion bias for other-race (African and Chinese) faces, and, importantly, differences in eye-movements between own- and other-race faces. Specifically, I found that for my Caucasian participants, relatively more eye-region fixations landed on Caucasian than African and Chinese faces. Also, compared to Caucasian faces, African faces received more mouth and nose fixations, and Chinese faces received relatively more nose fixations. These fixation pattern differences were, however, quite subtle. Detection of these differences was analysis dependent, suggesting that prior discrepant reports with respect to the presence of these differences is due to differences in statistical power.

My study is unique in that I tested participants on two other-race face categories (African and Chinese) not just one as in most prior studies. This enabled me to determine not only if recognition and fixations differ between own- and other-race faces, but also if and how they differ between out-group races of faces. I additionally found that my Caucasian observers were only impaired in discrimination of Chinese faces in my paradigm, though both other-race faces elicited a less stringent criterion for responding that a face had been recognized. Thus, African faces were discriminated equally as well as Caucasian faces, and this is likely due to the fact that my participants were living in Washington DC, which has a large African-American population.

Despite this lack of an ORE for African faces, fixation patterns differed between Caucasian and African faces. It is unclear whether this is because (i) the relative diagnostic value of different facial features differ between Caucasian and African faces and so the fixation differences reflect greater attention to those features (e.g. mouth and nose) which optimally enable individuation for each race of face (Hills et al., 2013; Hills & Pake, 2013), or (ii) the fixation patterns do not precisely reflect the facial information extracted (Caldara et al., 2010; Sébastien Miellet et al., 2012, 2013). Evidence for the former possibility comes from two prior eye-tracking studies (Hills et al., 2013; Hills & Pake, 2013) that report for Black and White observers exhibiting an ORE, that relative to White observers, Black observers tended to look more at the noses of Black and White faces, but importantly that forced nose-region fixation enabled Black faces to be recognized more accurately than White faces for both Black and White observers, whereas forced eye-region fixation enabled White faces to be recognized more accurately for both Black and White observers. Thus, the increased nose fixations to African faces in my Caucasian participants may be an explanation for their lack of an ORE (in d') for African faces, and the increased nose fixations may be the result of a strategy acquired through my participants' substantive experience with African faces. Evidence for the latter possibility that fixation patterns do not precisely reflect the facial information extracted comes from

three eye-tracking studies that restricted information sampling of the face stimuli through virtual apertures (Caldara et al., 2010; Sébastien Miellet et al., 2013) or virtual scotomas (Sébastien Miellet et al., 2012) and suggested that even though their Asian participants predominantly fixated at the center of the face, the eyes are nonetheless the region principally attended for recognition. Thus in the context of my study, it is unclear whether increased nose and mouth fixations to African faces compared to Caucasian faces indicates that those facial features were more greatly utilized for African facial recognition.

Relatedly, it is unclear how the fixation differences observed between Caucasian and Chinese faces are related to the facial information used as the differences in fixation patterns were similar to those between Caucasian and African faces, which, as just discussed, could not be related to differences in recognition performance. However, if it is the case that the diagnostic facial information tends to be in the eyes of Chinese faces, but in the nose and/or mouth of African faces, it is possible that it is precisely the same relative shift in fixation away from the eyes for both other-race faces compared to own-race faces, that led to the presence of an ORE for Chinese faces, yet an absence of an ORE for African faces in my participants. Such a race of face difference in diagnostic facial information is consistent with the studies discussed in the preceding paragraph, though a study directly comparing between African and Chinese facial feature diagnosticity would be of value in determining if such specific differences in facial feature diagnosticity are true. This lack of a clear relationship between eye-movements and identification performance possibly also suggests that perceptual exposure (higher to African than Asian faces in Washington, D.C.) may have less effect on eye-movements than the physiognomy associated with the race of the face (J. C. Brigham, Maass, Snyder, & Spaulding, 1982; Chiroro & Valentine, 1995; Lavrakas, Buri, & Mayzner, 1976; MacLin, Van Sickler, MacLin, & Li, 2004; Sangrigoli, Pallier, Argenti, Ventureyra, & de Schonen, 2005; Slone, Brigham, & Meissner, 2000; Walker & Hewstone, 2006; Wright, Boyd, & Tredoux, 2003). Future studies will be needed to establish how these differential

fixation patterns to different race faces relate to identification performance and processing of facial information.

Analysis-dependent sensitivity to differences: An account of prior discrepant results

Notably, however, my results reveal that these fixation differences between races of faces were rather small, and quite importantly, sensitivity for detecting these differences was analysis-dependent. Specifically, analyses utilizing Areas of Interest (AOIs) were statistically sensitive to these differences, whereas analyses of spatial densities over entire faces were not. Spatial density analyses were merely numerically in agreement with the AOI analyses. This important result thus helps clarify the source of the discrepancy in the literature regarding the influence of race of face on fixation patterns, and indeed indicates an issue of broader methodical importance in the study of fixations. It is likely that because the magnitudes of these other-race effects are small that other studies have failed to detect (Blais et al., 2008; Caldara et al., 2010; Hills et al., 2013; Hills & Pake, 2013; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet et al., 2012, 2013; Rodger et al., 2010; Tan et al., 2012) or only partially detected such effects (Nakabayashi et al., 2012), whereas three studies have reported these effects (Fu et al., 2012; Goldinger et al., 2009; C. Hu et al., 2014) between own- and other-race faces. All of the studies that detected differences between own- and other-race faces utilized AOI analyses, whereas seven out of ten of those that did not detect any difference utilized only spatial density analyses. Two of the studies to detect a difference through AOI analysis additionally detected differences through spatial density analysis (Fu et al., 2012; C. Hu et al., 2014), though perhaps due to statistical inflation resulting from some limitations recently found with a portion of the analysis package that was used (McManus, 2013; Sebastien Miellet, Lao, & Caldara, 2014; see http://perso.unifr.ch/roberto.caldara/index.php for the updated package). Though substantial statistical sensitivity over spatial density analysis may be increased through AOI analysis, AOI analysis has the limitation that it often requires

subjective or variable *a priori* segmentation of visual features (Caldara & Miellet, 2011). By increased statistical sensitivity, I do not mean an increased likelihood of finding any statistically significant difference whatsoever since a spatial density map would be more likely to detect a true difference over a given region than an AOI analysis on the same data but restricted to a different region where there is no difference. Rather statistical sensitivity is greater for the AOI analysis than the spatial density analysis for a true effect within the restricted region defined by the AOI (e.g. a true difference over the left eye is more likely to be detected with a left eye AOI than a full-face spatial density analysis). Such resolution versus statistical sensitivity tradeoffs between AOI and spatial density analyses are highly analogous to those respectively between Region of Interest (ROI) and whole brain analyses well known in fMRI studies (see e.g. Friston, Rotshtein, Geng, Sterzer, & Henson, 2006; Saxe, Brett, & Kanwisher, 2006). It is important then to keep the same considerations in mind when analyzing and interpreting eye-movement data. Neither approach is universally more advantageous or limited than the other, though one may be more appropriate than the other in a given circumstance. For example, an AOI approach would be advantageous in detecting an effect expected to be subtle within a well defined region associated with an *a priori* hypothesis, whereas a spatial density analysis would be advantageous when attempting to map highly significant differences in a data-driven manner at high spatial resolution or when hypotheses regarding regions cannot be incontrovertibly defined specifically with an AOI. In this study I also employed profile density analyses and this approach (or a similar dimensional reduction) may be a useful technique for compromising between these tradeoffs.

Issues requiring further investigation

In prior studies, differences between own- and other-race faces were often reported concomitantly with an absence of an effect of race of observer and vice versa. While my results potentially account for the discrepancy in prior studies in detecting effects of race of face on fixations, a limitation of my study is that it did not investigate the

effects of race of observer, in which double dissociations between races of observers, characteristic of the Other-Race Effect, could be detected. The reasons behind the discrepancy in reports of the influence of race of observer on fixations to faces still requires elucidation in future studies. For example, one hypothesized cause proposed (Hills & Pake, 2013) as requiring investigation is a potential difference between White European/British participants and White American participants, given that many European and British research groups find that participant culture affects the way faces are viewed, whereas US teams tend to find that the ethnicity of the face is key.

The majority of the studies reporting such an influence of race of observer come from a single research group (Blais et al., 2008; Caldara et al., 2010; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet et al., 2012, 2013; Rodger et al., 2010) utilizing the same base stimuli and highly similar paradigms across studies, which have all yielded patterns of fixations mainly over the center of the face for East Asian (Chinese) participants versus the "classical" T-shaped pattern with highest density over the eyes for Western Caucasian participants. A subset of those studies which have restricted information sampling of the face stimuli through virtual apertures (Caldara et al., 2010; Sébastien Miellet et al., 2013) or virtual scotomas (Sébastien Miellet et al., 2012) were interpreted as revealing that though Western Caucasian and Eastern Asian participants employ different eye-movement patterns, the same facial information is attended for recognition, namely principally the eyes. It is proposed then that East Asian participants process visual information more efficiently from extrafoveal vision and thus that the center of the face is optimal for extracting information on the eyes. A second research group comparing instead the eye-movement patterns between White and Black participants report that Black participants fixate the nose more than the eyes, and vice versa for White participants (Hills et al., 2013; Hills & Pake, 2013). Interestingly, the ORE was eliminated in White participants when they were forced to initially fixate at the location preceding the nose of Black faces, and likewise when Black participants were forced to initially fixate the location preceding the region between the eyes of White faces. More

specifically, nose-region fixation crosses preceding Black faces caused them to be recognized more accurately than White faces for both Black and White observers, whereas (in one (Hills et al., 2013) of the two studies from that second group) White faces were recognized more accurately by both Black and White observers when they were preceded by a eye-region fixation cross. One research group, therefore, proposes that differential eye-movements do not correspond to differential information use between races of observers, whereas the second group proposes that they do. The two groups curiously disagree conceptually over how these differences in eye-movements correspond to differences in diagnostic value of individual features between different race faces, and so clarification of this is warranted in future studies.

More fundamentally, however, the reports of a center-of-face pattern of eye-movements to faces (i.e. peak fixation density over the center of the face, rather than over the eyes) for East Asian participants at the group level (albeit with individual participant differences) (Blais et al., 2008; Caldara et al., 2010; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet et al., 2012, 2013; Rodger et al., 2010) seem to be unique to the group reporting this and are thus perplexing in light of other eye-tracking studies involving East Asian participants viewing faces. In stark contrast to these reports, another eye-tracking study of the ORE (Goldinger et al., 2009) has reported that regardless of the race of the observer (East Asian or Caucasian), own-race faces elicited a relatively greater proportion of fixations to the eyes and hair, while other-race faces elicited a relatively greater proportion of fixations to the nose and mouth. Further, several other studies involving East Asian (Chinese or Japanese) participants viewing faces robustly show the "classical" T-shaped fixation pattern of fixations that, notably, almost exclusively demonstrate peak density over the eyes when spatial density or scatter plot analyses were utilized (Fan et al., 2013; Fu et al., 2012; C. Hu et al., 2014; Nakano et al., 2010; Wang, Hu, Short, & Fu, 2012; Yi et al., 2014) or show greater fixation over the eyes relative to the nose when area-normalized AOI analyses were utilized (Y.-Z. Hu et al., 2013; Watanabe, Matsuda, Nishioka, & Namatame, 2011). Other studies without

area normalized AOIs are also at least suggestive of the same tendency for East Asian observers to principally fixate the eyes (Sekiguchi, 2011; Senju, Vernetti, Kikuchi, Akechi, & Hasegawa, 2013; Senju, Vernetti, Kikuchi, Akechi, Hasegawa, et al., 2013; Tan et al., 2012). One study with Japanese participants even found that better facial recognition performance was strongly associated with more fixations over the eyes (Sekiguchi, 2011), directly contradicting the account that the center of the face is the optimally informative location for East Asian observers to look for facial recognition (also see Or et al., 2013). An interesting exception to the eye-bias in fixation patterns though is a study (Watanabe et al., 2011) that found a nose greater than eyes (i.e. center-of-face) bias for Japanese participants viewing emotionally expressive faces, but an eyes greater than nose (i.e. "classical") bias when viewing neutral expressions. Because emotional face stimuli were used in the ORE studies reporting a center-of-face fixation bias for East Asian, but not for Western Caucasian, participants (Blais et al., 2008; Caldara et al., 2010; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Sébastien Miellet et al., 2012, 2013; Rodger et al., 2010), it would be valuable to investigate whether the use of emotional stimuli could be a factor contributing to this perplexing differential pattern (though see Jack, Blais, Scheepers, Schyns, & Caldara, 2009).

Conclusion

Caucasian observers in my study exhibited impairment for discriminating Chinese faces, less conservative criterion bias for other-race (African and Chinese) faces, and, importantly, differences in eye-movements between own- and other-race faces. Relatively more eye-region fixations landed on Caucasian than African and Chinese faces. Also, relative to Caucasian faces, African faces received more mouth and nose fixations, and Chinese faces received relatively more nose fixations. These were very subtle fixation pattern differences, however, and detection of these differences was analysis dependent. Thus, prior discrepant reports with respect to the presence of these differences are likely due to differences in the statistical power of different analyses across studies. Further study is warranted now to account for

another discrepancy in prior reports regarding the presence and meaning of differences in eye-movement patterns to faces between different racial groups of observers.

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2.6 - Supplemental Material

Temporal Dynamics of Fixations (Supplemental)

To examine fixation patterns, I first focused on the temporal duration of individual fixations. A three-way ANOVA on study phase fixation durations with Ordinal Fixation (1st through 5th), Race (Caucasian, African, Chinese) and Start Position (left,

right, up, down) as within-subject factors revealed a significant main effect of Ordinal Fixation ($F_{(4,116)} > 23.67$, $p < 0.001$, Greenhouse-Geisser corrected), and Start Position ($F_{(3,87)} > 3.47$, $p < 0.030$, Greenhouse-Geisser corrected), but not of Race ($F_{(2,58)} < 1.25$, $p > 0.28$, Greenhouse-Geisser corrected). Qualitatively, there was a tendency for longer fixations for Chinese faces at the later ordinal fixations, although the interaction of Ordinal Fixation and Race ($F_{(8,232)} > 2.10$, $p < 0.083$, Greenhouse-Geisser corrected) was not significant. All other interactions were not significant (all $p > 0.33$, Greenhouse-Geisser corrected). Thus, in the first five fixations of the study phase while both Start Position and Ordinal Fixation affected fixation durations independently, there is no evidence that Race did.
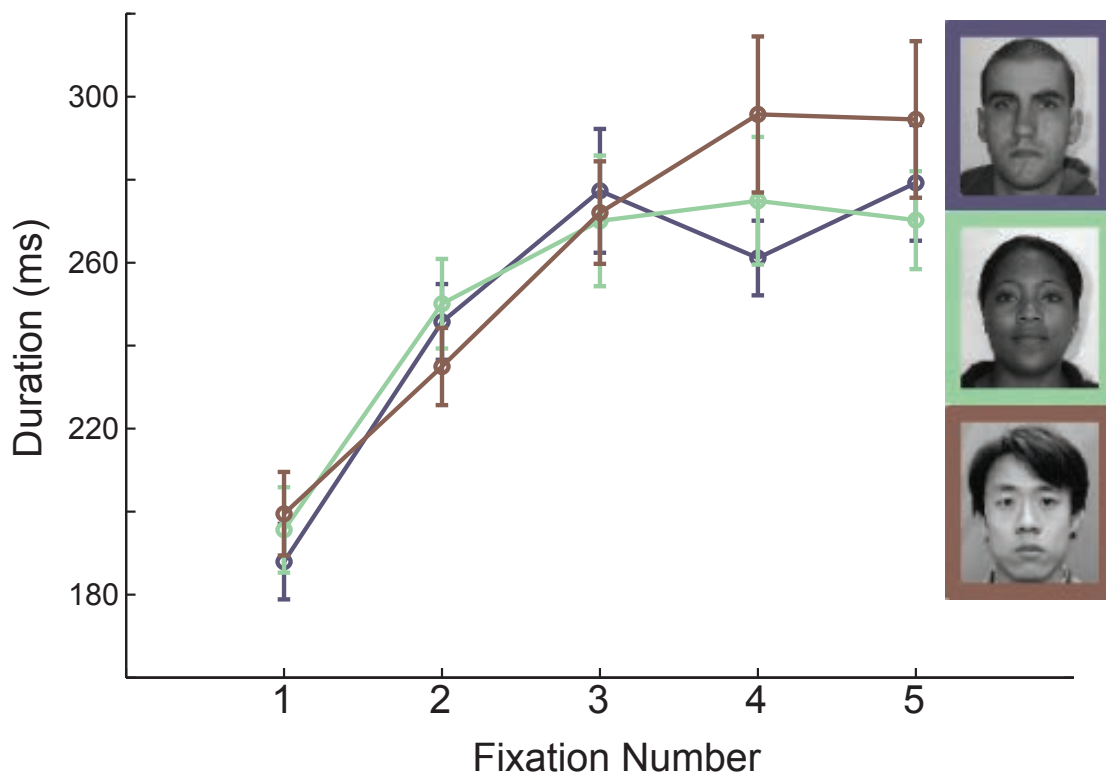
Supplemental Figure 1. Fixation durations of each of the first five fixations during the study phase. *The first fixation was significantly shorter than the subsequent fixations, as was the second fixation.*

A similar three-way ANOVA on test phase fixation durations with Ordinal Fixation (1st and 2nd only, due to short stimulus presentations in the test phase truncating many fixation durations beyond the 2nd fixation), Race (Caucasian, African, Chinese) and

Start Position (left, right, up, down) as within-subject factors revealed a significant main effect of Ordinal Fixation ($F(1,28) > 52.38$, $p < 0.001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.65$), and a marginal main effect of Race ($F(2,56) > 2.88$, $p < 0.073$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.094$), but not of Start Position ($F(3,84) < 1.50$, $p > 0.22$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.051$). All interactions were not significant (all $p > 0.25$, Greenhouse-Geisser corrected, $\eta_p^2 < 0.047$). Thus only Ordinal Fixation significantly affected fixation durations in the first two fixations of the test phase.
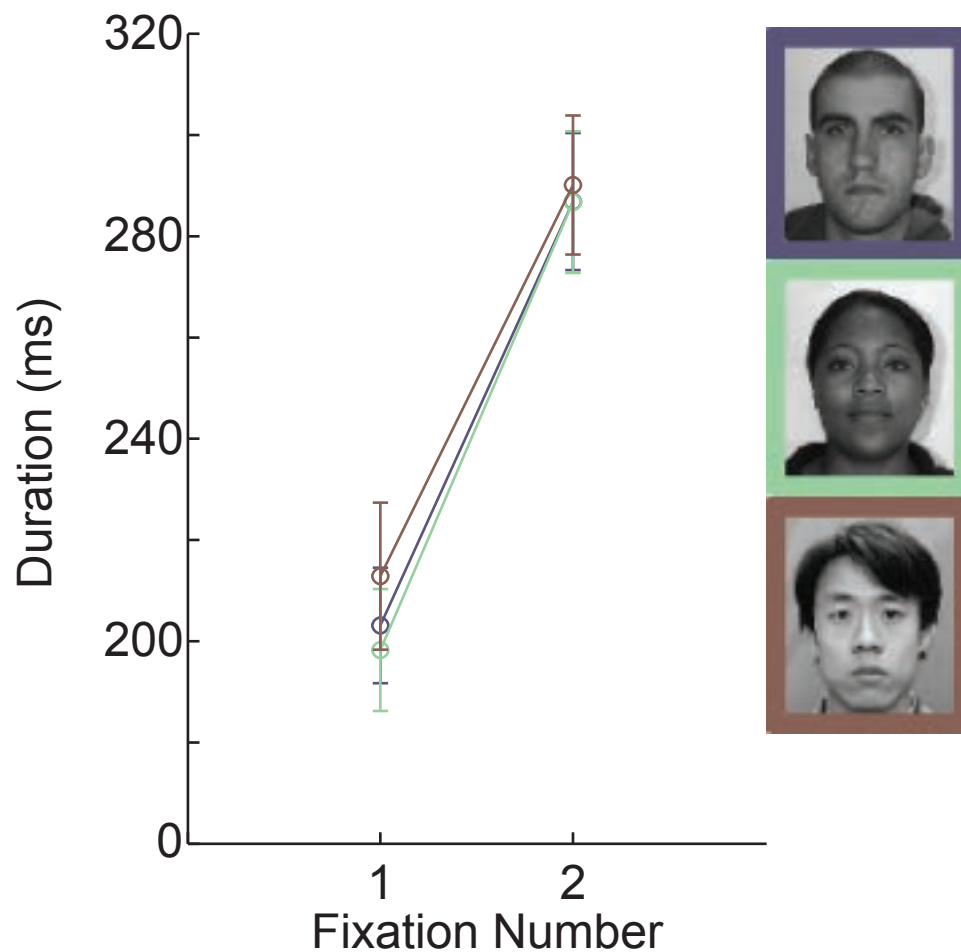
Supplemental Figure 2. Fixation durations for each of the first two fixations during the test phase. *The first fixation was significantly shorter than the second fixation.*

Prior studies have indicated that facial information for individuation is not deeply processed during the first fixation to a face. In particular, Hsiao and Cottrell (2008) found that at least two fixations are needed for optimal face recognition performance.

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Further, in my earlier studies (Arizpe, Kravitz, Yovel, & Baker, 2012) detailed in chapers 3 and 4, I found that the first fixation was significantly shorter than the subsequent fixations. To determine if the same held true for the current data I conducted follow-up pairwise comparisons on Ordinal Fixation (Figure S1) first on the study phase, demonstrating that average duration of the first fixation was significantly shorter than subsequent (2nd through 5th) fixations (all four comparisons $t(29) > 6.31$, $p < 0.001$, one tailed). Further, the second fixation was also significantly shorter than subsequent (3rd through 5th) fixations (all three comparisons $t(29) > 8.46$, $p < 0.009$, two-tailed), but no other comparisons yielded significant differences (all three $t(29) < 0.77$, $p > 0.44$, two-tailed).

Comparison of the first and second fixations in the test phase (Figure S2), also demonstrated that average duration of the first fixation was significantly shorter than the second ($t(28) > 7.22$, $p < 0.001$, one tailed). Given the findings of Hsiao and Cottrell and following my earlier work, my subsequent analyses were primarily conducted with the first fixation removed, although qualitatively the same results were observed when it was included (see *Supplementary Materials: Fixation Patterns*).

I additionally investigated the influence of Phase (Study, Test) on the temporal dynamics of fixations. A two-way ANOVA on subject average fixation durations with Ordinal Fixation (1st and 2nd) and Phase (Study, Test) as within-subject factors revealed main effects of Ordinal Fixation ($F(1,28) > 77.64$, $p < 0.001$, $\eta_p^2 = 0.74$) and of Phase($F(1,28) > 19.41$ $p < 0.001$, $\eta_p^2 = 0.41$), as well as an interaction between Ordinal Fixation and Phase ($F(1,28) > 8.70$, $p < 0.007$, $\eta_p^2 = 0.24$) indicating that the temporal dynamics of fixations differed between Study and Test Phase though the first fixation was significantly shorter in duration than the second fixation for both phases. Indeed, post-hoc paired comparisons between Study and Test Phase revealed significantly longer duration fixations for Test Phase for both the first ($t(28) < -2.11$, $p < 0.045$, two-tailed uncorrected) and second ($t(28) < -4.22$, $p < 0.001$, two-tailed uncorrected) fixations. This influence of Phase seen in my data may reflect

the difference between encoding and recognizing or it may reflect the influence of restricted time to view the stimulus (i.e. one second limit in the test phase).

Differences in Fixation Patterns for Study versus Test Phases by Ordinal Fixation

Because it has been shown that not all ordinal fixations are equally important in processing facial information and also that the first two fixations suffice for face recognition (Hsiao & Cottrell, 2008), I analyzed fixation patterns across AOIs in more detail by considering the first three fixations separately. Further, because subjects were implicitly performing different tasks on faces between the Study and Test phases, I additionally investigated the influence of Phase on fixation patterns for each of the first three fixations (Figure S4).
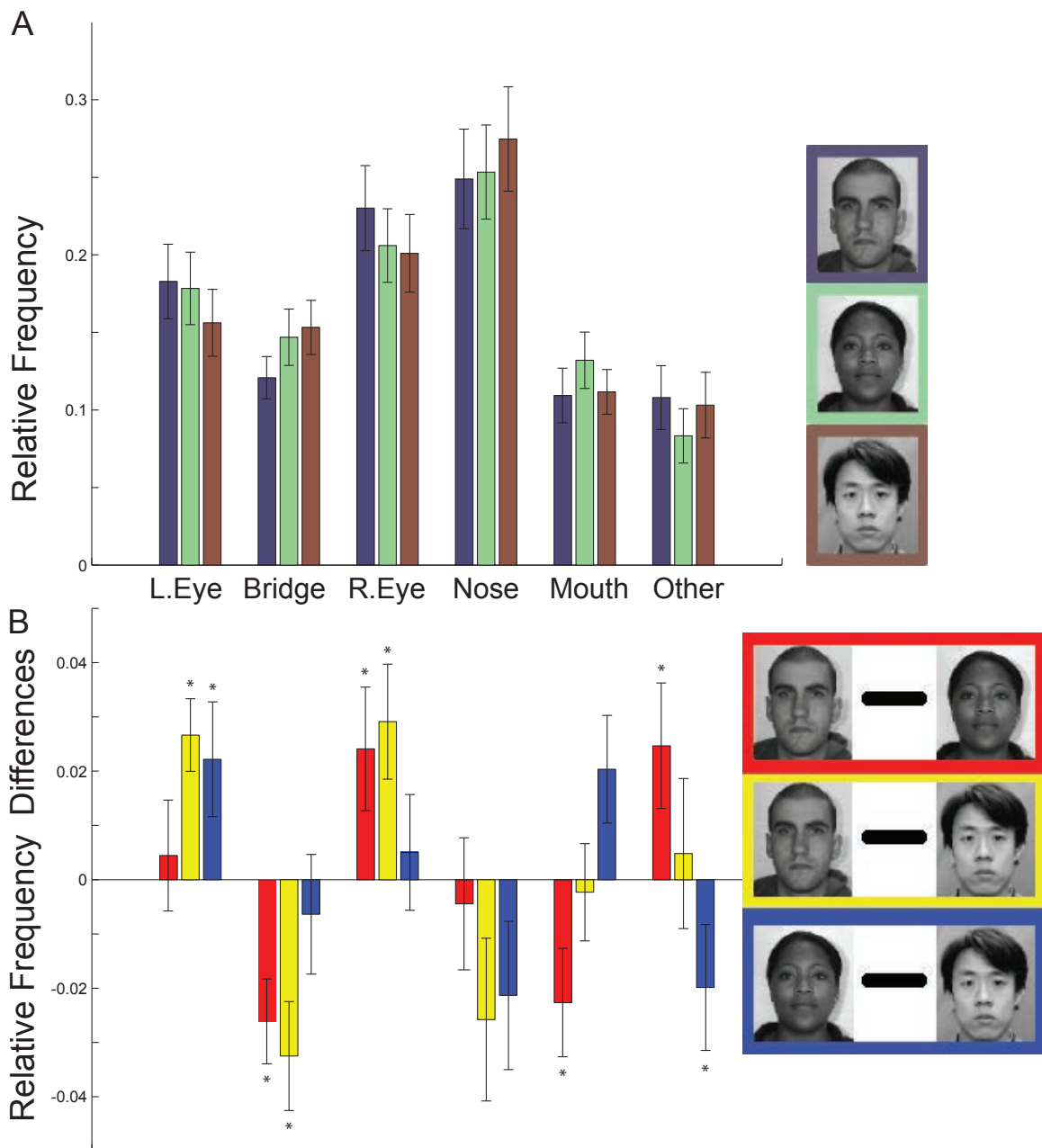
Supplemental Figure 3. Distribution of fixations across AOIs for own- and other-race faces during the test phase. (A) *Relative frequencies of fixations for each race of face across AOIs for the all fixations except the first pooled across the entire period during which the stimulus was visible.* **(B)** *Within-subject differences among race of face conditions from (A) reveal significantly more eye fixations for Caucasian than Chinese faces, significantly more right eye fixations for Caucasian than African faces, and significantly fewer mouth fixations for Caucasian than African faces. Error bars indicate the between-subjects standard error.*
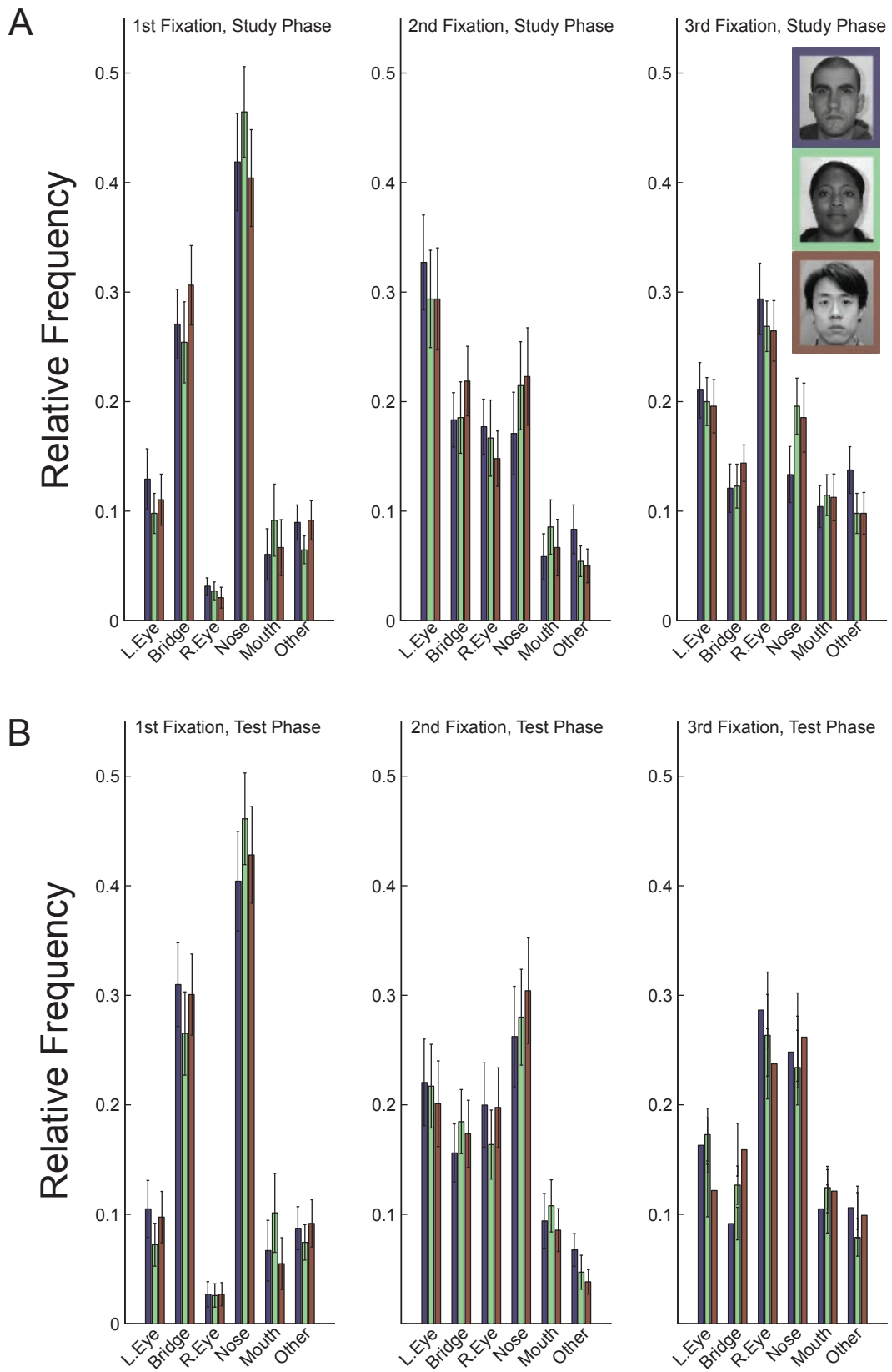
Supplemental Figure 4. Study (A) versus test (B) phase distributions across AOIs for each of the first three fixations. *Relative to study phase, there were significantly fewer fixations to the left eye and significantly more fixations to the nose in the test phase for the second and third fixations.*

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For the first fixation, a three-way ANOVA on the relative frequency of fixations with AOI (left eye, bridge, right eye, nose, and mouth), Race (Caucasian, African, Chinese), and Phase (study, test) as within-subject factors yielded a main effect of AOI ($F_{(4,112)} > 27.72$, $p < 0.001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.50$) and marginal main effect of Race ($F_{(2,56)} > 3.13$, $p < 0.059$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.10$), but no main effect of Phase ($F_{(1,28)} < 0.002$, $p > 0.97$, Greenhouse-Geisser corrected, $\eta_p^2 = 0$). The interaction of AOI and Race ($F_{(8,224)} > 4.318$, $p < 0.005$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.13$) was significant, but no other interactions were (all $p > 0.42$, Greenhouse-Geisser corrected, $\eta_p^2 < 0.032$). These indicate that for the first fixation, my participants employed different fixation patterns for different races, but did not seem to employ different patterns between Study and Test Phase. Prior studies have indicated that facial information for individuation is not deeply processed during the first fixation (Arizpe et al., 2012; Hsiao & Cottrell, 2008) and my prior analyses showed that the first fixation was distinct from the later fixations in terms of fixation duration, so my interest focused on subsequent fixations.

For the second fixation, the same three-way ANOVA yielded main effects of AOI ($F_{(4,112)} > 3.62$, $p < 0.021$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.12$) and Race ($F_{(2,56)} > 5.97$, $p < 0.012$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.18$), but no main effect of Phase ($F_{(1,28)} < 0.97$, $p > 0.33$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.033$). The interaction of AOI and Race ($F_{(8,224)} > 2.78$, $p < 0.013$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.090$) was again significant, and notably the interaction of AOI and Phase ($F_{(4,112)} > 9.63$, $p < 0.001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.26$) was also significant, reflecting relatively more left eye fixations for study and relatively more nose fixations for the test phase (see below). The other interactions were not significant (both $p > 0.44$, Greenhouse-Geisser corrected, $\eta_p^2 < 0.034$). These indicate that in the second fixation, Race and Phase both influenced fixation patterns, but seem to have done so independently.

For the third fixation, a final three-way ANOVA yielded the same main effects and interactions as the second fixation did. Main effects of AOI ($F(4,112) > 6.52$, $p < 0.002$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.19$) and Race ($F(2,56) > 3.46$, $p < 0.039$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.11$) were again significant, but not the main effect of Phase ($F(1,28) < 1.50$ $p > 0.23$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.051$). The interaction of AOI and Race ($F(8,224) > 3.101$, $p < 0.011$ Greenhouse-Geisser corrected, $\eta_p^2 = 0.10$) and of AOI and Phase ($F(4,112) > 5.74$, $p < 0.002$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.17$) were also significant, but no other interactions (both $p > 0.31$, Greenhouse-Geisser corrected, $\eta_p^2 < 0.041$). These indicate that in the third fixation, like in the second fixation, Race and Phase both influenced fixation patterns independently. Further ordinal fixations could not be reliably compared individually or in aggregate between Study and Test phases given the limited duration (1 second) of the presentation of the stimuli in the test phase.

I found influences of Phase (Study, Test) and Race (Caucasian, African, Chinese) on fixation patterns for the second and also for the third ordinal fixations. For this reason, I more closely investigated the influence of Phase. In my data for second and third fixations, post-hoc paired test phase versus study phase comparisons on relative frequency of fixation at each AOI when Race conditions were pooled together yielded several significant differences. For the second fixation, the left eye AOI contained significantly more fixations ($t(28) > 4.31$, $p < 0.001$, two-tailed uncorrected) for the study than test phase, and the nose AOI contained significantly fewer fixations ($t(28) < -3.57$, $p < 0.002$, two-tailed uncorrected) for the study than test phase. All other AOIs yielded no significant differences (all $t(28) < |1.57|$, $p > 0.12$, two-tailed uncorrected) for the second fixation. For the third fixation, the same pattern of differences emerged. The left eye AOI contained significantly more fixations ($t(28) > 3.55$, $p < 0.002$, two-tailed uncorrected) for the study than test phase, the nose AOI contained significantly fewer fixations ($t(28) < -4.27$, $p < 0.001$, two-tailed uncorrected) for the study than test phase, and all other AOIs yielded no significant differences (all $t(28) < |1.28|$, $p > 0.21$, two-tailed uncorrected) for the third fixation. It is not clear, however, if these differences reflect encoding versus

recognizing or rather a modification of eye-movement strategy due to the short duration (limit of one second) of the stimuli in the test phase. For this reason, my subsequent analyses focus just on data from the study phase, where viewing time was under the control of the participant. The potential influence of encoding versus recognizing a face on fixation patterns and visual processing warrants deeper investigation in future experiments.

A note about the Study and Test phase eye-movement differences

A point worth further investigation, with potentially broad theoretical or methodological implications, is the modulation of fixation patterns between study and test phase I observed in the current study. I observed significantly more fixations to the left eye, and also significantly fewer fixations to nose AOI, for the study than test phase for both the second and third ordinal fixations. Longer duration fixations were also observed in the test compared to the study phase. Other studies have reported modulations of fixation patterns between study and test phase (e.g. Henderson et al., 2005; Hsiao & Cottrell, 2008), but like in my study those also had time restricted stimuli or speeded response in the test phases. Like those studies, in the context of my paradigm it is not clear whether the differences I observe reflect the difference in implicit task (encoding versus recognition) being performed between the two phases, or rather that fixation dynamics were modified because time to view the stimulus was limited (up to 1 second) in the test phase. These two possibilities are not mutually exclusive, but if the former drives this phenomenon, it may indicate an important set of mechanisms in visual perception, and if driven by the latter, it would suggest that caution should be applied in designing and interpreting eye-movement studies with speeded response or restricted time tasks.

Fixation Patterns: AOIs (Supplemental all 5 fixations)

Independent Influences of Race of Face and Start Position

Area of Interest (AOI) analyses revealed that Race and Start Position both influence fixation patterns, but further that their influences are independent. A three-way ANOVA on the relative frequency of fixations in the study phase with AOI (left eye, bridge, right eye, nose, and mouth), Race (Caucasian, African, Chinese) and Start Position (left, right, up, down) as within-subject factors, on the relative frequency of fixations revealed a significant main effect of AOI ($F(4,116) > 5.40$, $p < 0.004$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.16$), which indicates that not all AOIs were fixated with equal frequency. Further, there was a significant interaction between Race and AOI ($F(8, 232) > 3.05$, $p < 0.008$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.095$) indicating that fixation patterns varied by Race. Finally, there was also a significant interaction between Start Position and AOI ($F(12, 348) > 9.32$, $p < 0.001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.24$) indicating that fixation patterns varied by Start Position. There was no significant three-way interaction among AOI, Race, and Start Position ($F(24, 696) < 1.26$, $p > 0.24$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.041$), suggesting that the influences of Race and Start Position on fixation pattern are independent.

Small but Systematic Influences of Race of Face

The preceding analysis suggested an effect of Race of face on fixation patterns. To test for replication of a prior study (Goldinger, He, & Papesh, 2009) specifically reporting a greater proportion of fixations over both eyes in own-race faces and greater proportion of mouth and nose fixations for other-race faces, I conducted separate one-way ANOVAs on the study phase, with Race as the within-subject factor, on left eye, right eye, nose and mouth AOIs and performed the relevant pairwise comparisons between races for each of these AOIs. For both eye AOIs, only marginal main effects of Race were found (left eye: $F(2,58) < 2.89$ $p > 0.068$,

Greenhouse-Geisser corrected, $\eta_p^2 = 0.090$; right eye: $F(2,58) < 2.70$, $p > 0.075$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.085$). However, additional planned pairwise comparisons testing the hypothesis of greater proportion of fixations for own- (Caucasian) versus other-race (African or Chinese) in these AOIs revealed significant differences in the hypothesized direction for three of the four contrasts (all three $t(29) > 1.81$, $p < 0.04$, one-tailed, $G_{Hedges} > 0.17$). Only the Caucasian versus African contrast in the right eye AOI failed to reach significance ($t(29) < 0.94$, $p > 0.17$, one-tailed, $G_{Hedges} = 0.11$), though it tended in the hypothesized direction. Similar one-way ANOVAs for the mouth and nose AOIs revealed a significant main effect of Race in the mouth AOI ($F(2,58) > 3.47$, $p < 0.042$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.11$) but only a marginally significant main effect of Race ($F(2,58) < 2.76$, $p < 0.075$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.087$) in the nose AOI. The pairwise comparisons, now testing the hypothesis of greater proportion of fixations for other- (African and Chinese) versus own-race (Caucasian) in the mouth and nose AOIs revealed that all four comparisons again tended in the hypothesized direction, but only African versus Caucasian comparisons were significant for mouth and nose AOIs (both $t(29) > 2.60$, $p < 0.008$, one-tailed, $G_{Hedges} > 0.22$). Though the Chinese versus Caucasian comparisons for mouth and nose failed to reach significance, both were marginally significant (both $t(29) > 1.46$, $p < 0.077$, one-tailed, $G_{Hedges} < 0.15$). A plot of the relative frequencies of fixations falling in my AOIs for each race (Figure 2) highly resembles the analogous plot in the prior study (Figure 2 in Goldinger, He, & Papesh, 2009, which is the data for Caucasian observers looking at Caucasian and Asian faces with five second encoding duration), even though the precise way my AOIs were drawn differs slightly and my data utilizes only the first five fixations. Notably, as previously indicated, relative frequency differences between own- and other-race faces in the left eye, right eye, nose, and mouth AOIs all tended in the same direction as the prior study.

Chapter 3 - Start Position Strongly Influences Fixation Patterns During Face Processing: Difficulties with Eye Movements as a Measure of Information Use

3.1 - Introduction

The location of visual fixations are often assumed to directly reflect the allocation of visual attention (J. Findlay & Gilchrist, 2003). Thus, their spatial and temporal pattern may indicate the regions of a stimulus being processed for use in a particular task and give direct insight into cognitive processes (Henderson, 2003; Just & Carpenter, 1980; Rayner, 1998, 2009). Consider the following two examples. First, based on fixation locations during face recognition, Hsiao and Cottrell concluded that fixations near the center of the nose were optimal for recognition (Hsiao & Cottrell, 2008). Second, Blais and colleagues(Blais, Jack, Scheepers, Fiset, & Caldara, 2008) noted a difference in fixation patterns during face viewing between Asian and Caucasian observers and concluded that this difference reflected the impact of culture on high-level face processing strategies. However, the use of fixations to infer stimulus- and task-dependent visual processing assumes that the specific stimuli and the task are the primary determinants of the fixation pattern rather than, for example, visuomotor factors. Here I tested this assumption in a study of face processing by varying the initial starting position of the eyes relative to the face, a factor which varies both within and across previous studies. If the pattern of fixations is largely determined by the stimulus and the task, this manipulation should have minimal impact on the overall pattern of fixations.

Analyses of fixation patterns have been used extensively in studies of face processing. While much information can be extracted from single fixations to rapidly presented faces, eye movements appear to be functionally useful, with impaired recognition when fixation location is fixed compared to when participants are free to move their eyes (Henderson, Williams, & Falk, 2005; Kealey, Sekuler, & Bennett, 2008). Most eye tracking studies of face perception report the same basic pattern,

with the vast majority of fixations falling on internal facial features and a tendency toward the upper part of the face, and in particular the eyes (Althoff & Cohen, 1999; Barton, Radcliffe, Cherkasova, Edelman, & Intriligator, 2006; Blais et al., 2008; Heisz & Shore, 2008; Janik, Wellens, Goldberg, & Dell'Osso, 1978; Yarbus, 1967). Further, the specific pattern of fixations observed is modulated by task (Armann & Bulthoff, 2009; Malcolm, Lanyon, Fugard, & Barton, 2008; Walker-Smith, Gale, & Findlay, 1977) and face familiarity (Althoff & Cohen, 1999; Barton et al., 2006; Heisz & Shore, 2008; Stacey, Walker, & Underwood, 2005; Van Belle, Ramon, Lefevre, & Rossion, 2010). Variations in the basic pattern of fixations have been used as evidence for differences in visual processing between identity and expression tasks (Malcolm et al., 2008), upright and inverted faces (Barton et al., 2006) (but see Williams & Henderson, 2007), Asian and Caucasian observers (Blais et al., 2008; Jack, Blais, Scheepers, Schyns, & Caldara, 2009), 5- and 7- week old infants (Haith, Bergman, & Moore, 1977), own- and other-race faces (Goldinger, He, & Papesh, 2009), patient groups and controls (e.g. Autism Spectrum Disorders: Kliemann, Dziobek, Hatri, Steimke, & Heekeren, 2010; Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Pelphrey et al., 2002) and between conspecific and non-conspecific faces (Dahl, Wallraven, Bulthoff, & Logothetis, 2009). However, the extent to which measured fixations during facial processing reflect factors other than stimulus and task is unclear.

I was interested in the impact of starting fixation position on the pattern of visual fixations. Most studies of fixation patterns during face perception consist of a series of trials on which individual faces are presented one at a time with sudden onset. The location of fixation at the onset of the faces is typically controlled (e.g. Barton et al., 2006; Bindemann, Scheepers, & Burton, 2009; Blais et al., 2008; Hsiao & Cottrell, 2008) although in some cases it is relatively unconstrained (Dahl et al., 2009; Pelphrey et al., 2002). In those studies that do fix the start position, the center of the screen, typically corresponding to the center of the upcoming stimulus is commonly used (Althoff & Cohen, 1999; Goldinger et al., 2009; Heisz & Shore, 2008), although exactly which part of the face this corresponds to is highly variable and often unclear). However, increasingly, single (Van Belle et al., 2010; Williams &

Henderson, 2007) or multiple off-face starting positions are employed (Bindemann et al., 2009; Blais et al., 2008; Hsiao & Cottrell, 2008; Jack et al., 2009). In studies in which fixation is unconstrained, observers may spontaneously orient to the center of the screen (i.e. the center of the expected face). Whether start position is constrained or not, all of these studies make the implicit assumption that differences in start position have negligible impact on the overall pattern of fixations.

However, there are several ways in which start position may impose significant biases on the pattern of fixations. In particular, the position of the observer's eye relative to the upcoming face defines the initial sampling of that face, which can affect the pattern of fixations throughout a trial. For start positions on the face (e.g. center), initial saccades must of necessity be directed away from the start position, constraining the first observer-generated fixation location. Further, information is sampled at the start position, perhaps making it less likely the participants will return to that position on later fixations. These considerations have led many to adopt initial fixation locations away from the face (e.g. Hsiao & Cottrell, 2008). However, moving the start position off the face doesn't eliminate potential effects of the initial fixation location. For example, participants may be more likely to saccade initially to the nearest high contrast part of the face, or to saccade to the center of gravity of the face stimulus (Bindemann et al., 2009; J. M. Findlay & Gilchrist, 1997; Henderson, 1993). Even if the first saccade is aimed at the center of the face, the tendency for saccades to undershoot or overshoot (Kapoula, 1985; Kapoula & Robinson, 1986) may mean that the actual location of the first fixation differs for different start positions, and the location of this initial fixation may influence subsequent fixations (Henderson, 1993). Finally, face processing has been shown to differ with retinotopic position in the periphery (Afraz, Pashkam, & Cavanagh, 2010) and high-level face-selective cortex has been shown to have position information about presented faces (Kravitz, Kriegeskorte, & Baker, 2010). Given all these considerations, it is important to determine the extent to which eye movements are affected by changes in start position if fixations are to be considered a measure of information use.

Here I systematically tested the effect of start position during a face recognition task on both upright and inverted faces. I chose to manipulate face orientation since inversion produces a reduction in face recognition performance (Yin, 1969), reflecting differences in cognitive processing (Kanwisher & Yovel, 2006; Rossion & Gauthier, 2002), and has also been reported to have a significant effect on fixation patterns (Barton et al., 2006) (but see Rodger, Kelly, Blais, & Caldara, 2010; Williams & Henderson, 2007). Thus, I can determine the joint impact of both start position and cognitive factors on fixation patterns during face processing. In my study, participants viewed a series of 40 faces during a study phase before being tested on recognition during a later test phase. I found that the pattern of fixations during both the study and test phase was strongly influenced by start position for both upright and inverted faces. There was also a general effect of inversion, with a greater proportion of fixations on the lower part of inverted compared with upright faces. However, the precise effect of inversion also varied as a function of start position. These findings suggest that eye movements to faces are not wholly predicted by stimuli and task, but may also reflect visuo-motor factors or simple sampling strategies. I conclude that caution is needed in interpreting eye movement patterns solely in terms of information use and high-level visual processing strategies.

3.2 - Methods

Ethics Statement

All participants gave written informed consent and were compensated for their participation. The study was approved by the Institutional Review Board of the National Institutes of Health, Bethesda.

Participants

20 Caucasian participants (12 male), age 20 to 39. Due to time constraints, one participant only completed the study phase of the experiment and therefore 19/20

participants contributed behavioral and test phase data.

Eye-tracking

I used an EyeLink II headmounted eye-tracker (SR Research, Mississauga, ON, Canada), and sampled pupil centroid at 500 Hz. The default nine point calibration and validation sequences were repeated throughout the experiment. Both eyes were calibrated and validated, but only the eye with the lowest maximum error was recorded for the trials following a particular calibration. Calibration was repeated when maximum error at validation was more than 1°. Before each trial, a drift correction was performed. Default criteria for fixations, blinks, and saccades implemented in the Eyelink system were used.

Stimuli

I used 80 grayscale neutral expression face images (40 male) of Caucasians between the ages of 18 and 29 from the Productive Aging Lab Face Database at the University of Texas at Dallas (http://vitallongevity.utdallas.edu/stimuli/facedb/categories/neutral-faces.html)(Minear & Park, 2004). As stated on the website for the database: "This [database] contains a range of face of all ages which are suitable for use as stimuli in face processing studies. Releases have been signed by the participants we photographed and the faces may be included in publications or in media events." Each face was scaled to have a 10 degree forehead width at presentation and was rotated to correct any tilt of the head. Images were cropped to remove most of the white background, but not the hair or other external features, and all images were equated for overall luminance (Figure 1a). At presentation, images were centered on a black background. To eliminate any possible stimulus bias as the source of any laterality effects, half of the upright faces were randomly left-right flipped for each participant. Inverted faces were created by simply reflecting each image around the horizontal axis.

Areas of Interest (AOIs)

For the purposes of analysis and for aspects of my experimental design, rectangular areas-of-interest (AOIs) were drawn for each face around the right and left eyes, bridge of nose (i.e. middle of eye region), right and left half of nose, and right and left half of mouth (Figure 1b, for example) using EyeLink Data Viewer software. AOIs were never visible to participants during the experiment.

Design

I varied face orientation (upright or inverted) and pre-stimulus fixation location ("start position") across the trials of an experiment comprised of two phases: study and test. During study, participants observed 40 faces (20 male) in a self-paced manner. At test, participants observed 80 faces (the 40 study phase faces plus 40 new faces) for a limited duration and indicated whether or not they recognized each face as one observed during study (old/new task) (Figure 1c). For each participant, a random half of the faces were inverted in each phase, with the orientation of a given face identical in both phases. The experiment was programmed in Python and interfaced with the eye-tracker.

During study, participants were instructed to study the faces for later recognition and viewed each face for as long as desired up to 10 seconds, self-terminating trials with a button press. The test phase began immediately after the study phase. During test, each face was presented for only one second and then disappeared. Participants indicated by button press whether they recognized the face or not. Participants were instructed to respond within two seconds following stimulus onset, as soon as they thought they knew the answer (Figure 1c).

Start positions were either above, below, right of, left of, or in the center of the internal features of the upcoming face stimulus (e.g. Figure 1b). Coordinates for a

start position were calculated uniquely for each face stimulus to be equidistant from all of the nearest internal facial features. For right and left start positions, the unique coordinate that was equidistant from the centers of the nearest eye, nearest half-nose, and nearest half-mouth AOI was calculated numerically for each face. Upper start positions were equidistant from the center of the two eye AOIs, and the lower start positions were equidistant from the two half-mouth AOIs. Distances from the upper and lower start positions to their respective AOI centers were constrained to be the mean of the of the right and left start position distances from their respective AOI centers. The center start position was at the midpoint between the two half-nose AOI centers (Figure 1b).

Before stimulus onset, participants fixated at the start position, indicated by a standard Eyelink II calibration target (0.17° diameter black circle overlaid on a 0.75° diameter white circle) on the black screen. Participants initiated the trial by pressing a button while looking at the fixation target. In this period, a drift correction was performed. A colored dot (0.5° diameter) remained after drift correction, and the stimulus appeared only after a participant had fixated at the dot for an accumulated total of 1500 ms. This ensured that drift correction and fixation were stable prior to stimulus onset. If more than 1500 ms of fixation away from the start position accumulated before the trial could be initiated, drift correction was repeated. A fixation was considered off the start position if it landed more than 0.5° from the center of the dot. Dot color changed successively from red to yellow to green in order to signal to the participant that a maintained fixation was successfully detected at the start position.

In both the study and test phases, there were equal proportions of trials of each combination of levels of the factors of face orientation, face gender, and start position. The particular subset of faces that were in the study phase and also that were inverted was randomized across participants. For a given face, orientation was identical during the study and test phases, but start position varied. Half the faces were presented with the same start position at study and test and for the other half,

the start position on the other side of the face was used (e.g. left to right start position between study and test; upper to lower between study and test).

Figure 1 - Study design
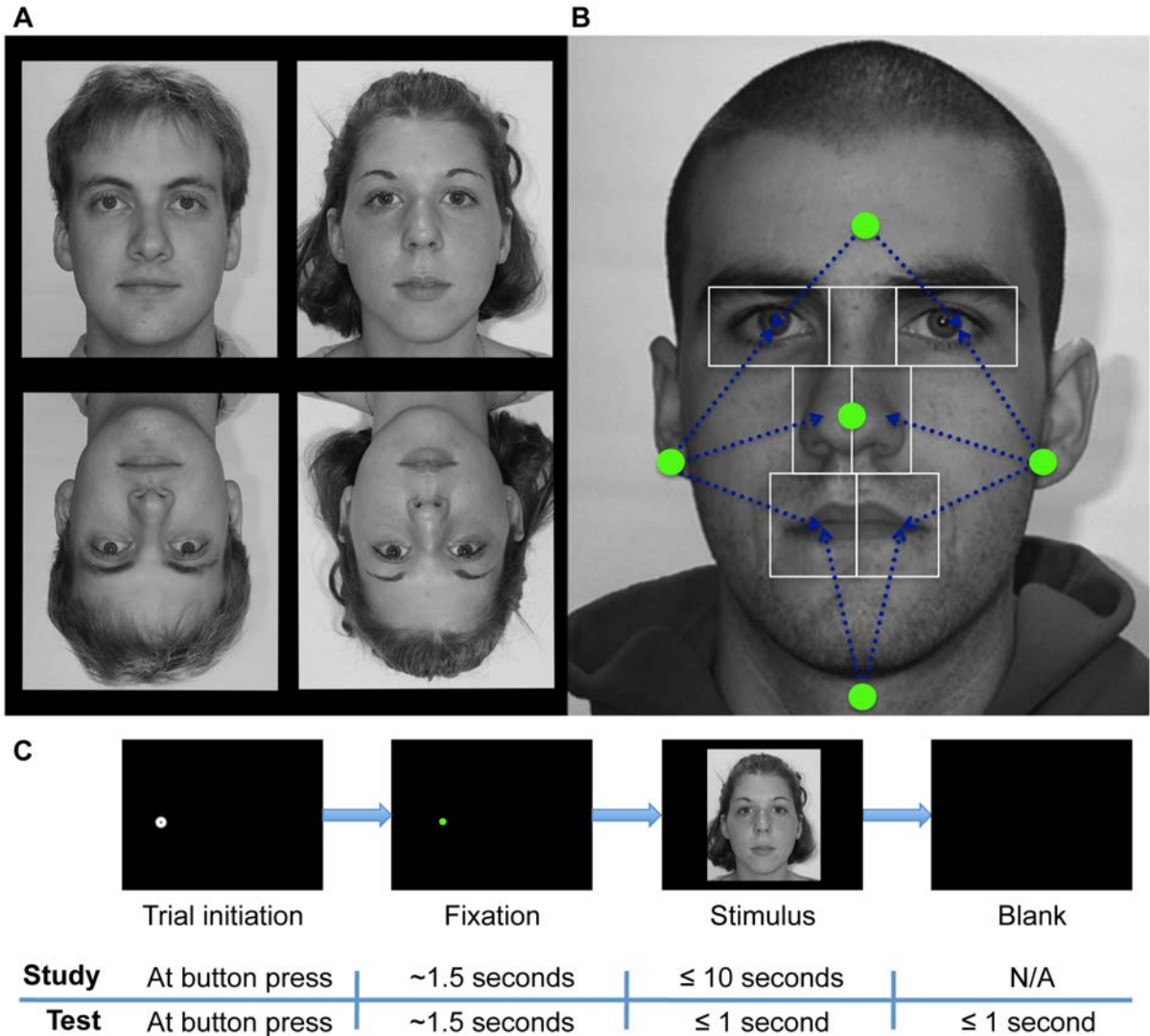
Figure 1. Study design. *(A) Four example stimuli. Note that all faces were aligned to one another and scaled to be the same size. (B) Calculation of start positions. Start positions were determined separately for each face and were defined relative to the face. Left and right start positions were equidistant from centers of the nearest eye, nose and mouth AOIs. Upper and lower start positions were equidistant from the centers of the two eye or two mouth AOIs, respectively. (C) Trial sequences in study and test phases. A face was only presented if the participant successfully maintained fixation for a total of 1.5 seconds. After face onset in the study phase, participants were free to study the face for up to 10 seconds and pressed a button to begin the next trial. In the test phase, faces were presented for one second only and participants responded with button presses to indicate whether the face was 'old' or 'new'.*

Analyses

Software

Fixation and AOI data were obtained through EyeLink Data Viewer software by SR Research. Subsequent analyses on these data and behavioral data from the test phase were performed with Matlab (The MathWorks, Inc., Natick, MA, USA). ANOVAs were performed in SPSS (IBM, Somers, NY).

Behavior

I assessed participants' discrimination performance and reaction time on the old/new recognition task in the test phase. d' was computed for discrimination performance for each participant, broken down by face orientation and start position. Reaction times for correct trials, broken down by face orientation and start position, were averaged across trials for each participant, and analyses were performed using these values.

AOI Analyses

I assessed the relative frequencies of fixations across the AOIs as a function of my experimental manipulations. Given the variable numbers of fixations across trials and across participants, only the first five fixations of each trial were included in the analyses. Relative frequency was calculated for each AOI as the number of actual fixations divided by the total number of possible fixations. ANOVAs on relative frequencies excluded the relative frequency value for the region outside of the AOIs.

Spatial Density Analyses

I mapped the spatial density of fixations as a function of my experimental

manipulations. Each fixation was plotted with equal density and spatial extent, and so fixations were not weighted by the fixation duration. Fixations beyond the fifth fixation were excluded from the analysis to ensure equal data size across trials. To ensure that summation of fixation maps across different face trials produced spatially meaningful density maps, fixation maps for individual faces were first aligned to a common reference frame using simple translations only. This reference frame was defined by the internal facial features. Specifically, the alignment minimized the sum of the squared differences between the center of the AOIs for each face and the average centers of the AOIs across all 80 faces. Within this common reference frame, fixations were then plotted as Gaussian densities with a mean of 0 and a standard deviation of 0.3° of visual angle in both the x and y dimensions. These density plots were then averaged across trials and across participants. A small proportion of analyzed fixations (< 1.6% during study, < 0.25% during test) fell outside of the bounds of the stimulus image region (i.e. onto the black background). To ensure equal numbers of fixations in the analyses these fixations were translated to the image edge nearest to the veridical fixation position. The resulting maps show the spatial fixation densities, using a color scale from zero to the maximum density value observed, with zero being transparent. All maps within a single figure contain the same total number of fixations and so are scaled the same to allow for direct comparison. For the same reason, equivalent plots for upright and inverted faces are scaled the same.

Spatial Density Contrasts

1) Difference Maps. In order to view differences in the spatial fixation density between two conditions, a pixel-wise subtraction between two spatial density maps was performed for each participant and then averaged across participants. For contrasts between upright and inverted faces, the spatial density map for inverted faces was flipped and aligned with the spatial density map for upright faces before the subtraction.

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2) Statistical Maps. In order to produce maps of statistically significant differences in the spatial density map contrasts, a Monte Carlo permutation test was performed on fixation locations between the contrasted conditions. A Monte Carlo permutation test (also called an approximate permutation test or a random permutation test) is a standard, accurate and robust method of performing a significance test on data that is not known to have a parametric (e.g. normal) distribution of values, such as my data. My statistical analysis is based on methods applied to the analysis of functional brain imaging data (Nichols & Holmes, 2002) and similar to that used in a prior study of eye tracking (Leonards et al., 2007) .

The null hypothesis in the Monte Carlo permutation tests was that the distributions of fixation locations of each ordinal fixation (i.e. fixation 1, fixation 2 etc.) were the same between the contrasted conditions (e.g. fixation 1 in upright versus inverted trials, or fixation 3 in right start position versus left). Thus, exchangeability of fixation locations between the given contrasted conditions was assumed only for fixations of the same ordinal value in the sequence of five fixations per trial. 10,400 resampling iterations were performed for each statistical map. For each iteration, locations of fixations were resampled for each individual participant according to the assumed exchangeability, then a new resampled spatial density contrast was produced. These resampled maps were then averaged across participants to produce 10400 group difference maps, the distribution of which was used to determine significance. Maps of p-values were computed pixel-wise based on the number of corresponding pixels in the resampling iterations that were greater than a given positively valued pixel (i.e. where condition 1 had a greater density) in the true spatial density contrast and that were less than a given negatively valued pixel (i.e. condition 2 greater) in the true spatial density contrast. The maps were thresholded at a pixel significance of $p < 0.01$.

For eye-tracking data, my statistical analysis has advantages over other methods of performing significance tests on contrasted fixation maps. A pixel-wise t-test is inappropriate because fixation density data across participants does not

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approximate a normal distribution at each pixel of a heatmap. Pixel-wise non-parametric tests could create a large multiple comparisons problem, which grows as the pixel resolution of heatmaps grow. In my analysis, fixation locations are exchanged rather than pixels; therefore, increasing the resolution at which heatmaps are displayed does not exacerbate the multiple comparisons problem. My analysis is an alternative to a Random Field Theory approach, which has been implemented recently by Caldara and colleagues in a free Matlab toolbox called iMap (Caldara & Miellet, 2011).

3) Cluster Corrections for Multiple Comparisons on Statistical Maps. In order to reduce the chance of false positives in my statistical maps due to multiple comparisons, I implemented a nonparametric cluster correction. This correction is based on principles that have been applied to the analysis of functional brain imaging data (Nichols & Holmes, 2002), but, to my knowledge, is novel in the eye-tracking literature. For each analysis, statistical maps were produced for 2600 of the 10400 resampled maps that had resulted from the permutation test. For each of the resulting statistical maps, the size (in pixels) of the largest cluster of $p<0.01$ significance was recorded. Thus a distribution of the maximum cluster size across the iterations of the permutation test was obtained. The size of each cluster in the statistical map of the true data was then compared to the maximum cluster size distribution just obtained. The cluster threshold was set to be $p < 0.05$; therefore, any significant clusters of the true data smaller than the top 5% of the maximum cluster size distribution were eliminated from the statistical map.

3.3 - Results

Discrimination

Consistent with prior reports I observed a face inversion effect on discrimination scores (d'). A two-way ANOVA, with Orientation (upright, inverted) and Start Position (left, right, center, up, down) as within-subject factors revealed a significant main

effect of Orientation with better discrimination for upright than inverted faces ($F(1,18)$ = 29.42, $p < 0.001$, $\eta_p^2 = 0.62$). However, there were no main effects or interactions involving Start Position ($p > 0.15$, , $\eta_p^2 < 0.066$, Figure 2a). An identical two-way ANOVA on reaction time data also revealed a significant main effect of Orientation ($F(1,18) = 8.45$, $p < 0.01$; Figure 2b) and no main effects or interactions involving Start Position ($p > 0.14$). Further, during study, participants viewed inverted faces longer than upright faces (mean viewing time: upright, 6300 ms, inverted, 6636 ms, t = 3.69, $p < 0.002$).

Figure 2 - Effects of face inversion on recognition
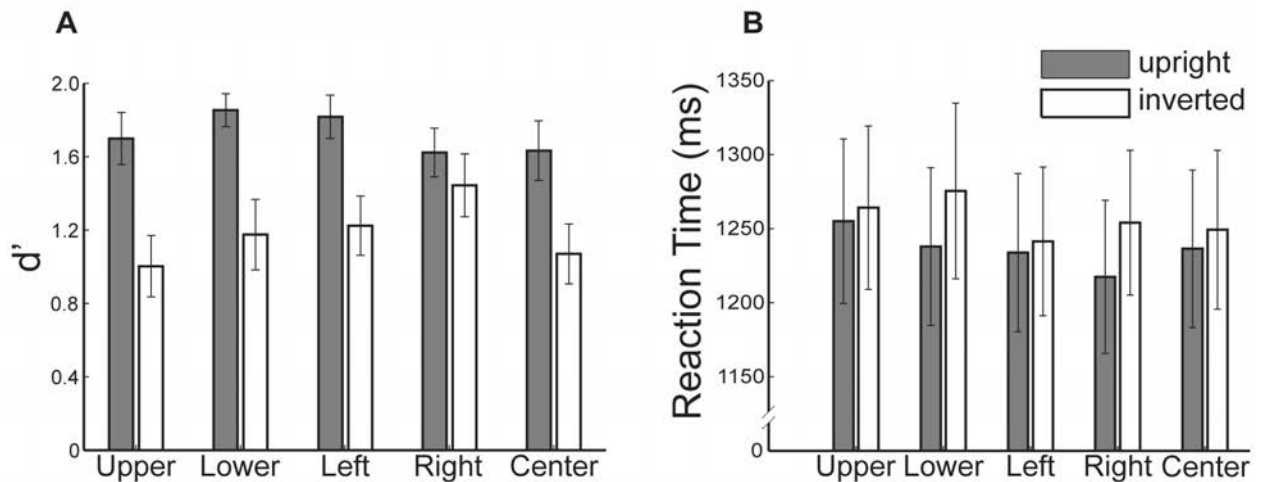
Figure 2. Effects of face inversion on recognition. (A) *Face recognition, measured by d',* *was significantly greater for upright than inverted faces.* **(B)** *Reaction time also showed an* *effect of inversion, with longer reaction times for inverted compared to upright faces. Error* *bars indicate the between-subjects standard error.*

Fixation Patterns: Upright Faces

I focus first on eye tracking data for upright faces during the study phase before considering the impact of inversion on the pattern of fixations, and the effect of experiment phase (study versus test).

Figure 3 - Distribution of fixations for upright faces averaged across start positions
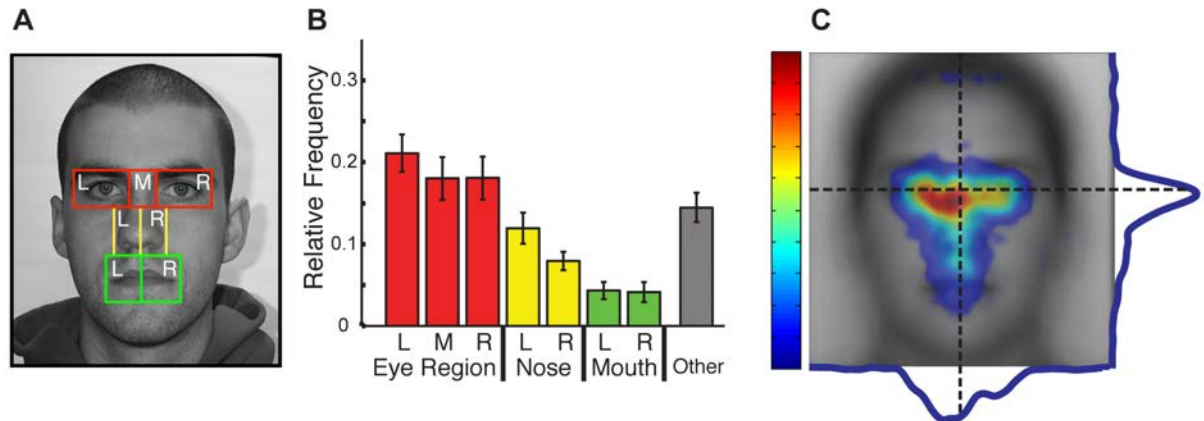
Figure 3. Distribution of fixations for upright faces averaged across start positions. *(A) Example of AOIs for one face. AOIs could be divided into three separate feature regions: eye (red), nose (yellow), and mouth (green). 'L', 'M' (eye region only), and 'R' refer to the left, middle, and right, respectively, of the facial feature regions. (B) Relative frequencies of fixations across AOIs for the first five fixations revealed more fixations to the eye region compared with the nose and mouth regions. Error bars indicate the between-subjects standard error. (C) Spatial density and profile plots for the first five fixations showing more fixations to the eye region with a tendency toward the left side of the face. The face plotted beneath the spatial density plot is the average of all faces after alignment. Fixations are plotted as Gaussian densities summed across trials and participants. Fixation density is indicated using a colorscale from zero to the maximum density value observed, with zero being transparent. Profile plots to the right and below the spatial density map are summations of the spatial densities across each dimension. The vertical dotted line indicates the midline of the average face. The horizontal dotted line indicates the vertical position of the center of the eyes.*

Average Fixations Collapsed Across Start Position Show a Tendency Toward the Left Eye

In order to establish that my data agreed with prior studies (e.g. Blais et al., 2008; Hsiao & Cottrell, 2008; Janik et al., 1978) in which the effect of start position was not considered, I first analyzed the eye tracking data by pooling across start positions. In both AOI and spatial density analyses I observed the expected tendency toward the upper part of the face (Figure 3). A one-way ANOVA on the relative frequency of fixations (Figure 3b) revealed a significant effect of AOI ($F(6,114) = 10.82$, $p < 0.001$). Post-hoc t-tests revealed significantly higher relative frequency of fixations for each of the three eye-region AOIs than either of the mouth AOIs (all Bonferroni corrected $p < 0.015$, unbiased G_{Hedges} ranged from 1.47 to 2.01). This is also clear in the spatial density maps where the peak fixation density is just below the eyes and

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falls off rapidly toward the lower part of the face (Figure 3c). Further, consistent with prior reports (e.g. Hsiao & Cottrell, 2008; Mertens, Siegmund, & Grusser, 1993), there appears to be a tendency toward the left side of the face with a higher relative frequency of fixations for the left than right eye and for the left than right nose. In terms of the spatial density of fixations, the peak of the distribution across participants was shifted to the left of the midline of the face.

While these analyses reveal a similar pattern of fixations to prior studies, I observed a significant effect of start position. In the following section, I break down the results by start position.

Fixation Patterns Are Dependent on Start Position

Both AOI and spatial density analyses revealed striking differences in fixation patterns as a function of start position (Figure 4). At a coarse level, data from each of the five start positions showed some similarities, with a general tendency for fixations to fall toward the eye region over other parts of the face. However, the specific distribution of fixations across the eyes and other internal features varied substantially. A two-way repeated-measures ANOVA on the relative frequency of fixations with Start Position and AOI (R Eye, M Eye, L Eye, R Nose, L Nose, R Mouth, L Mouth) as factors revealed a significant interaction between start position and AOI ($F(24,456) = 5.29$, $p < 0.001$, $\eta_p^2 = 0.22$). This effect persisted across the first few fixations. A sequence of two-way ANOVAs for each ordinal fixation out to the fifth, with AOI and Start Position as within-subject factors, revealed significant interactions between Start Position and AOI for each of the first three ordinal fixations, and a trend for the fifth (First Fixation: $F(24,456) = 5.11$, $p < 0.001$, $\eta_p^2 = 0.21$; Second Fixation: $F(24,456) = 4.34$, $p < 0.001$, $\eta_p^2 = 0.19$; Third Fixation: $F(24,456) = 2.499$, $p < 0.013$, $\eta_p^2 = 0.12$; Fourth Fixation: $F(24,456) = 1.46$, $p > 0.17$, $\eta_p^2 = 0.071$; Fifth Fixation: $F(24,456) = 1.725$, $p < 0.083$, $\eta_p^2 = 0.083$). Thus, the effect of start position persists beyond the initial fixation.

Figure 4 - Impact of start position on distribution of fixations for upright faces
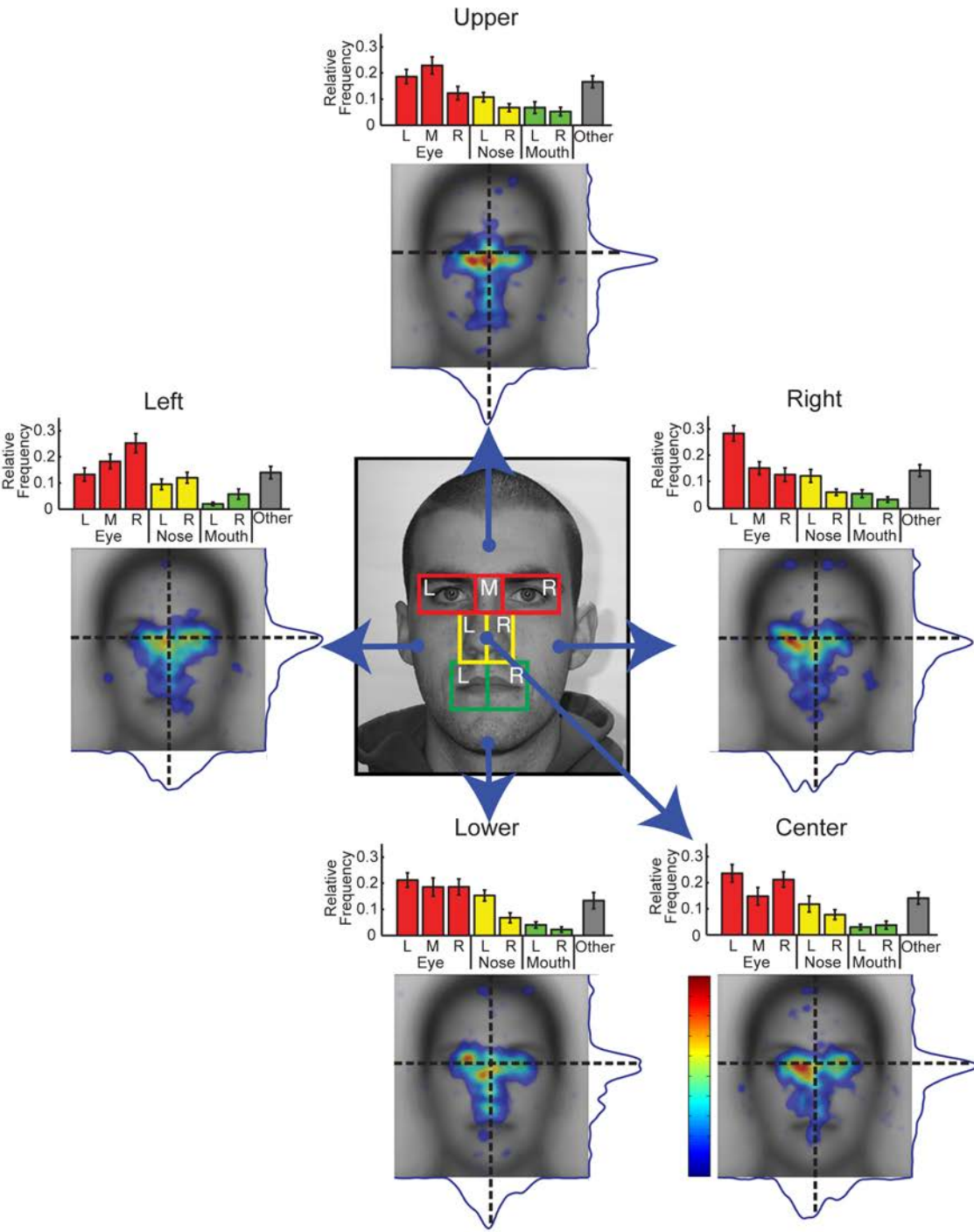
Figure 4. Impact of start position on distribution of fixations for upright faces. *AOI, spatial density, and profile plots reveal a strong effect of start position on the distribution of fixations. For example, the overall tendency to one side of the face varies across start positions and switches from the left side of the face for the right start position to the right side of the face for the left start position. Fixation density in the heatmaps is indicated using a colorscale from zero to the maximum density value observed across the five heatmaps, with zero being transparent. Error bars indicate the between-subjects standard error.*

However, it is clear from the spatial density maps (Figure 3) that the peak fixation density does not often correspond to a unique AOI. Thus, the differences revealed in this analysis are subject to my AOI definitions, which may not be ideal. In later sections, I will consider direct contrasts of the fixations patterns in spatial density maps. However, this initial analysis suffices to establish that start position has a significant impact on the pattern of eye movements observed. Before characterizing the precise impact of start position on the spatial distribution of fixations, I consider the temporal properties of the eye movements and fixations.

Eye Movements for Center Start Position are Qualitatively Different From Other Start Positions

As noted earlier, one of the concerns about the commonly used center start position is that observers could be sampling information about the face even before making any eye movements. To investigate the possibility that information is sampled at center start position even before a saccade is made, I analyzed the latency to the first saccade i.e. the time between the onset of the face and the first saccade (Figure 5a). A one-way repeated measures ANOVA revealed a highly significant effect of Start Position ($F(4,76) = 18.95$, $p < 0.001$). Paired comparisons (Bonferroni corrected) revealed that latencies did not vary across the four peripheral start locations (all $p > 0.38$), but the latency to first saccade for the center start location was significantly longer than every one of the other start positions (all $t > 5.33$, $p < 0.001$). The increased time to make an eye movement away from the initial fixation position strongly suggests that there is some increased face processing at the center start position even before any eye movements have occurred.

Figure 5 - Impact of start position on timing of initial saccades and fixations for upright faces

Figure 5. Impact of start position on timing of initial saccades and fixations for upright faces. (A) Average latency to first saccade by start position. Note the longer delay between face onset and the first saccade for the center compared to peripheral start positions. (B) Average duration of first fixation by start position. Note the longer fixation duration for the center compared to peripheral start positions. All error bars indicate the between-subjects standard error.

Given this difference in saccade latency between center and peripheral start locations I further examined the duration of the first fixation following this initial saccade (Figure 5b). Two participants evidenced average durations less than 2.5 standard deviations from the group mean, and were excluded from this analysis. However, the overall results do not change with the inclusion of these participants. I observed the same pattern as for the initial saccade with longer fixation duration for the center start position compared with the others. A one-way repeated measures ANOVA revealed a significant effect of Start Position ($F(4,68) = 3.07$, $p < 0.05$).

Taken together, these results suggest that, for the center start position, the experimenter and not the participant determine the initial information sampled. More generally, given the qualitative differences in the timing of eye movements between central and peripheral start positions, central and peripheral starting positions cannot be directly compared, and I focus in the rest of my analyses on the four peripheral start positions only.

I found that first fixation was shorter than subsequent fixations for all peripheral start positions (Figure 6a). Two-way ANOVA on fixation duration with peripheral Start Position (Left, Right, Upper, Lower) and Fixation Number (1-5) as factors revealed a significant main effect of Fixation Number ($F(4,68) = 20.57$, $p < 0.001$), and a main effect of Start Position ($F(3,51) = 2.96$, $p < 0.048$) arising from slightly longer average fixation durations for the lower and left start positions. Paired comparisons (Bonferroni corrected) between durations for each Fixation Number collapsed across Start Position revealed that the first fixation was shorter in duration than the other fixations (all $t > 5.50$, $p < 0.001$) and that the other fixations did not differ from each other in duration (all $p > 0.1$).

To investigate the evolution of the fixation patterns with the center start position excluded, I plotted for each combination of peripheral start position and ordinal fixation number the average fixation location for each individual participant (Figure 6b). To evaluate the effect of start position I considered the group average location of each fixation in the horizontal and vertical dimensions (Figure 6c). On the first fixation there was a clear effect of start position. The first fixations landed near the center of the face, regardless of peripheral start position, with a slight tendency toward the start position itself. In particular, the first fixations for the right start position were significantly to the right of the first fixations for the left start position ($t = 4.10$, $p < 0.001$) but these fixations did not vary in vertical position ($t = 0.53$, $p > 0.1$) (Figure 6b, 6c). The opposite was true for the upper and lower start positions, for which the first fixations for the upper start position were significantly higher than the first fixations for the lower start position ($t = 5.28$, $p < 0.001$) but did not vary in horizontal position ($t = 1.70$, $p > 0.1$). On subsequent fixations, there was also a clear effect of start position, but with a tendency toward the side of face opposite the start position. Thus, the second fixations for the right start position were significantly to the left of the second fixations for the left start position ($t = 7.76$, $p < 0.001$), but again there was no difference in vertical position ($t = 0.99$, $p > 0.1$).

Figure 6 - Evolution of fixations over ordinal number for upright faces

Figure 6. Evolution of fixations over ordinal number for upright faces. (A) Average duration of each ordinal fixation. Note the much shorter duration of the first than subsequent fixations. (B) Distribution of individual participants' fixation locations broken down by start position for each ordinal fixation (F1-F5). Fixation locations for the first fixation were generally toward the center of the face, but with a relative tendency to fall closer to the start position. Fixation locations for subsequent fixations tended to fall on the side of the face opposite the start position. For example, on the first fixation, fixations for the left start position show a tendency to the left side of the face while those for the right start position show a tendency to the right side of the face. On subsequent fixations, these tendencies reverse with the right start position showing a tendency to the left side of the face and the left start position to the right side of the face. A similar effect can be observed for the upper and lower start positions. (C) Average locations from (B). The two left plots give the average horizontal position of fixations in degrees of visual angle relative to the midline of the face (dotted line). The two right plots give the average vertical position relative to the vertical position of the eyes (Figure 3B). Note the strong effect of the left and right start positions on horizontal but not vertical position (top panels) and the opposite effect for the upper and lower start positions (bottom panels). Error bars indicate the between-subjects standard error.

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Similarly the second fixations for the upper start position were significantly lower than the second fixations for the lower start position (t = 3.87, p < 0.001) with no difference in horizontal position (t = 0.45, p > 0.1). This tendency toward parts of the face opposite the start position was maintained throughout fixations 2-5 for the left/right start positions (all t > 4.74, p < 0.001), but was slightly weaker for the upper/lower start positions and was significant on fixations 2-4 only (all t > 2.43, p < 0.05). Importantly, the general spatial patterns observed on average across the first five fixations (Figure 4) only emerged on the second fixation. Combined with the finding that the first fixation is relatively short, this result suggests that the location of the first fixation is very heavily constrained by start position and may reflect a generic scanning strategy rather than any face specific processing. In light of this, I excluded the first fixation from the remainder of my fixation analyses for upright faces.

Direct contrasts of fixation patterns between start positions

To characterize the effect of start position more precisely I conducted direct comparisons of the fixation patterns observed for the peripheral start positions. I conducted subtractions of the spatial density maps and computed statistical significance using Monte Carlo permutation tests (see Methods). For these analyses I used only fixations 2-5. Here, I focus on the comparison of left and right start positions (Figure 7a) and upper and lower start positions (Figure 7b). Note that in the spatial density maps for each start position in Figure 7 (with the first fixation removed), the profiles are more distinct than those shown earlier in Figure 4 with a weaker spatial density toward the center of the face.

Figure 7 - Direct comparison of spatial distributions of fixations for different start positions on upright faces
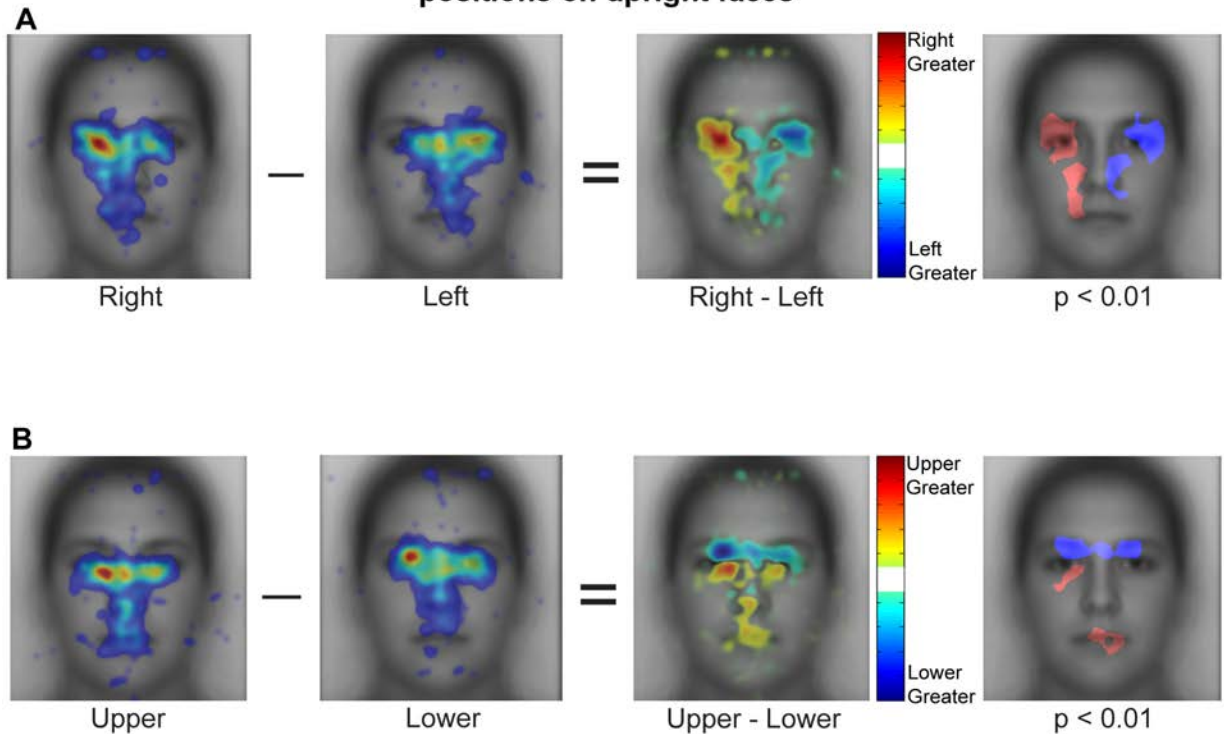
Figure 7. Direct comparison of spatial distributions of fixations for different start positions on upright faces. **(A)** Right vs. left start position. The first two panels are the raw spatial density maps for fixations 2-5. The third panel shows the subtraction of these spatial density maps. The fourth panel plots those locations where that difference was significant (p < 0.01) according to a Monte Carlo permutation test, which assumed exchangeability of fixations across contrasted start positions for each ordinal fixation. The map was cluster corrected (cluster threshold p < 0.05, see methods). Note the significant advantage for the side of the face opposite the start position. **(B)** Same as (A) but for the upper and lower start positions. Note again the strong and significant advantage for the side of the face opposite the start position. Fixation density in the raw heatmaps is indicated using a colorscale from zero to the maximum density value observed across the heatmaps for start position, with zero being transparent. The difference in fixation density in contrast heatmaps is indicated using a colorscale from plus to minus the largest absolute difference observed across start position contrast maps.

Contrasting right versus left start position reveals a general advantage for the opposite side of the face (Figure 7a). The direct subtraction of these results reveals a symmetrical pattern with each start position showing a relative advantage for the opposite side of the face, primarily around the eyes but extending onto lower parts of the face as well. Thus, the right start position showed a relative advantage for the left eye while the left start position showed a relative advantage for the right eye.

A similar relative advantage for the opposite side of the face is also clear in the direct comparison of upper and lower start positions (Figure 7b). The upper start position showed a relative advantage for the mouth and nose while the lower start position showed a relative advantage for the upper part of the eye region bilaterally. Note that even though the eye region was fixated substantially with both upper and lower start positions, the precise locations of those fixations differed, with fixations for the upper start location predominantly below the eyes and fixations for the lower start position predominantly above the eyes.

In summary, fixation patterns for upright faces were highly influenced by start position. Most strikingly the often-reported advantage for the left side of the face was abolished for the left start position, which evidenced a right side advantage. This effect of start position was present even on the fifth fixation. The central start position, commonly used in prior studies (Althoff & Cohen, 1999; Goldinger et al., 2009; Heisz & Shore, 2008), evidenced a longer latency to first saccade and first fixation duration than peripheral start positions suggesting that information is being sampled substantially even before the first saccade and highlights the strong potential biases likely introduced by the use of this start position. Regardless of start position, the first fixation was significantly shorter than the subsequent fixations and heavily impacted by start position. Finally, in general, fixations tended to fall on the opposite side of the face to the start position.

Fixation Patterns: Inverted Faces

I conducted the same series of analyses on inverted faces as I did for upright faces, finding very similar effects of start position and ordinal fixation number. As with upright faces, latency to first saccade (Figure 8a) was dependent on start position ($F(4,76) = 23.903$, $p < 0.001$). Paired comparisons (Bonferroni corrected) revealed that the latency to first saccade for the center start position was significantly longer than any of the other start positions (all $t > 4.77$, $p < 0.001$), and there were no significant differences between latencies for the non-center start positions (all $p >$

0.05). Further, as for upright faces, the duration of the first fixation was similarly dependent on start position (Figure 8b) (F(4,68) = 4.53, p < 0.01) with longer first fixation durations for the center compared with peripheral start positions.

Figure 8 - Impact of start position on timing of initial saccades and fixations for inverted faces
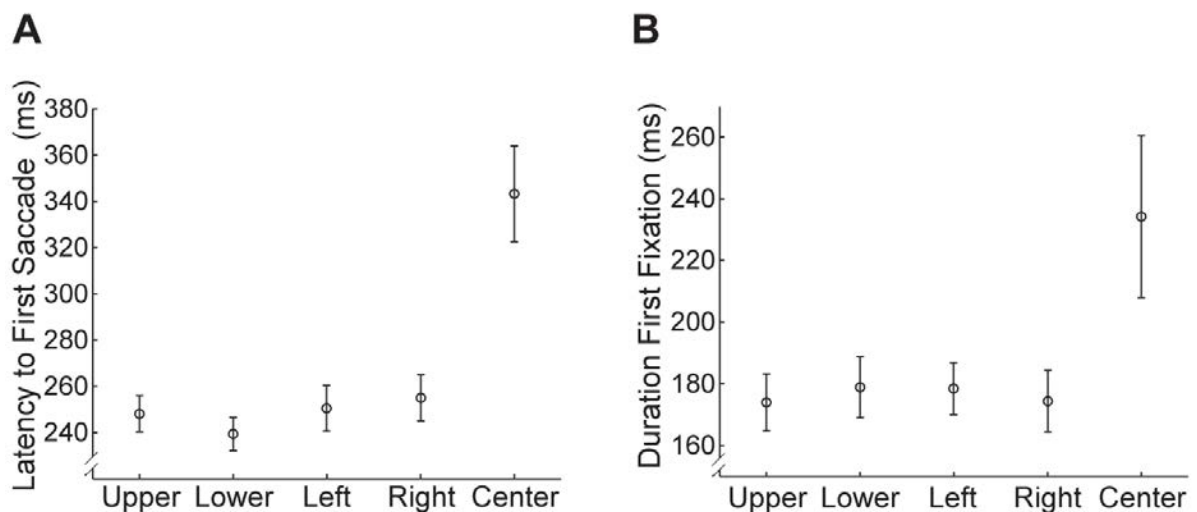
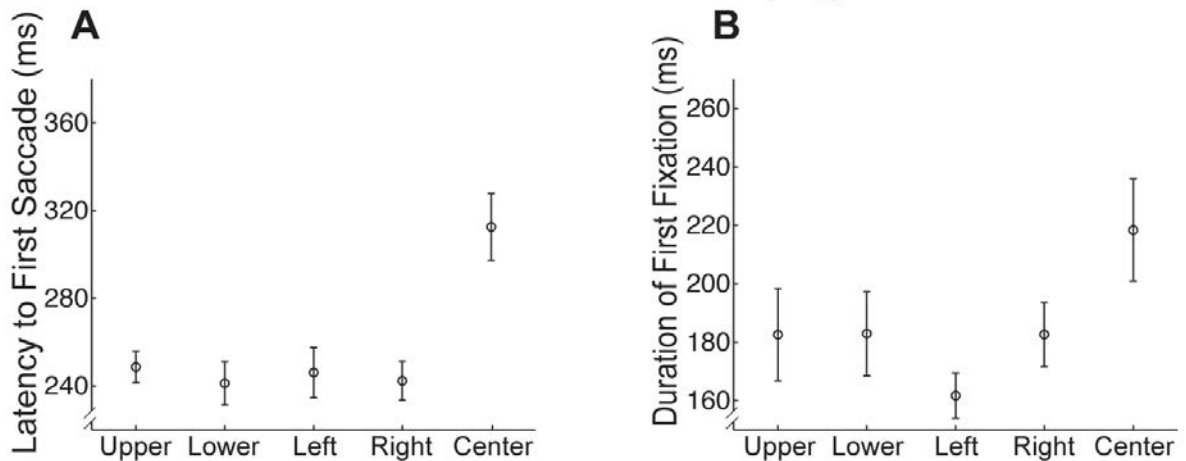*Figure 8: Impact of start position on timing of initial saccades and fixations for inverted faces. (A) Latency to first saccade. Note that the effect of start position was similar to that observed for upright faces with a longer latency for center compared to peripheral start positions (Figure 5a). (B) Duration of the first fixation. Again that the effect of start position was similar to that observed for upright faces with a longer fixation duration for center compared to peripheral start positions. All error bars indicate the between-subjects standard error.*

To directly test the effect of inversion on the temporal properties of the eye movements I ran a series of ANOVAs including Orientation as a factor. For latency to first saccade, as expected, there was a main effect of Start Position (F(4,76) = 34.98, p < 0.001). In addition there was a main effect of Orientation (F(1,19) = 4.73, p=.042), arising from slightly longer latencies for inverted than upright faces, but there were no interactions involving Orientation (p > 0.1). Thus, inversion had little impact on the overall effect of start position. An identical ANOVA on the duration of the first fixation (Figure 8b) revealed a main effect of Start Position only (F(4,68) = 7.83, p < 0.001), reflecting the longer duration of the first fixation for the center start position, and no effects involving Orientation (p > 0.1).

Focusing on the peripheral start positions only, an ANOVA on the fixation durations for inverted faces (Figure 9a) with Fixation Number and Start Position revealed a main effect of Fixation Number only ($F(3,51) = 29.90$, $p < 0.001$). As with upright faces, the duration of the first fixation was shorter than fixations 2-5 (all $t > 5.18$, $p < 0.001$). However, unlike upright faces, the duration of the second fixation was also shorter than fixations 3-5 (all $t > 3.46$, $p < 0.01$). To directly compare upright and inverted faces, fixation durations were entered into an ANOVA with Fixation Number and Orientation as factors, revealing a main effect Fixation Number only ($F(4,68) = 25.41$, $p < 0.001$) and no main effects or interactions involving Orientation ($p < 0.05$). Thus, inversion had minimal impact on the different fixation durations for the first five fixations.

Plotting the average fixation location for each combination of peripheral start position and fixation number in each individual participant revealed very similar effects to those observed for upright faces. First fixations landed near the center of the face with a tendency toward the start position (Figure 9b). Thus, first fixations for the left start position were significantly to the left of those for the right start position ($t = 3.09$, $p < 0.01$), and first fixations for the lower start position were significantly lower than first fixations for the upper start position ($t = 4.98$, $p < 0.001$). As with upright faces, the central tendencies for each start position switched to the side of the face opposite the start position on the second and subsequent fixations. The horizontal difference in fixation location between the left and right start positions was significant for fixations 2-5 (all $t > 3.46$, $p < 0.01$), and the vertical difference between the upper and lower start positions was significant on fixations 2-4 (all $t > 3.60$, $p < 0.002$) (Figure 9c).

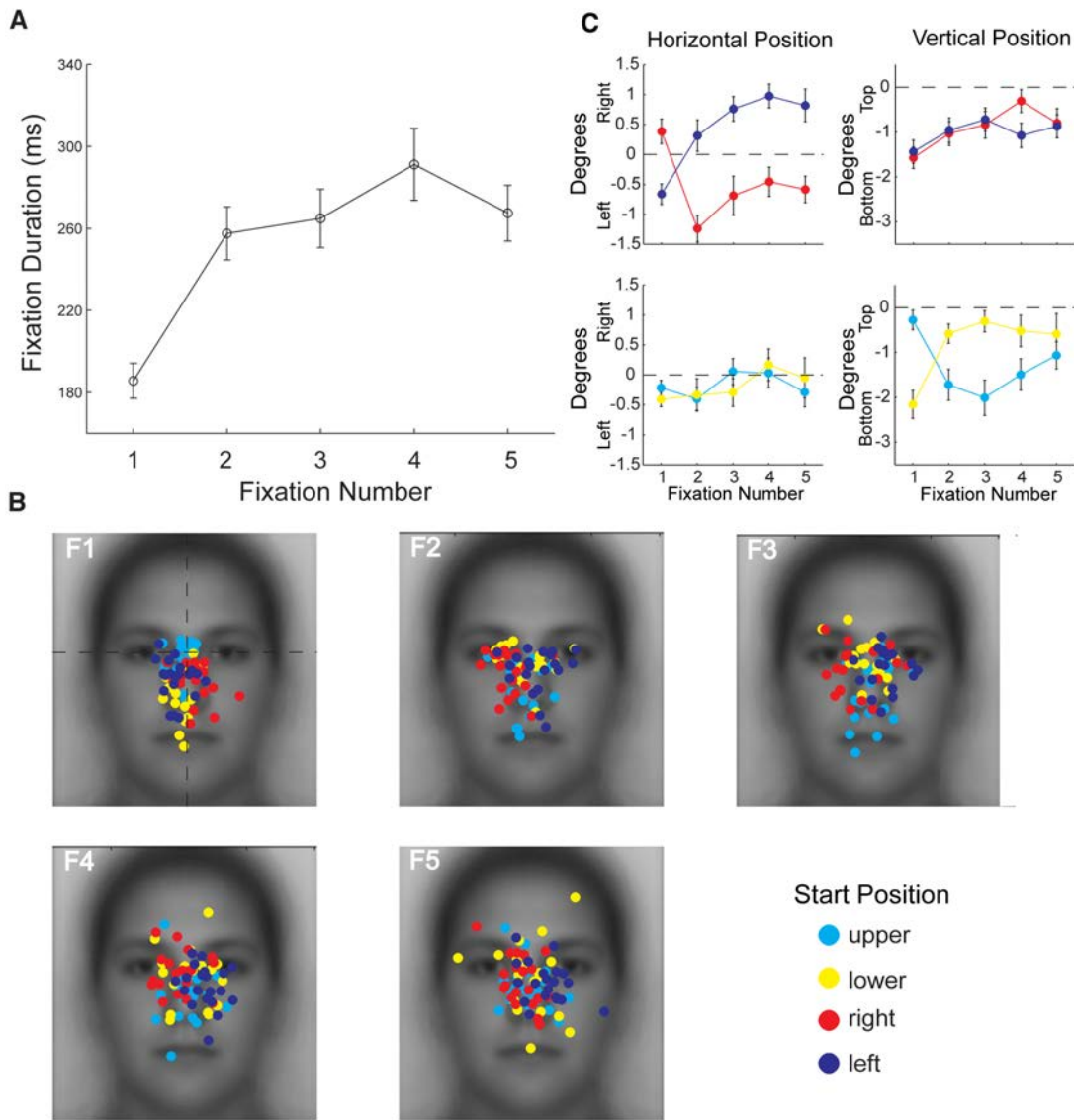# Figure 9 - Evolution of fixations over ordinal number for inverted faces
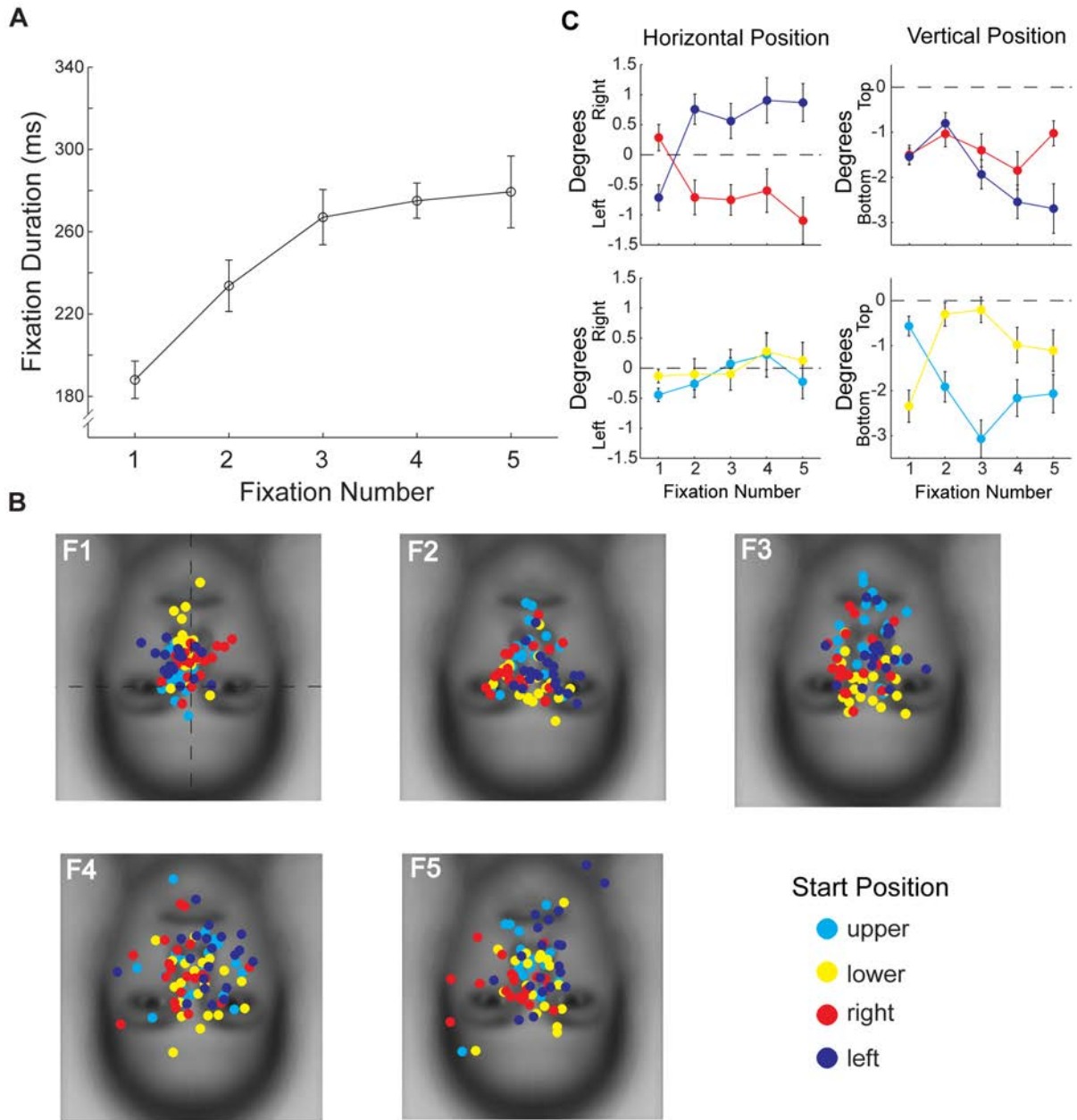
Figure 9: Evolution of fixations over ordinal number for inverted faces. (A) Average duration of each ordinal fixation. Note the much shorter duration of the first than subsequent fixations as was observed for upright faces. (B) Distribution of fixation locations across individual participants broken down by start position for each ordinal fixation (F1-F5). As for upright faces, fixation locations for the first fixation were generally toward the center of the face, but with a relative tendency to fall closer to the start position. Subsequent fixations locations tended to fall on the side of the face opposite the start position just as for upright faces. Note that all start positions are defined relative to the face. (C) Average locations from (B). Note the similar effects to those shown in Figure 6C. Error bars indicate the between-subjects standard error.

Direct comparison of the spatial density maps for the right and left start positions across fixations 2-5 revealed a similar pattern to that observed for upright faces, with each start position showing a relative advantage toward the opposite side of the face (Figure 10a). Similarly, comparison between upper and lower start positions revealed a relative advantage for the right side of the mouth and nose regions for the upper start position and toward the upper central part of the eye region for the lower start position (Figure 10b).

Figure 10 - Direct comparison of spatial distributions of fixations for different start positions on inverted faces
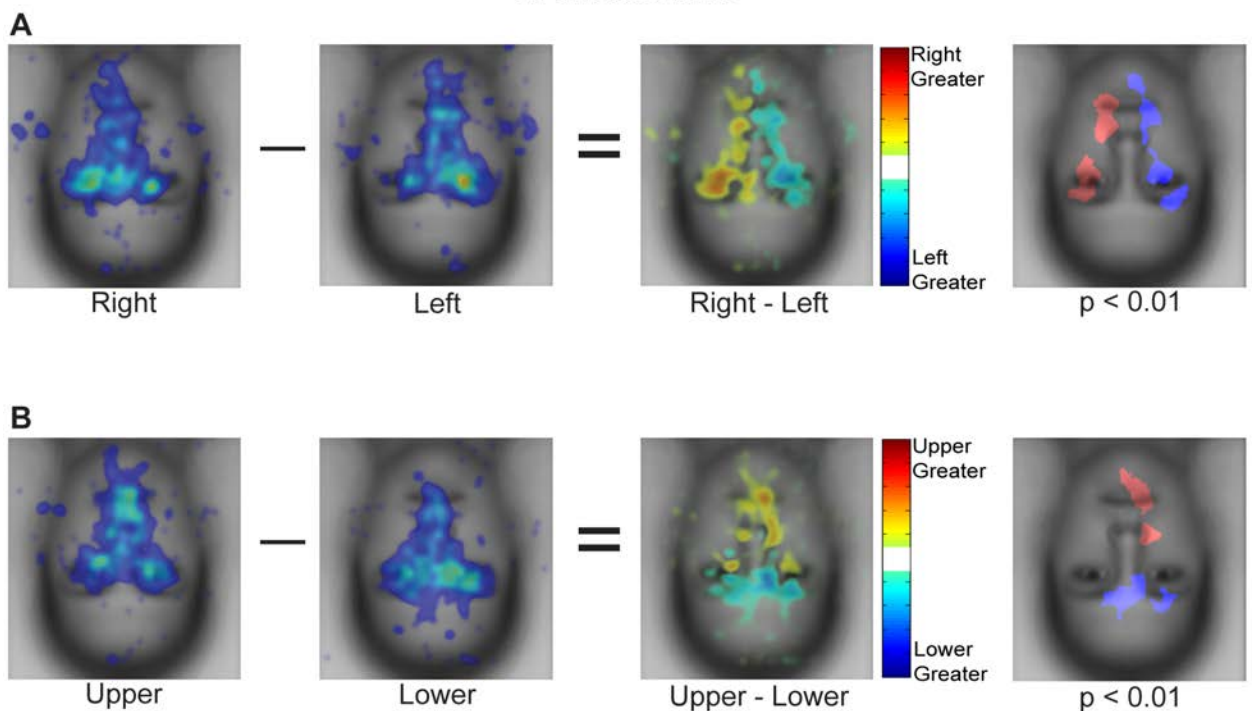
Figure 10: Direct comparison of spatial distributions of fixations for different start positions on inverted faces. (A) Contrast between right and left start positions. All conventions are the same as in Figure 7. Note the symmetrical advantage for the side of face opposite the start position as with upright faces. (B) Contrast between upper and lower start positions. Note, again, the advantage for the side of the face opposite the start position.

Overall, with inverted faces, I saw very similar effects of start position to those observed with upright faces. There was an increased latency to first saccade for the center compared with non-center start positions, a shorter first fixation, a general advantage for the upper parts of the face and a strong effect of start position with a relative advantage for the opposite side of the face for the non-center start positions.

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Spatial density of fixations: upright versus inverted faces

So far I have demonstrated similar effects of start position on upright and inverted faces, but have not directly compared the spatial density of fixations for upright versus inverted faces. A prior study (Barton et al., 2006) reported that for upright faces people make relatively more fixations to the eyes and relatively fewer fixations to the mouth region compared with inverted faces (but see Rodger et al., 2010; Williams & Henderson, 2007). Comparison of Figures 7 and 10 shows that the overall spatial envelope of fixations is quite similar between upright and inverted faces. However, the relative advantage for the eye regions over the mouth regions is weaker for inverted compared with upright faces. To directly compare the pattern of eye movements for upright and inverted faces, I first contrasted the patterns of fixations averaged across start position, but excluding the first fixation and the central start position (Figure 11). While this difference reveals more fixations to the eye region for upright faces and more fixations to the mouth region for inverted faces it is important to note that there are some parts of the eye region that show a relative advantage for inverted faces. In particular, there are relatively more fixations to the upper part of the right eye for inverted faces compared with upright faces.

However, as I have shown above, there is a large effect of start position even for inverted faces. This effect of start position on both upright and inverted faces must inevitably affect the contrast of upright and inverted faces. Breaking down the contrast by start position, I find that while upright faces do seem to have relatively more fixations to the eyes and inverted faces relatively more fixations to the mouth region, the precise differences between upright and inverted are dependent on start position (Figure 12). For example, for both the upper and lower start positions, inverted faces have relatively more fixations above the right eye. This is not observed for the center and left start positions. Similarly, while the lower start position shows a relative advantage for inverted faces in the center of the mouth, for other start positions the advantage for inverted faces is on the chin or closer to the nose. These findings suggest that while the coarse difference between upright and

inverted faces is similar across start positions (more fixations to the eye region for upright, more fixations to the mouth region for inverted), the specific locations of the difference in fixation pattern between upright and inverted faces vary as a function of start position.

Figure 11 - Direct comparison of spatial distributions of fixations for upright and inverted faces
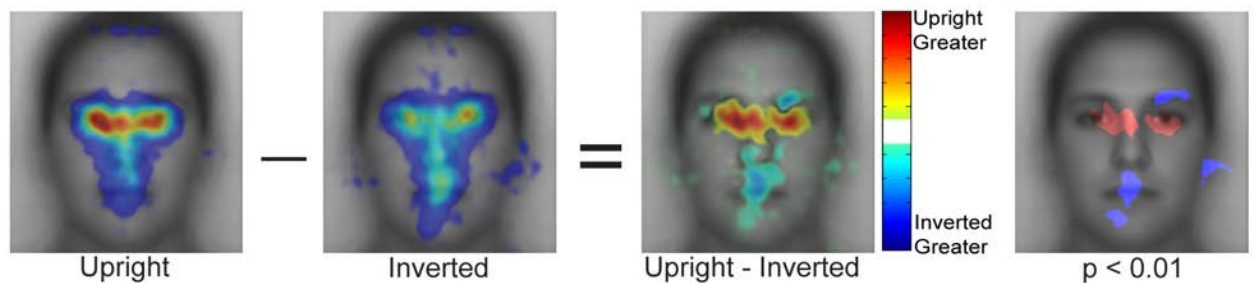
Figure 11: Direct comparison of spatial distributions of fixations for upright and inverted faces. The first two panels show the spatial density of fixations averaged across the peripheral start positions for upright and inverted faces, respectively. Note that there is greater variability in the location of fixations across the internal features for inverted than upright faces, but that the same general pattern holds. The third panel shows the subtraction of the first two panels and the fourth panel shows statistically significant differences. Overall, there are relatively more fixations to the eye region for upright compared to inverted faces and relatively fewer fixations to the mouth region. Fixation density in the raw heatmaps is indicated using a colorscale from zero to the maximum density value observed across the heatmaps pooling the peripheral start positions, with zero being transparent. The difference in fixation density in contrast heatmaps is indicated using a colorscale from plus to minus the largest absolute difference observed in the contrast map.

Thus, fixation patterns for upright and inverted faces both show a relative advantage for the upper over the lower part of the face. At a coarse level, upright faces show relatively more fixations to the eye region and inverted faces to the mouth region consistent with at least one prior report (Barton et al., 2006). However, the fine-scale differences in fixations between upright and inverted faces are dependent on start position.

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Figure 12 - Impact of start position on the comparison of upright and inverted faces
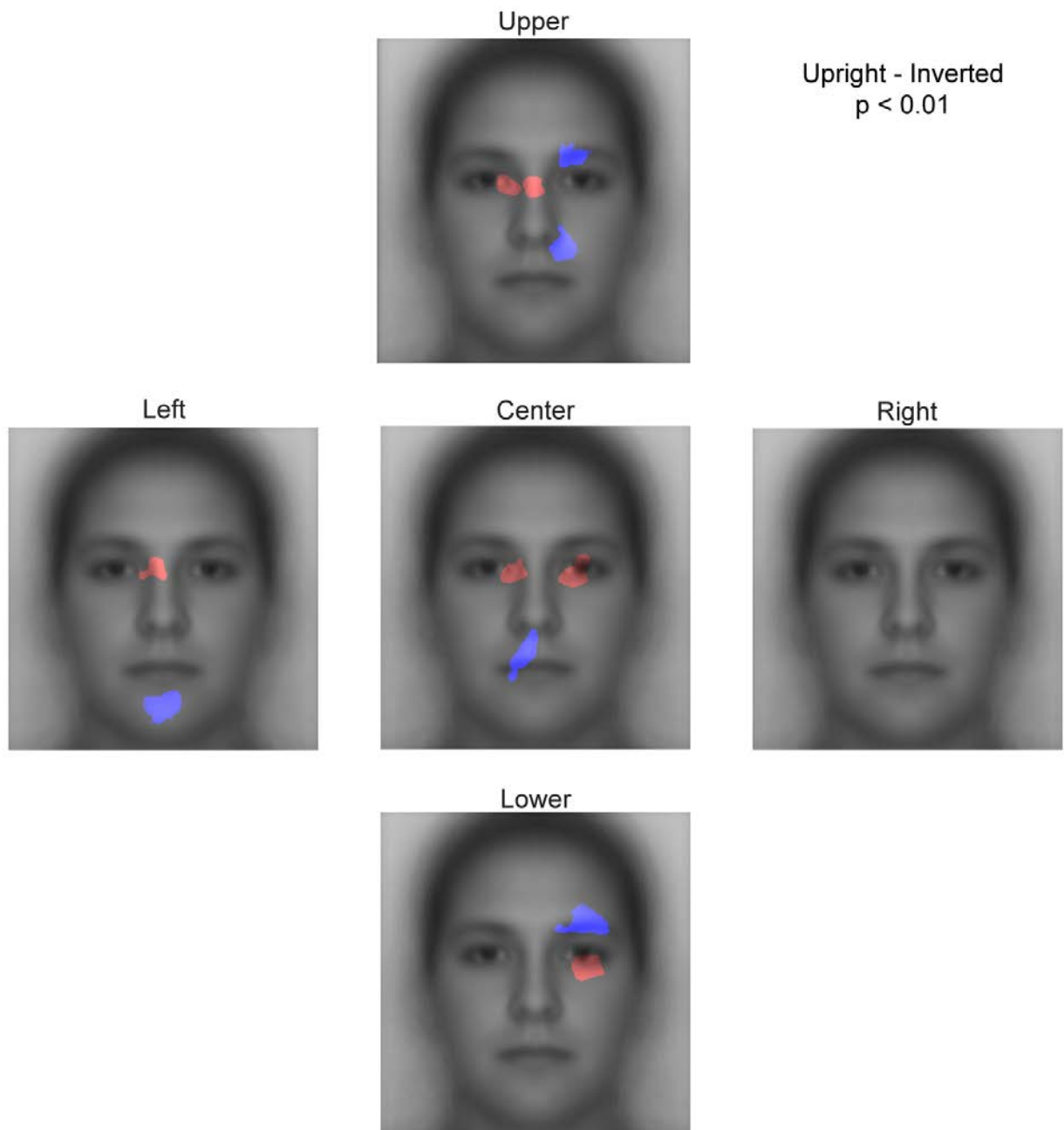
Figure 12: Impact of start position on the comparison of upright and inverted faces. *Statistically thresholded maps for the contrast between upright and inverted faces by start position. Regions with p < 0.01 significance for upright faces are shown in red and those for inverted faces are shown in blue. At a coarse scale, the difference is consistent with more fixations to the eyes in upright and toward the lower part of the face in inverted. However, the precise location and extent, particularly of which part of the lower face accrues more fixations in inverted and which part of the eye region accrues more fixations in upright varies with start position.*

Fixation Patterns: Study Versus Test

So far I have only considered data from the study phase of the experiment, when viewing of the faces was relatively unconstrained. In the test phase of the experiment, faces were only presented for 1 second each and participants had to judge immediately whether they recognized the face or not. Participants made fewer fixations during face presentation in the test phase, but the basic patterns of fixations and effects of start position were very similar to the study phase.

In particular, the pattern of Start Position timing differences for the first saccade and subsequent fixations were nearly identical in study and test for both upright and inverted faces (Figure 13a-b). An ANOVA on latency to first saccade with Phase (Study, Test), Start Position, and Orientation as within-subject factors revealed a main effect of Start Position ($F(4,76) > 55.40$, $p < 0.001$), reflecting the longer latency for the center start position, and a main effect of Orientation ($F(1,19) > 8.82$, $p = 0.008$), reflecting slightly longer latencies to the first saccade for inverted than upright faces. There was also a main effect of Phase ($F(1,19) > 21.12$, $p < 0.001$), and an interaction of Orientation and Start Position ($F(4,76) > 2.70$, $p = 0.037$). An identical ANOVA on the duration of the first fixation also revealed a main effect of Start Position ($F(4,60) = 12.79$, $p < 0.001$), again reflecting the longer duration for the center start position, but no other significant effects. Finally, an ANOVA on fixation duration across the peripheral start positions (Figure 13c) with Phase, Fixation Number (1,2,3), and Orientation revealed a main effect of Fixation Number ($F(2,32) = 47.52$, $p < 0.001$), reflecting the shorter duration of the first fixation, and Phase ($F(1,16) = 6.47$, $p < 0.05$) reflecting longer fixations during test than study. There was also an interaction between Orientation and Fixation Number ($F(2,32) = 4.21$, $p < 0.05$), reflecting shorter 2nd fixations for inverted than upright faces. Thus, overall, the temporal characteristics of the eye movements I observed during study were very similar during test.

Figure 13: Analysis of fixations during the test phase. *(A) Latency to first saccade by start position for upright and inverted faces. As for the study phase, there was a longer latency for the center start position compared with the peripheral start positions. (B) Duration of first fixation by start position for upright and inverted faces. Note the longer duration for the center start position, as observed during the study phase. (C) Duration of the first three fixations for the peripheral start locations for both upright and inverted faces. As for the study phase, the first fixation was significantly shorter than the subsequent fixations. All error bars indicate the between-subjects error. (D) Distribution of individual participants' fixation locations for upright faces broken down by start position for each fixation number (F1-F3). The same pattern was observed as during the study phase with first fixation close to the center of the face and subsequent fixations landing on the opposite side of the face to the start position.*

The general pattern of fixations observed in test was also very similar to that observed in study (Figure 13d). In general, the first fixation showed a strong tendency toward the side of the face closest to the start position, while the subsequent fixations showed a strong tendency toward the other side. Thus, the pattern of fixations observed in test were very similar to those observed in study, with the exception of there being fewer of them due to the restricted viewing time.

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3.4 - Discussion

I investigated the effect of start position on the pattern of fixations observed when people view upright and inverted faces. Consistent with at least one previous study (Barton et al., 2006), I found greater consistency and more fixations on the eye region and less on the mouth region for upright compared with inverted faces, possibly reflecting differences in cognitive processing. However, I also found that start position, a non-stimulus, non-task factor, has a large impact on the location of fixations throughout the first five fixations of face viewing. In addition, I found that i) the center start position was qualitatively different from other start positions, with longer initial saccade latencies suggesting significant processing of facial information even prior to the first eye movement, and ii) for all start positions, the first fixation was qualitatively different from subsequent fixations with a shorter duration and a different spatial distribution of fixations. These effects were observed for both upright and inverted faces and during both study and test phases, suggesting they reflect basic properties of scanning eye movements. Taken together, the temporal and spatial effects of start position demonstrate that the absolute locations of fixations during face processing are strongly influenced by factors beyond stimuli and task, possibly reflecting influences of visuomotor effects or simple scanning strategies. Critically, my results suggest that previously reported fixation patterns based on a single start position or the average across multiple start positions may not accurately reflect the information used in face processing.

Considering first the peripheral start positions, each strongly influenced the pattern of fixations observed. First fixations landed near the center of face with a slight tendency toward the start position (see also Renninger, Verghese, & Coughlan, 2007). On subsequent fixations this tendency flipped, and a strong tendency for fixations to land on the side of the face opposite the start position emerged. Combined with the much shorter duration of the first compared to subsequent fixations, this suggests that the location of the first fixation is highly dependent on the start position and may reflect a simple initial localizing saccade.(Renninger et al.,

2007) It has previously been suggested (Bindemann et al., 2009) that the location of the first fixation on faces may reflect the center-of-gravity effect or the tendency of saccades to land at the center of objects (J. M. Findlay & Gilchrist, 1997; Henderson, 1993). Note, however, that Bindemann and colleagues (Bindemann et al., 2009) pooled their data across start positions making it unclear to what extent the effect they observed reflects a center-of-gravity effect or an artifact of averaging. Arguably, the location of the first fixations in my data could reflect a center-of-gravity effect combined with a saccadic undershoot (Kapoula, 1985; Kapoula & Robinson, 1986), causing the maintained tendency toward the start position. However, this explanation is insufficient to explain the persistence of the differences in fixation patterns across the subsequent fixations. Further, and most importantly, in terms of information use it is the precise fixation location that is critical, as it is the point of highest acuity, not the presumptive target of any saccade.

Following the initial fixation, I observed a subsequent strong bias to the opposite side of the face. Strikingly, the previously reported tendency to fixate the left over the right side of the face (Butler et al., 2005; Hsiao & Cottrell, 2008; Leonards & Scott-Samuel, 2005; Mertens et al., 1993), which has been assumed to reflect a left-side bias and right hemisphere dominance in face perception (Burt & Perrett, 1997; Butler et al., 2005; Gilbert & Bakan, 1973), was reversed in my data for the left start position (but present for other start positions). This pattern of results is consistent with a naive sampling strategy in which the observer simply fixates high contrast facial features as far from those that have already been sampled as possible, increasing information gain. However, recent studies suggest that simple information gain alone may not drive eye movements. For example, in a study of eye movements to simple geometric contours (Renninger et al., 2007), eye movements were better characterized as reducing local uncertainty, not maximizing total information gained. Further, when peripheral background information is masked or blurred, eye movements tend to follow intact information near the fovea, rather then projecting into unseen regions, counter to the predictions of information gain (Foulsham, Teszka, & Kingstone, 2011).

Previous studies adopting multiple off-face starting positions (Bindemann et al., 2009; Blais et al., 2008; Hsiao & Cottrell, 2008; Jack et al., 2009) have varied the position of the face, with an initial fixation at the center of the screen, I used a constant face position at screen center and varied the location of the initial fixation. I chose this approach so that any differences in eye movements could not be ascribed to effects caused by, for example, the varying location of the edge of the screen with respect to the face. While the general position of the face was therefore predictable in my study, in prior studies the position was unpredictable preventing participants from planning any eye movements until the face had actually appeared on the screen. Although, this predictability may have contributed to the effect of start position I observed, I would still expect an effect of start position when face position is unpredictable since there is still variation in the relative location of facial features with respect to the start position.

Despite the large differences in fixation patterns caused by varying start position, behavioral performance was very similar across start positions. Even, for the left start position when participants showed a preference for the right rather than the left side of the face, there was no impact on behavioral performance. These results suggest two main possibilities, which are not mutually exclusive. First, the processing of facial information may not be tightly restricted to the fovea, and the specific fixation locations only weakly linked to the information being extracted (Caldara, Zhou, & Miellet, 2010). For example, fixation locations near the eyes for the upper start position tended to land below the eyes, whereas those for the lower start position tended to land just above the eyes. In both cases the participants may be extracting similar information from the eyes. Second, a recent study, in which starting positions were above and below the face, reported that two fixations only were sufficient for participants to achieve optimal recognition performance (Hsiao & Cottrell, 2008). This finding implies that only a very limited subset of the information foveated during free scanning is necessary for recognition. Given the large variation in fixation patterns I observed over the first two fixations across start positions, this

finding implies many different fixation patterns are capable of supporting face recognition. These considerations highlight how important it is to directly relate eye movement patterns with behavioral performance to ascertain their significance (e.g. Hsiao & Cottrell, 2008).

Based on the average fixation locations over the first two fixations, Hsiao and Cottrell concluded that fixations near the center of the nose were optimal for recognition (Hsiao & Cottrell, 2008). However, it is important to note that they averaged data from two start positions roughly corresponding to my upper and lower start positions. A close look at my data shows that for upright faces while the average fixation location for both the first and second fixation indeed land near the center of the nose, there are large differences in fixation patterns for these two start positions (Figure 14a). First, very few fixations actually land in the location identified by the averaging and thus suggestions that either information available at this location or that fixations to this location are optimal are tenuous. Second, the locations of fixations for the upper and lower start position reverse across the first two fixations. On the first fixation, the fixations for the upper start position are near the bridge of the nose, while those for the lower start position are near the tip of the nose. However, on the second fixation, these distributions completely switch. This striking difference is completely obscured by averaging across start positions (Figure 14b).

The problem of biases introduced by specific start positions is perhaps most serious for the frequently used center start position. In my data, the delayed initial saccade latency and longer initial fixation both suggest that substantial face processing begins at the initial presentation of the face. Despite its wide use in the literature (e.g. Althoff & Cohen, 1999; Goldinger et al., 2009; Heisz & Shore, 2008), this start position clearly introduces processing of facial information which is entirely dependent on the experimenter's choice of the position of the fixation cross on the face rather than on anything particular to the stimulus and task. Unfortunately, there is no easy solution to this problem as excluding the fixation prior to the first saccade simultaneously excludes the processing occurring during that fixation, and including

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the first fixation blends the experimental bias into the analysis. The difference in the temporal dynamics between the center and peripheral start locations also renders direct comparisons either within or across studies very difficult. It is impossible to reasonably equate the first fixation of a center start position trial with one that used a peripheral start position. This is not to suggest that the center start position should never be used, rather it can only provide useful information based on comparisons between conditions that used only the center start position and if it is used any interpretation of fixation data must take into account the information that is likely extracted prior to the first saccade.

Figure 14: The problem of averaging start positions
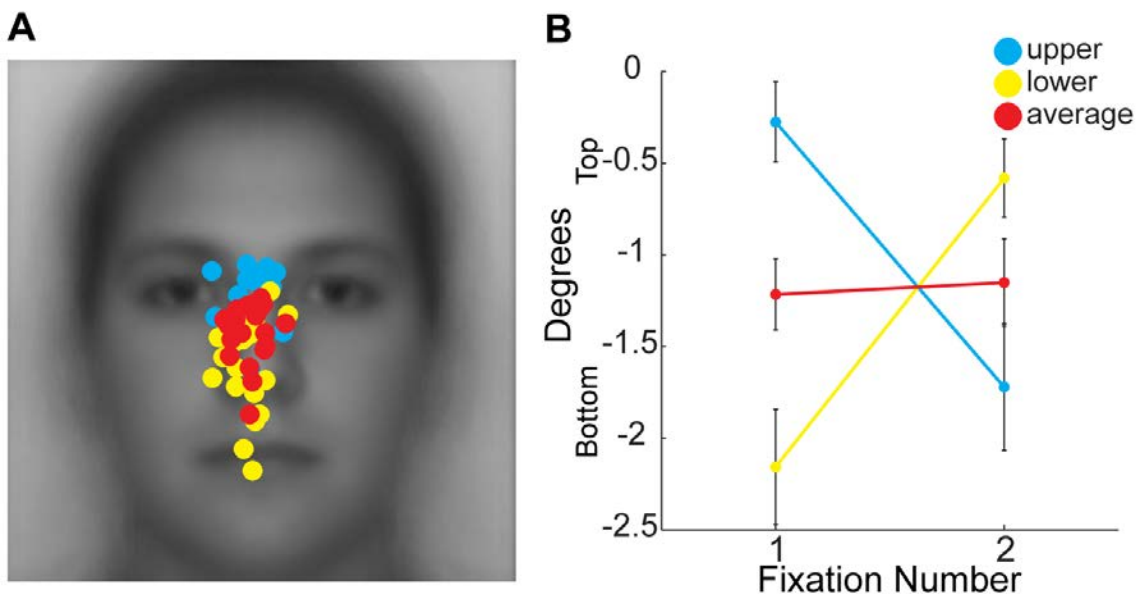
*Figure 14: The problem of averaging across start positions. **(A)** First fixation locations across participants for the upper (blue) and lower (yellow) start positions for upright faces are replotted from Figure 6. The average location across these two start positions is plotted for each individual subject in red. Note that this averaging causes a regression to the center of face and obscures the tendency to fixate the side of face closest to the start location. Importantly, there is very little overlap in the distributions of fixation locations for the upper and lower start positions. **(B)** Average fixation locations, relative to the position of the eyes, in the vertical dimension for the upper and lower start positions for the first two fixations replotted from Figure 6. The average vertical location between these two start positions is plotted in red. Note that the average completely obscures the large shift in vertical bias between the first and second fixation. Error bars indicate the between-subjects error.*

Consistent with differences in cognitive processing for upright and inverted faces and data from at least one prior eye tracking study (Barton et al., 2006), I did observe

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differences in fixations to upright and inverted faces. While the distributions of fixations for upright and inverted faces were both largely confined to the internal facial features with a similar spatial envelope, for inverted faces there were *relatively* fewer fixations on the eye region and *relatively* more on the lower part of the face. However, the *absolute* tendency toward the upper part of the face was not completely eliminated under inversion. These differences in fixations between upright and inverted faces may contribute to the poorer behavioral performance for inverted faces. Further, while the course effects were similar, the precise location of the differences between upright and inverted faces differed by start position.

In contrast to my findings and those of Barton and colleagues (Barton et al., 2006), two other studies of fixations to upright and inverted faces reported little or no effect of orientation (Rodger et al., 2010; Williams & Henderson, 2007). There are a number of possible explanations for this discrepancy. First, differences in experimental design may be important. For example, Rodger and colleagues did observe differential fixation patterns between upright and inverted faces that are qualitatively similar to those I found (compare my Figure 11 with the data from Western Caucasian participants in their Figure 5). These differences did not reach significance in their analyses, but this may largely be an issue of power as inversion was a between-subjects factor in their study but within-subjects in mine. Williams and Henderson (Williams & Henderson, 2007) did test inversion within-subject, but they principally used AOI analyses, which are strongly impacted by the precise definition of the AOI borders (for discussion of this issue see, for example, Caldara & Miellet, 2011; Rodger et al., 2010). Second, and more generally, the strong effect of start position I observed suggests that other non-stimulus, non-task factors may have also influenced fixations during face processing. For example, in comparing my findings with those of Rodger and colleagues (Rodger et al., 2010) and Williams and Henderson (Williams & Henderson, 2007) design differences such as the size of the faces or the distance of the initial fixation from the faces may also be having an impact. To the extent that non-stimulus, non-task factors affect fixation patterns, comparisons between studies and generalizations of findings are difficult to make.

Implications for Eye tracking Research

My findings have important implications for the use of fixation patterns as an index of information processing and for the design of eye tracking studies. My study focused on face processing, but my findings likely extend to use of visual fixations in other stimulus domains. Most importantly, my results demonstrate that interpreting the absolute location of fixations is extremely difficult. This caveat, particularly as it relates to potential visuomotor effects on fixation locations, is already well understood in the reading literature (e.g. McConkie, Kerr, Reddix, & Zola, 1988; Radach & McConkie, 1998) but seems to be largely ignored in studies of eye movements to faces. Eye tracking studies must take into account even the simple case of variation in start position, as absolute fixation locations may reflect tendencies introduced by the start position as much as the stimuli and the task. In particular, given the processing that likely occurs even prior to the first saccade, it is preferential to avoid using a center start position. Given the wide variation in fixation patterns observed between start positions, multiple start positions should be used and direct comparisons should be made between these start positions. Importantly, my findings suggest that simply averaging data across start positions will tend to artificially regress fixation locations toward the center of the face. Importantly, I do not mean to suggest that fixation patterns cannot provide useful information about visual processing, nor that eye movements are epiphenomenal. In fact, it has been demonstrated that the ability to freely make eye movements improves discrimination performance for faces (Henderson et al., 2005; Kealey et al., 2008). Furthermore, prior studies demonstrating differences in fixation patterns between groups or between conditions are not incorrect. The problem is in interpreting what the differences in absolute location actually mean with respect to the information utilized. Additionally, my study shows that the non-stimulus, non-task factors imposed in experiments can drastically influence eye-movement patterns, and so the eye-movements observed in previous studies may not reflect ecological eye-movements as closely as has been assumed. Alternative approaches, such as gaze-contingent

paradigms (e.g. Caldara et al., 2010; Foulsham et al., 2011; Mcconkie & Rayner, 1975) in which the information available at each fixation is systematically controlled, may help overcome some of these difficulties. The addition of converging evidence from other paradigms assessing information use, such as Bubbles (Gosselin & Schyns, 2001) or reverse correlation analyses (Gosselin & Schyns, 2003; Jack, Caldara, & Schyns, 2011), would also strengthen any claims. In sum, what I am suggesting is that the effect of experimental procedure must be carefully considered and controlled before making direct links between eye movement patterns and information use.

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Chapter 4 - Characteristic visuomotor influences on eye-movement patterns to faces and other high level stimuli

4.1 Introduction

The locations of fixations are commonly regarded as spatial indices of the information used to process given stimuli or perform given tasks, as it is assumed that the specific stimuli and the task are the primary determinants of the fixation pattern rather than, for example, visuomotor factors. However, in a previous study (Arizpe et al., 2012), detailed in chapter 3, I found that throughout at least the first five fixations to face stimuli, a non-stimulus, non-task factor, namely the pre-stimulus start position, had a robust impact on the location of fixations. For peripheral start positions (above, below, left of, and right of the upcoming face), the first fixation was likely the result of a simple initial localizing saccade as it was qualitatively different from subsequent fixations having a shorter duration and having a different spatial distribution compared to subsequent fixations, landing near the center of face with a slight tendency toward the start position. Notably though, on subsequent fixations, this spatial tendency flipped to one strongly tending on the side of the face opposite the start position. Those results indicate that the absolute locations of fixations during face processing can be strongly influenced by factors beyond stimuli and task, reflecting influences of visuomotor effects. My results, critically, suggested that previously reported fixation patterns based on a single start position or the average across multiple start positions may not accurately reflect the information used in face processing.

In the present study, I first sought to further investigate potential sources of such non-stimulus, non-task visuomotor influences on eye-movements by manipulating lateral distance of the start position from the upcoming stimulus (4°, 8°, 12°, and 16° of visual angle from midline), with the principal aim of determining whether lateral starting distance from a face impacts subsequent eye movement patterns. To my

knowledge, no prior published studies have investigated the influence of starting distance on eye-movements to high level stimuli; however, there are previous reports of a systematic saccadic range error for word and simple point stimuli (Kapoula & Robinson, 1986; Kapoula, 1985; McConkie, Kerr, Reddix, & Zola, 1988; Radach & McConkie, 1998, but see Vitu, 1991). In light of those reports, and taking the midline of my stimuli as the reference, I specifically hypothesized that for the first ordinal fixation I would find an overshoot of the midline for near stimuli and an undershoot for far stimuli. Additionally, given the results of my prior study (Arizpe et al., 2012) reported in chapter 3, fixations subsequent to the first ordinal fixation were expected to show a tendency opposite to the start position, though I was also interested in any evidence that starting distance could modulate the strength of this tendency. Given that what is of interest in most eye-tracking studies is how stimulus and/or task influence eye-movement patterns, a clear characterization of the influences of non-stimulus, non-task factors, such as starting distance, can be informative for the design, analysis, and interpretation of eye-tracking studies so that artifactual fixation pattern effects are not confounded with effects of interest. Further, faces in real-life typically appear in peripheral vision and require an initial saccade to bring them close to the fovea, so the impact of starting distance from the face is important for understanding eye movements to faces.

Second, to extend and confirm the findings from my prior study, I also manipulated the relative location of the start position to the stimulus (left and right side). In particular, given that the approximate location of the upcoming face stimulus relative to the start position was predictable in my prior study, I instead utilized a paradigm rendering the location of the upcoming stimuli unpredictable so as to test my hypothesis that the visuomotor influences induced by the start position also apply when predictability is greatly reduced.

Third, to determine whether any visuomotor effects are specific to face stimuli, the present study also utilized butterfly stimuli as line symmetrical control stimuli. I hypothesized that visuomotor influences are not specific to stimulus category.

Last, informed by a trend observed in my prior study I also tested a hypothesis that differences in fixation patterns associated with starting side, and possibly also distance, relate to recognition performance. Specifically, I hypothesized that left start position (which induces a right sided fixation tendency) is associated with higher recognition performance.

I observed strong effects of Distance on the first ordinal fixation, with an increasing undershoot of the midline of the stimulus with increasing distance. Notably, there was no strong impact on later fixations. These effects of Distance, as well as the previously reported effects of left and right starting side, were not specific to faces. I also established that the subsequent contralateral tendency in fixation patterns does not depend on predictability of the location of the upcoming stimulus or on stimulus category (faces and butterflies). I observed a correspondence between face and butterfly stimuli in overall left laterality in fixation tendency, indicating that left lateral tendency in fixation patterns is not specific to face perception. Lastly, I found a relationship between left starting Side (right-sided fixation pattern tendency) and increased recognition performance for faces. I discuss what the methodological implications for eye-tracking studies and the mechanistic implications for visual perception are given the visuomotor influences I report.

4.2 - Methods

Ethics statement

All participants gave written informed consent and were compensated for their participation. The study was approved by the Institutional Review Board of the National Institutes of Health, Bethesda, Maryland, USA.

Participants

I recruited 17 right-handed participants, living in the Washington D.C. area. Three were excluded because of poor eye-tracking calibration or because of unusually rapid pace through the experiment resulting in very few fixations on each face. Thus, 14 participants (6 male) are included in analyses.

Eye-tracking

I used an EyeLink II headmounted eye-tracker (SR Research, Mississauga, ON, Canada), and sampled pupil centroid at 250 Hz. Participants' eyes were 57 cm from the stimulus display screen. The default nine point calibration and validation sequences were repeated throughout the experiment. Both eyes were calibrated and validated, but only the eye with the lowest maximum error was recorded for the trials following a particular calibration. Calibration was repeated when maximum error at validation was more than 1.33° of visual angle. Average validation error was always substantially lower than 1° of visual angle. The mean of the average validation errors was 0.35° of visual angle with a standard deviation of 0.086° of visual angle. The mean of the maximum validation errors was 0.86° of visual angle with a standard deviation of 0.22° of visual angle. To minimize head motion artifacts, all participants had their heads fixed with a chin rest and, additionally, the "Head Camera" feature of the EyeLink II was engaged so as to provide some compensation for head motion that could still occur. Further, before each trial, a drift correction was performed. Default criteria for fixations, blinks, and saccades as implemented in the Eyelink system were used.

Stimuli

I collected 96 Caucasian-American (48 male) grayscale neutral expression frontal-view face images (see Figure 1A for examples). All face images were taken from the neutral expression 18 to 29 age group of the Productive Aging Lab Face

Database established by the University of Texas at Dallas (http://vitallongevity.utdallas.edu/stimuli/facedb/categories/neutral-faces.html) (Minear and Park, 2004). Each face was scaled to have a forehead width subtending 10 degrees of visual angle at presentation and was rotated to correct for any tilt of the head. Images were cropped to remove most of the background, but not the hair or other external features, and all face images were equated for overall luminance. At presentation, images were centered on a black background. To eliminate any possible stimulus bias as the source of any laterality effects, half of the faces were randomly left-right flipped across the vertical midline of the image for each participant. The website of the Productive Aging Lab Face Database states: "This [database] contains a range of face of all ages which are suitable for use as stimuli in face processing studies. Releases have been signed by the participants we photographed and the faces may be included in publications or in media events."

I also collected 96 grayscale "butterfly" images each of a pinned specimen of a unique species of Lepidoptera on a white background. All butterfly images were taken from Butterflies of America (http://www.butterfliesofamerica.com), a website devoted to the study and enjoyment of American butterflies (Warren et al., 2013). The butterflies were aligned at the convergence of the upper and lower wings, and scaled so that the maximum width of the upper wing close to the point of alignment was the same. This width matched the width of the faces. As with the faces, the butterfly images were cropped to remove most of the background and were equated for overall luminance. Likewise, at presentation, butterfly images were also centered on a black background and half were randomly left-right flipped across the vertical midline of the image for each participant to eliminate any possible stimulus bias as the source of any laterality effects.

Areas of interest (AOIs)

To aid alignment of the face images and positioning relative to the fixation starting position, rectangular areas-of-interest (AOIs) were manually-drawn uniquely for each

face around the right and left eyes, bridge of nose (i.e. middle of eye region), right and left half of nose, and right and left half of mouth (Supplementary Figure 1, for example) using EyeLink Data Viewer software. These AOIs were never visible to participants during the experiment.

Design

The experiment comprised of two parts, one with face stimuli and the other with Lepidoptera ("butterfly") stimuli. Both parts were completed within the same experimental session. Each part had two phases: study and test. During the study phases, participants observed 48 faces (24 female) or 48 butterflies (each of a unique Lepidoptera species) in a self-paced manner (up to 5 seconds, self-terminating trials with a button press). At test, participants observed 96 faces or butterflies (the 48 study phase faces or butterflies plus 48 new faces or butterflies) for a limited duration (1250ms limit) and indicated with a button press whether or not they recognized each stimulus (old/new task) as one observed during the study phase. Participants were given up to three seconds to respond following stimulus onset and were instructed to respond as soon as they thought they knew the answer (Figure 1C) and to guess if they were not sure. The experiment was programmed in Python and interfaced with the eye-tracker.
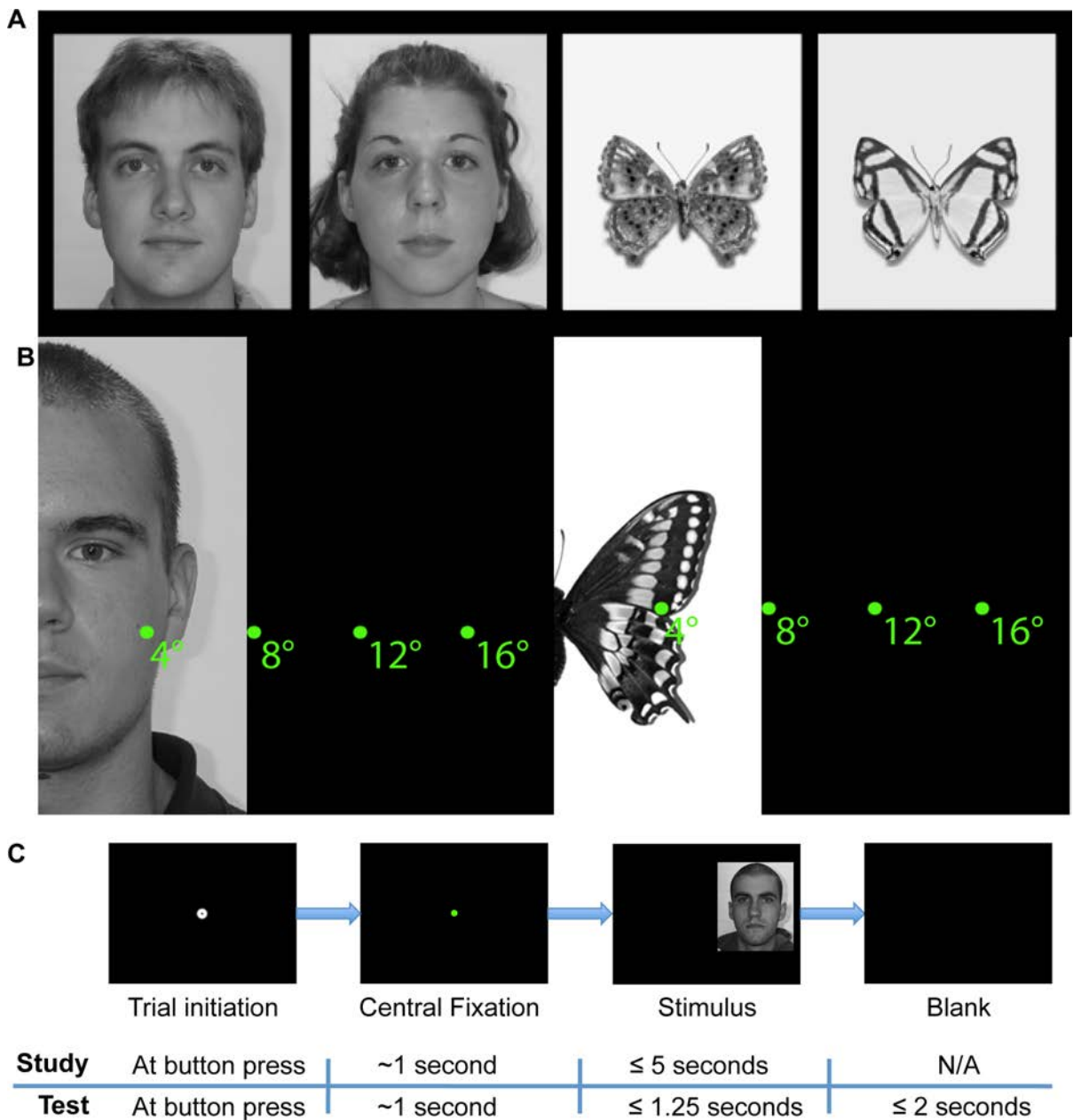
Figure 1: Study design. *(A) Example face and butterfly stimuli. (B) Schematic depiction of starting distances from midline of stimuli. (C) Schematic of trial sequences in study and test phases. A stimulus was presented only if the participant successfully maintained fixation for a total of 1 second. After stimulus onset in the study phase, participants were free to study the face for up to 5 seconds and pressed a button to begin the next trial. In the test phase, faces were presented for 1.25 seconds only and participants responded with button presses to indicate whether the stimulus was 'old' or 'new'.*

Across trials, I systematically varied two factors (i) the side of the visual field that the face or butterfly appeared relative to the central fixation dot at the beginning of each trial, which thus varied the start position ("Side") relative to the face or butterfly, and (ii) the distance along the horizontal-axis from midline of the face or butterfly stimulus

("distance") relative to the same starting fixation dot. I varied left and right side because fixation patterns are affected by visuo-motor factors (e.g. start position) in addition to stimulus factors (e.g. face) (Arizpe et al., 2012, which is chapter 3). Note that the manner in which side (start position) was varied in the present study differs from my prior study (Arizpe et al., 2012) detailed in chapter 3. Specifically, in the current study, I accomplished this by varying the side that the face appeared relative to a central starting fixation dot, whereas in the prior study I accomplished this by varying the location of the starting fixation dot relative to the centrally presented face stimuli. This difference in paradigm aimed to induce greater uncertainty about the location of the upcoming stimulus, and thus to allow me additionally to test whether the effects of start positions previously observed also occur under greater uncertainty about the stimulus location.

Side was defined in terms of the start position, so 'left' refers to starting on the left of the face, not to a face presented in the left visual field. In the case of faces, position along the y-axis of the screen was calculated uniquely for each face stimulus such that the central starting fixation dot would always have the same y-coordinate component as the unique point equidistant from all of the nearest internal facial features. Specifically, that unique coordinate was calculated numerically for each face such that it was equidistant from the centers of the nearest eye, nearest half-nose, and nearest half-mouth AOI. In the case of butterflies, the y-coordinate of each butterfly stimulus was selected such that the starting fixation dot was always at the same y-coordinate as the convergence of the upper and lower wings of the butterfly. Distance varied such that the midline of the face or butterfly was 4, 8, 12, or 16 degrees of visual angle from the starting fixation dot along the x-axis (see Figure 1B for examples, see Supplementary Figures 2-7 for full screen examples and schematics).

Before stimulus onset, participants fixated the start position at the center of the screen, indicated by a standard Eyelink II calibration target (0.17° diameter black circle overlaid on a 0.75° diameter white circle) on the black screen. Participants

initiated the trial by pressing a button while looking at the fixation target. In this action, a drift correction was performed. A colored dot (0.5° diameter) remained after drift correction, and the stimulus appeared only after the participant had fixated the dot for an accumulated total of 750 ms. This process ensured that drift correction and fixation were stable prior to stimulus onset. If more than 750 ms of fixation away from the start position accumulated before the trial could be initiated, drift correction was repeated. A fixation was considered off the start position if it landed more than 0.5° from the center of the dot. Dot color changed successively from red to yellow to green in order to signal to the participant that a maintained fixation was successfully detected at the start position.

In both the study and test phases, there were equal proportions of trials for each combination of levels of the factors of side, distance, and, in the case of the face stimuli, face gender. The particular subset of faces and butterflies used in the study phases was randomized across participants. Of the faces and butterflies presented in both study and test phase, all were presented on the same side of the visual field and the same Distance condition at study and test. The order in which the face and butterfly parts of the study were run was counterbalanced across subjects.

Analyses

Software

Fixation and AOI data were obtained through EyeLink Data Viewer software by SR Research. Subsequent analyses on these data and behavioral data from the test phase were performed with custom Matlab (The MathWorks, Inc., Natick, MA, USA) code. Statistical tests were performed in SPSS (IBM, Somers, NY).

Behavior

I assessed participants' discrimination performance, response bias, and reaction

time on the old/new recognition task in the test phase. d' (d' = z(hit rate) - z(false alarm rate)) and criterion c (c = -[z(hit rate) + z(false alarm rate)]/2) were computed for discrimination performance for each participant, broken down by Stimulus Category, Side and Distance. Reaction times were analyzed for correct trials only. Reaction time analyses were also broken down by start position and stimulus conditions with analysis being performed on the medians calculated for each participant. Medians, rather than means, were calculated for each participant (as is common practice for reaction time analyses) because reaction time distributions tend to be skewed to high reaction times. The mean reaction times displayed in my figure are the means of the participant medians.

Spatial density analyses

I mapped the spatial density of fixations during the study phase as a function of my experimental manipulations. Each fixation was plotted with equal density and spatial extent, as fixations were not weighted by the fixation duration. Fixations beyond the fifth fixation were excluded from the analysis to ensure an equal amount of data across trials. To ensure that summation of fixation maps across different face trials produced spatially meaningful density maps, fixation maps for individual faces were first aligned to a common reference frame using simple translations only. The internal facial features defined this reference frame. Specifically, the alignment minimized the sum of the squared differences between the center of the AOIs for each face and the average centers of the AOIs across all 96 faces. For the same purpose, fixation maps across different butterfly trials were first aligned such that the line of convergence between the top and bottom wing coincided across stimuli. All stimulus images had already been scaled to be comparable size, so rescaling was not necessary in order to align fixation maps.

Within this common reference frame, fixations were then plotted as Gaussian densities with the peak density over the fixation coordinate and a standard deviation of $0.3°$ of visual angle in both the x and y dimensions. These density plots were then

averaged across trials and across participants. The negligible proportion of fixations (< 1.1% during study phase) that fell outside of the bounds of the stimulus image analysis region (i.e. onto the black background outside the square frame of the face or butterfly stimulus) were shifted to the nearest edge within the analysis region so that total fixation density was comparable across analyses. The resulting maps show the spatial fixation densities, using a color scale from zero to the maximum density value observed, with values approaching zero being deep blue. All maps within a single figure contain the same total number of fixations and so are scaled the same to allow for direct comparison.

Profile density analyses

I calculated profile densities (i.e. densities summed along a single dimension of a heatmap) for the different conditions during the study phase. The x-profile plots were produced by summing along the vertical dimension (y-axis) of a spatial density heatmap, and y-profile plots were produced by summing along the horizontal dimension (x-axis) of a spatial density heatmap. The x-profile plots visualize the overall left-right laterality of fixations. The y-profile plots visualize fixation density over specific vertical (e.g. facial) features without respect to laterality or fine differences in horizontal position. Since the main focus of this study was to determine the laterality of fixations with respect to the midlines of my stimuli, I largely focused on x-profile plots.

Similarity matrix analyses

In order to quantify and visualize the degree of similarity between fixation patterns among the different side and distance conditions, I computed similarity matrices for the spatial density data. This data visualization method allows for concise visualization of the relative similarities in overall data patterns between given conditions, and enables further quantitative analysis on the relative degrees of similarity. A similarity matrix simply is an organized matrix, in which each cell

represents a comparison between given conditions, or a given combination of conditions, and contains a value of a specific similarity measure (e.g. correlation value, Euclidean distance, etc) corresponding to that specific comparison, which is specified by its index in the matrix. This class of methods, along with the complementary class of discrimination analyses (see *Discrimination Analyses* subsection below), has become common in fMRI studies (e.g. Haxby et al., 2001; Kriegeskorte et al., 2008) and has also been used in prior eye-tracking studies (Benson et al., 2012; Borji and Itti, 2014; Greene et al., 2012; Tseng et al., 2013), including two on face perception (Mehoudar et al., 2014; Kanan et al., 2015).

In my study, the possible combinations of conditions for which fixation patterns were compared between were the levels of the factors of ordinal fixation number (1-5), side (left, right), and distance (4, 8, 12, 16 degrees visual angle) separately for each stimulus type (faces, butterflies). In my analyses, only the study phase data were utilized since the test phase had a limited duration (1250 ms limit) that the stimulus was on the screen, thus limiting the number of fixations possible to analyze and also potentially inducing a pattern of eye-movement dynamics different from those of the study phase due to the time constraints of the recognition task. For my analysis, I conducted "split-half" analyses in which eye-movement data was first split into two halves, namely, the first and last 24 trials of the study phase, as each half had equal numbers of all possible combinations of conditions (side, distance, face gender). Spearman's correlations between corresponding (i.e. located at identical spatial coordinates) pixels' density values across the split halves of the data were calculated for each given comparison for each subject, and, only when being visualized (i.e. in my figures), the values were then averaged across subjects. For similarity analyses in which the levels of a factor (e.g. left and right side) were pooled together, correlations were first computed between each half of the data containing identical levels of the pooled factor, and then values were averaged across levels.

The use of Spearman's correlations, rather than Pearson's correlation, for producing such pattern similarity measures is considered best practice (e.g. Rousselet and

Pernet, 2012). Further, in the context of my study, in which fixation density patterns are correlated with one another, I knew *a priori* that my data would not technically satisfy all of the assumptions of the Pearson's correlation. Principally this is because the distribution of fixation density values across the pixels of each heatmap can almost be guaranteed not to have a normal distribution, but rather a skewed distribution, owing to the fair number of pixels with density values at or near zero in the spaces where fixations did not tend to land (i.e. away from the internal features of the face or butterfly).

Discrimination analyses

In order to quantify and test the significance of the average distinctiveness ("discriminability") of the patterns of given conditions compared to those of other conditions, I conducted several discrimination analyses using the correlation values from the similarity matrix analyses. I particularly focused on discriminability among the levels of the distance factor. In the similarity matrices, the diagonals always corresponded to the correlation between the two halves of the data for the same condition, and the off diagonal cells to those of non-identical conditions; therefore, for each subject discriminability of each given condition was quantified as the mean difference between the diagonal and off diagonals for each row of the given similarity matrix, where along rows are all the given conditions for the first half (i.e. first 24 trials) of the data, and along columns are those of the second half (i.e. second 24 trials) of the data. Thus a discriminability value existed for each given condition and for each subject, in which greater positive values indicate greater relative discriminability. When testing for statistical significance of average discriminability for a given condition from the others, a one-tailed, one-sampled t-test of difference from zero was conducted on the discrimination index distribution across subjects for the given condition (row). A one-tailed test was chosen because only positive discrimination values are interpretable in that context. Note also that this is equivalent to a within-subject test, since discrimination indices were computed within subject.

4.3 - Results

Temporal dynamics of eye-movements

I first investigated the temporal dynamics of eye-movements (Figure 2) to test for influences of Distance and Stimulus, as well as to test for replication of my prior findings (Arizpe et al., 2012) reported in chapter 3 that revealed an influence of Ordinal Fixation, but not of left and right Side (start position), on the durations of fixations.
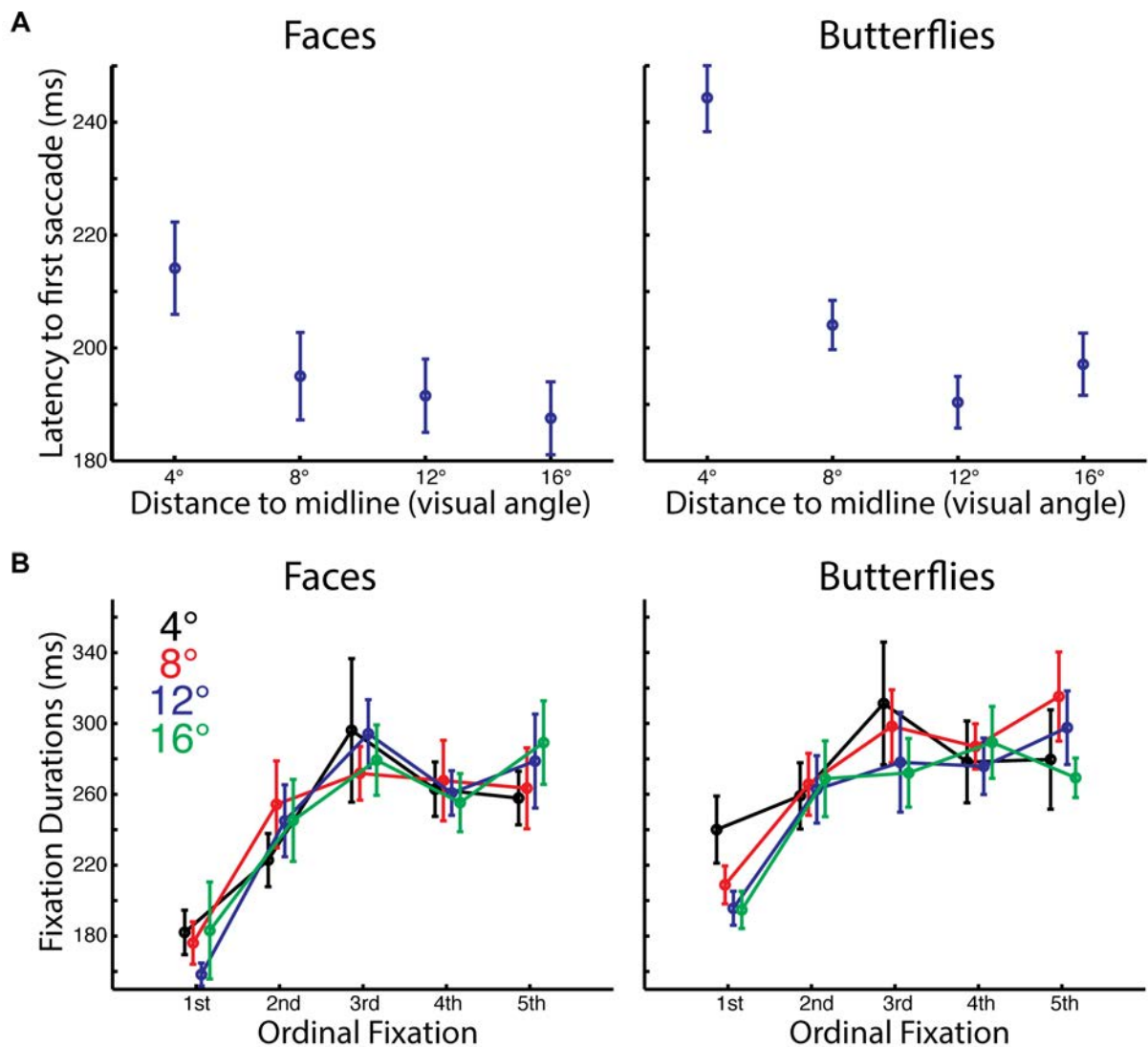
Figure 2: Impact of starting distance on timing of initial saccades and fixations. (A)
Average latency to first saccade by starting distance and stimulus category. There was a
longer delay between stimulus onset and the first saccade for the 4° distance compared to
farther starting distances. Also there was a longer delay for butterflies than faces for the 4°
*distance. **(B)** Average duration of each of the first five fixations by starting distance and*
stimulus category. The first fixations were significantly shorter than subsequent fixations,
and overall fixations were longer for butterflies than for faces.

Latency to First Saccade

For both faces and butterflies, the latency to the first saccade was longer for the

shortest distance than for the other distances. A three–way ANOVA with Stimulus

Category (faces, butterflies), Distance (4, 8, 12, 16 degrees visual angle from

stimulus midline), and Side (left, right) as within-subject factors revealed a main

effect of Distance ($F(3,39) = 54.65$, $p < 0.0005$, partial $\eta^2 = 0.81$) and an interaction

of Distance with Stimulus ($F(3, 39) = 7.31$, $p < 0.001$, partial $\eta^2 = 0.36$). A main effect of Stimulus approached significance ($F(1,13) = 4.42$, $p < 0.057$, partial $\eta^2 = 0.25$). While t-tests on latencies with Side conditions pooled confirmed that for both faces and butterflies there was a longer latency for the shortest Distance than the longer distances (all paired $t(13) > 3.33$, $p < 0.0055$, two-tailed, bias corrected $g_{Hedges} > 0.59$), for butterflies only the latency at 12 degrees was significantly shorter than that at 8 (paired $t(13) = 3.073$, $p < 0.01$, two-tailed, bias corrected $g_{Hedges} = 0.76$). Additionally, there was a longer latency for butterflies than faces for the shortest Distance only (paired $t(13) = 3.38$, $p < 0.0048$, two-tailed, bias corrected $g_{Hedges} = 1.05$).

The increased latency for the first saccade at the shortest distance, when the starting position was already on part of the stimulus, likely reflects that even before initiating a saccade, my participants were already processing the stimulus information more deeply.

Fixation durations

For both faces and butterflies, fixation duration tended to increase with ordinal fixation number. Also, overall fixation durations were longer for butterflies than for faces A four-way ANOVA on fixation durations with Stimulus Category (faces, butterflies), Distance (4, 8, 12, 16 degrees visual angle from stimulus midline), Ordinal Fixation (1st, 2nd, 3rd, 4th, 5th) and Side (left, right) as within-subject factors revealed main effects of Stimulus Category ($F(1,13) = 7.99$, $p < 0.015$, partial $\eta^2 = 0.38$) and Ordinal Fixation ($F(4,52) = 17.93$, $p < 0.0005$, Greenhouse-Geisser corrected, partial $\eta^2 = 0.58$), but no other main effects or interactions (all, $p > 0.12$, Greenhouse-Geisser corrected, partial $\eta^2 < 0.15$). Thus, Stimulus Category and Ordinal Fixation seem to have independently influenced fixation durations. The main effect of Stimulus Category was driven by overall longer duration fixations for butterflies than faces. T-tests on fixation durations pooling Stimulus Category, Distance, and Side revealed that the main effect of Ordinal Fixation was driven by a

shorter first fixation than all the later fixations (all paired $t(13) > 4.82$, $p < 0.0005$, one-tailed, bias corrected $g_{Hedges} > 1.29$), as in my prior study (Arizpe et al., 2012) detailed in chapter 3. Durations of later Ordinal Fixations were not significantly different from each other (all paired $t(13) < 1.65$. $p > 0.12$, two-tailed, bias corrected $g_{Hedges} < 0.36$), except the second fixation was shorter in duration than the third fixation (paired $t(13) = 3.30$, $p < 0.007$, two-tailed, bias corrected $g_{Hedges} = 0.51$) and approached significance for being shorter than the fifth fixation (paired $t(13) = 2.02$, $p < 0.066$, two-tailed, bias corrected $g_{Hedges} = 0.50$).

The longer fixation durations for butterflies than for faces suggests perhaps that a different kind or depth of information processing was necessary for butterflies than for faces, consistent with the reduced accuracy for butterflies.

Fixation patterns

I used a number of different methods to examine fixation patterns and the effects of Category, Distance and Ordinal Fixation number. I will first describe the spatial density profiles and differences in the overall patterns of fixations, computing similarity matrices across conditions. Then, since the main question of this study was the effect of Distance, which was manipulated in the x-direction only, I will focus on quantitative analyses of the distribution of fixations along this dimension.

Spatial density

To examine the overall pattern of fixations, I first produced spatial density plots broken down by Side and Category (Figure 3A-D), with the second through fifth Ordinal Fixations and all Distance conditions pooled. The first ordinal fixation was omitted because my prior study (Arizpe et al., 2012), which is chapter 3, as well as the current study, revealed that the first fixation is of a relatively short duration and thus is likely an orienting fixation, which is less meaningful in the current analysis. For faces, peak density of fixation occurred around the eye region, and for butterflies

the peak density was close to the top of the main body. For both categories, an effect of Side is apparent, such that when the fixation dot was on the left of the upcoming stimulus there was a rightward tendency in overall fixation patterns, and conversely when the fixation dot was on the right there was the opposite overall tendency (see later sections for detailed quantitative analysis). This effect is consistent with my earlier study (Arizpe et al., 2012), detailed in chapter 3, suggesting that the influences of pre-stimulus start position are not specific to faces, but rather likely reflect a general visuomotor phenomenon. Further, because the location of the upcoming stimulus in each trial was much more unpredictable in the current study than in my prior study (Arizpe et al., 2012), described in chapter 3, both in terms of visual field relative to the starting fixation and also distance from the starting fixation, these results therefore indicate that the contralateral tendency in overall fixation patterns induced by start position seen in my prior study are, in principal, generalizable to situations of much greater uncertainty with respect to the where a target stimulus will appear.

Stimulus-based laterality in spatial density of fixations

As an index of the lateral tendency in fixations to my stimuli, I calculated the proportion of spatial density to the left of midline, when left and right start positions and ordinal fixations two through five were again pooled. The result was greater than 50% on average for both faces (51.93% +/- 4.12 SEM) and butterflies (59.08% +/- 2.46 SEM) indicating a left-sided fixation tendency for both stimulus categories. A paired t-test between faces and butterflies on these left-sided proportions revealed that butterflies had a significantly greater left-sided fixation density proportion (paired $t(13) = 2.36$, $p < 0.035$, two-tailed, bias corrected $g_{Hedges} = 0.53$), indicating that butterflies may have had a more pronounced left-sided fixation tendency than faces, though the spatial density maps also indicate that peak density on average fell closer to midline for butterflies than for faces.

To test the correspondence between faces and butterflies in their lateral tendency in fixations, I performed a correlation between the two categories of stimuli on the proportions of spatial density of fixations to the left of midline (Side and Ordinal Fixations 2-5 pooled). This yielded a statistically significant positive correlation ($r(13) = 0.72$, $p < 0.0027$, two-tailed), indicating that individual differences in the lateral fixation tendency of one stimulus category directly related to that of the other stimulus category (see Supplementary Figure 8 for the scatterplot). Thus the overall group-level left-sided tendency in fixation, often reported for face stimuli, was not specific to faces, and the extent of the lateral bias in fixations for butterfly stimuli was related to that for faces.

Similarity of fixation patterns

To compare the fixation patterns across all conditions, I computed similarity matrices based on the spatial density plots (see Methods) containing comparisons between all levels of Distance (4, 8, 12, 16 degrees visual angle), Ordinal Fixation (1st, 2nd, 3rd, 4th, 5th), and Side (left, right) for each Stimulus Category (face, butterfly). Although there was an effect of side on the absolute fixation locations, there were no obvious differences using this relative similarity metric, therefore I pooled across this factor (Figure 3E-F).
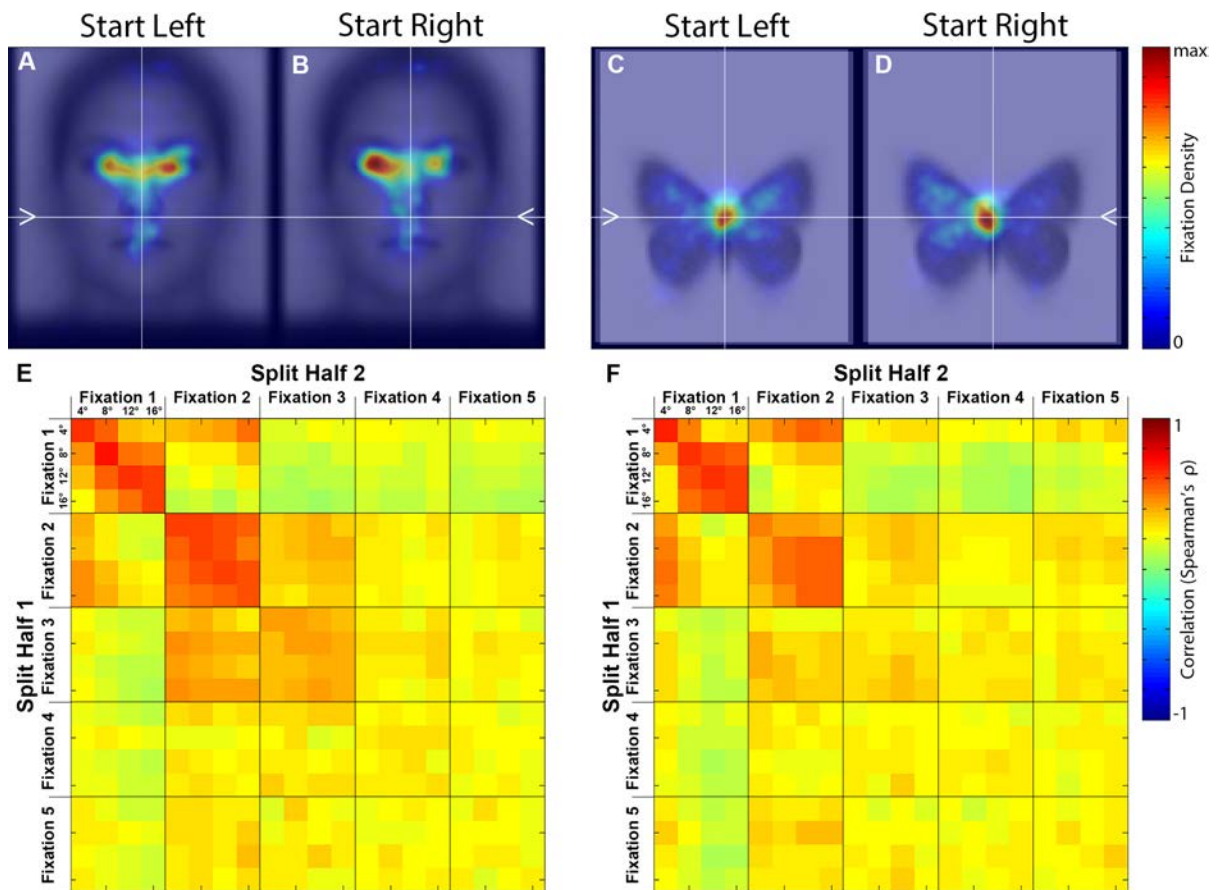
Figure 3: Spatial density maps and similarity matrices. (A-D) *Spatial density maps by stimulus category and starting side. These densities reflect the second through fifth ordinal fixations pooled. (E-F) Split-half correlation matrices by ordinal fixation and starting distance for each stimulus category. The correlations are between spatial fixation densities.*

First, the similarity matrices for faces and butterflies are remarkably similar, indicating that Distance and Ordinal Fixation influence fixation patterns in ways that are not specific to Stimulus Category. As will be apparent in subsequent analyses, the modulation by Distance is predominantly in the x-dimension. Second, correlations among conditions within the first two Ordinal Fixations are higher than those within the later fixations, and higher than across Ordinal Fixations, indicating a distinct fixation pattern for these two fixations. Third, for the first, and to some extent the second, Ordinal Fixation, correlations for the same Distance were higher than among different distances indicating an effect of Distance. There was not strong evidence for an effect of Distance on the later Ordinal Fixations.

Discrimination results

In order to test my hypothesis that Distance influences fixation patterns, and specifically to more quantitatively verify some of the suggested patterns in the similarity matrices just described, I conducted discrimination analyses (see Methods). Notably, Distance was fully discriminable (i.e. all four distances were significantly discriminable) only in the first ordinal fixation, for both faces (weakest discriminability among the four distances was $t(13) = 2.93$, $p < 0.0059$) and butterflies (weakest discriminability among the four distances was $t(13) = 2.72$, $p < 0.0088$). In each of the later ordinal fixations, Distance was totally indiscriminable (i.e. not a single distance was significantly discriminable) with the exception the shortest distance in the second ordinal fixation for butterflies ($t(13) = 4.33$, $p < 0.00042$), and the longest distance in the fifth fixation for faces ($t(13) = 2.26$, $p < 0.021$). This confirms that Distance influenced fixation patterns strongly only in the first ordinal fixation.

Profile analysis results

Given my finding that Distance significantly modulated fixation patterns in the x-dimension in the first ordinal fixation, and the fact that what drives the similarities and discriminations in fixation patterns as seen in my prior analyses are not fully apparent without looking at the specific fixation patterns, I next closely examined profile density plots for the x- (Figure 4) and y-dimensions (Supplementary Figure 9).
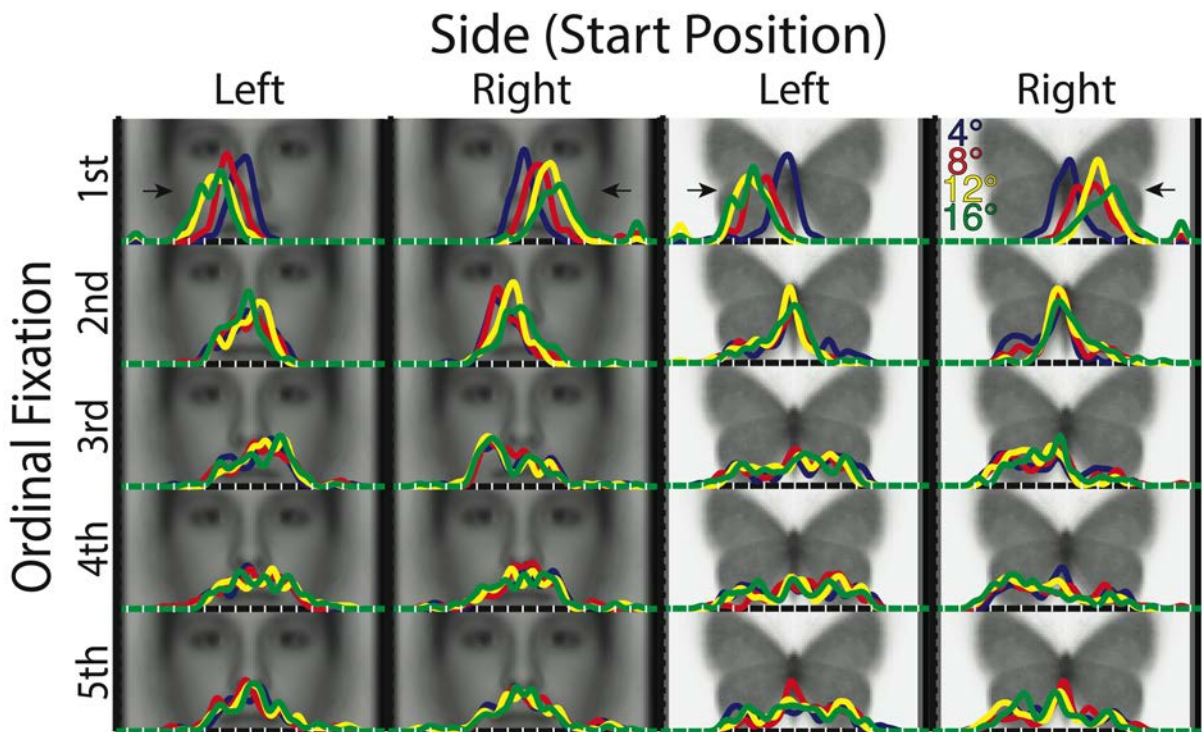
Figure 4: X-dimension profile density plots by stimulus category, starting distance, starting side, and ordinal fixation. *Of note is the increasing distance of fixations from midline of the stimulus in the first ordinal fixation with increasing starting distance. Also, there is a tendency for greater fixation density contralateral to the starting side overall following the first ordinal fixation. For reference, white tick marks along the x-axes indicate degrees of visual angle from stimulus midline.*

The x-profile plots broken down by Ordinal Fixation, Distance, and Side (Figure 4) revealed a number of striking patterns, some of which, notably, were not detectable with my similarity matrix analyses. In brief, peak densities from the first ordinal fixation revealed an "undershoot" of the stimulus midline ipsilateral to the Side condition for all Distance conditions, but which was of a degree proportionate to the distance (i.e. longer Distance induced a greater "undershoot"). Third ordinal fixations tended to show an overall relative fixation density laterality that was contralateral to the Side condition for both faces and butterflies, but which appeared weakly, if at all, modulated by Distance, in accord with the discrimination analysis results already reported. The same seemed to hold true to some degree in the fourth ordinal fixation in butterflies, though otherwise, later fixations' x-dimension densities tended to appear more variable in spread and less distinguishable among Side and Distance for both faces and butterflies.

The corresponding y-profile plots (Supplementary Figure 9) revealed, in accord with the patterns seen in the similarity matrices, that for faces, peak y-dimension density for the first ordinal fixation was slightly lower on the face than those of subsequent fixations, all of which had a peak in density just below the eyes. For butterflies, however, the peak y-dimension density did not seem to differ much across ordinal fixations, all of which had a peak just below the head or roughly near the convergence of the upper and lower wings. In general, for both faces and butterflies, fixation densities in the y-dimension did not seem to substantially differ between Side conditions, and the last three ordinal fixations seemed to become progressively more variable in spread in the y-dimension.

Behavioral measures

In addition to the spatial and temporal dynamics of fixations just described, I additionally investigated whether my factors influenced recognition behavior. A three-way ANOVA on discrimination performance (d') with Stimulus (faces, butterflies), Distance (4, 8, 12, 16 degrees of visual angle), and Side (left, right) as within-subject factors revealed a main effect of Stimulus ($F(1,13) = 61.45$, $p < 0.0005$, partial $\eta^2 = 0.83$), driven by overall higher discrimination performance for faces, but no main effects for either Distance or Side (both $p > 0.19$). No interactions reached significance (all $p > 0.24$). Given the quite low discrimination performance for butterflies overall and the hypothesis that Side would modulate face discrimination, I conducted additional planned t-tests on d' between Side conditions (left, right) for faces only. This yielded a significant difference in discrimination by Side (paired $t(13) = 1.97$, $p < 0.036$, one-tailed, bias corrected $g_{Hedges} = 0.41$), driven, as hypothesized, by higher discrimination performance for faces viewed starting on the left side. These results suggest that my participants found butterflies more difficult to discriminate than faces, and that faces were better discriminated when starting side was on the left (Figure 5).
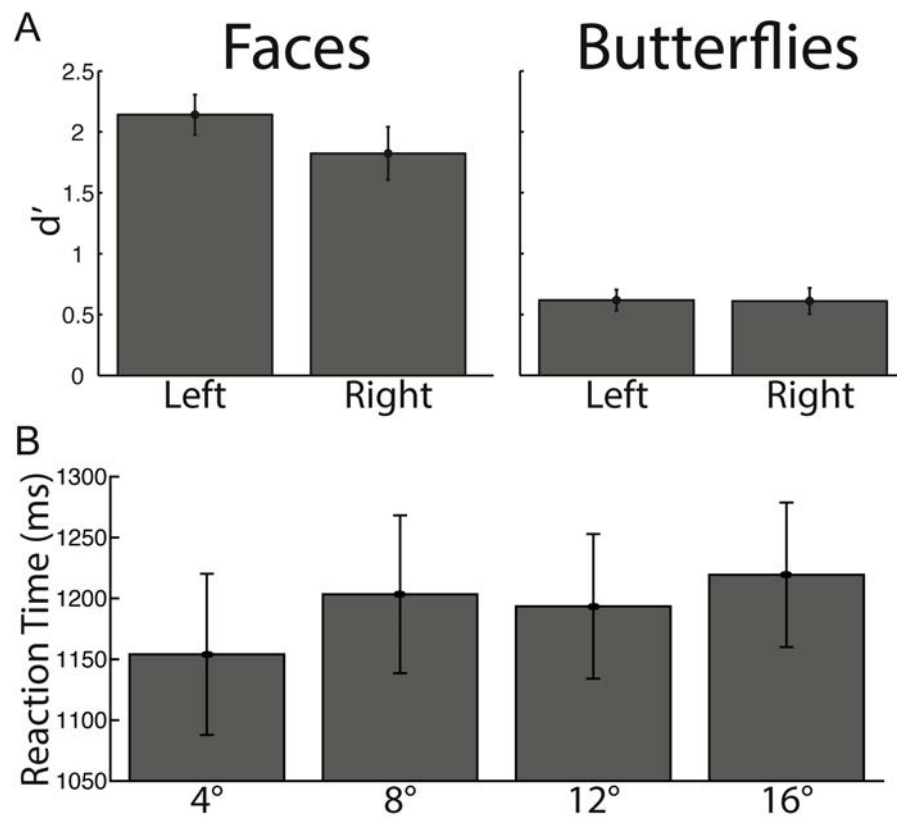
Figure 5: Recognition performance by stimulus category and starting side. (A) *Discrimination performance, measured by d'. There was significantly lower discrimination for butterflies than for faces, and significantly greater face discrimination for the left than for the right starting side* ***(B)*** *Reaction time. The longest distance elicited significantly longer reaction times than the shortest distance.*

A three-way ANOVA on criterion (c) again with Stimulus, Side, and Distance as within-subject factors was also conducted. No main effects or interactions yielded significant statistics (all $p > 0.26$), suggesting that these factors did not modulate response bias.

A three-way ANOVA on reaction time again with Stimulus, Side, and Distance as within-subject factors yielded a main effect of Distance ($F(3,39) = 3.84$, $p < 0.018$, partial $\eta^2 = 0.23$), driven by overall longer reaction time for the longest distance than the shortest distance (paired $t(13) = 3.16$, $p < 0.005$, bias corrected $g_{Hedges} = 0.26$) and possibly by a longer reaction time for the 8° distance than the 4° distance that approached statistical significance (paired $t(13) = 2.06$, $p < 0.061$, bias corrected $g_{Hedges} = 0.19$; all other comparisons, paired $t(13) < 1.45$, $p > 0.17$). This is likely due, at least in part, to the fact that a longer saccade requires more time than a

shorter one, which adds to the response time. No other main effects or interactions yielded significant statistics (all p > 0.096) from the three-way ANOVA.

4.4 - Discussion

Effects of distance, side, and stimulus category

The principal aim of this study was to determine whether lateral starting Distance from a face impacts subsequent eye movement patterns. Since faces in real-life typically appear in peripheral vision and require an initial saccade to bring them close to the fovea, determining the impact of starting Distance from the face is particularly important for understanding eye movements to faces. I have previously demonstrated strong effects of Start Position (specifically up, down, left, right, and center of face) leading to an overall contralateral tendency in fixations and so in the present study I also manipulated the starting Side (i.e. left or right Start Position) to replicate and extend my prior findings (Arizpe et al., 2012) reported in chapter 3. In particular I wanted to establish: (1) whether effects of starting side and distance are specific to faces, (2), whether the effects of starting side occur only when the location of the upcoming stimulus is predictable as in my original study and (3) whether any differences in fixation patterns associated with starting side and distance relate to behavioral performance. While I observed strong effects of Distance on the first ordinal fixation, with an increasing undershoot of the midline of the stimulus with increasing distance, there was no impact on later fixations. These effects of Distance, as well as the previously reported effects of Side, were not specific to faces. I also established that the subsequent contralateral tendency in fixation patterns does not depend on predictability of the location of the upcoming stimulus or on stimulus category (faces and butterflies). Lastly, I found evidence of a relationship between left starting Side (right-sided fixation pattern tendency) and increased recognition performance for faces.

Effect of distance in first ordinal fixation

I hypothesized that the location of the first fixation would systematically vary with distance. Given previous reports of a systematic saccadic range error for word and simple point stimuli (Kapoula & Robinson, 1986; Kapoula, 1985; McConkie, Kerr, Reddix, & Zola, 1988; Radach & McConkie, 1998, but see Vitu, 1991), and taking the midline of the face or butterfly as the reference, I specifically hypothesized that I would find an overshoot of the midline for near stimuli and an undershoot for far stimuli. I did indeed find a systematic variation of the horizontal location of the first ordinal fixation as a function of lateral starting distance as evinced by the fact that all four distances were significantly discriminable from the fixation patterns in the first ordinal fixation; however, I did not find an overshoot for any distance, but rather an increasing undershoot of the midline of the stimulus with increasing distance as is apparent in the profile density plots (Figure 4). Individual distance conditions were largely not significantly discriminable in later fixations, so I did not find strong modulation of subsequent ordinal fixations as a function of distance. The influence of distance in the first ordinal fixation was, notably, not specific to faces, indicating visuo-motor factors that strongly influence eye-movement patterns independently of stimulus category and task factors.

Effect of starting side robust to distance and predictability

Overall fixation patterns tended contralateral to the start position (Side), replicating the effect of start position as reported in my prior study (Arizpe et al., 2012) in chapter 3. Specifically, while the first fixation tended to fall ipsilateral to the start position, the later fixations tended contralateral. Importantly, this effect was not specific to faces. Rather, the asymmetry after the first fixation appeared even more pronounced for butterflies. Because the overall contralateral tendency in fixation patterns was present for all distances, even for the farthest distance, this contralateral effect of Side is unlikely to be due to presampling of stimulus information close to (ipsilateral to) the start position, since little or no presampling of

the stimulus could occur at the farther starting distances. Of note, the location of the upcoming stimulus, with respect to the start position, was much more unpredictable in the current study than in my prior study, both in terms of distance and visual field. Thus, the current study clarifies that the contralateral effect of start position was not dependent on the predictability of the location of the upcoming stimulus. The correspondence in the effects of Side on eye-movement patterns between faces and butterflies, further, suggests that visuomotor influences on eye-movements are general across stimulus categories.

Eye-movement relationship to behavior

I also investigated whether the differences in laterality of overall fixation patterns I observed were related to recognition performance. Distance did not significantly modulate the degree of contralateral tendency induced by starting Side, and so Distance conditions could be pooled to compare the effect of Side on recognition performance. It has previously been suggested that faces tend to be recognized better when presented in the left visual field (Dutta & Mandal, 2002; Hellige, Corwin, & Jonsson, 1984; Luh, Redl, & Levy, 1994; Luh, Rueckert, & Levy, 1991, though see Hellige et al., 1984; Rhodes, 1985; J. Sergent, 1982; Justine Sergent & Bindra, 1981), which likely reflects some right hemispheric specialization in the brain for face identity representation (Yovel et al., 2008), as suggested in split-brain (Levy et al., 1972), neuropsychological (Sergent et al., 1992b; Benton and Van Allen, 1968; Warrington and James, 1967; De Renzi et al., 1994), PET/fMRI (Sergent et al., 1992b, 1992a; Kanwisher and Yovel, 2006; Kanwisher et al., 1997; Chan et al., 2010), and electrophysiological (Rossion et al., 2003; Campanella et al., 2000; Bentin et al., 1996; Yovel et al., 2003) studies on humans. Intriguingly though, a bias for fixating on the left side of the face has also been reported when free viewing was allowed (Mertens et al., 1993; Gallois et al., 1989; Phillips and David, 1997; Saether et al., 2009; Guo et al., 2012, 2009, 2010; Everdell et al., 2007; Butler et al., 2005; van Belle et al., 2010). Given that start position strongly modulates the laterality of fixation patterns, it could be hypothesized that it therefore also modulates

recognition performance. In my prior study (Arizpe et al., 2012) detailed in chapter 3, I found a trend for higher discrimination performance with a left start position; however, several aspects of the design may have prevented strong detection of such effects. Specifically, left and right start positions were swapped between study and test phases for half of the trials, there were limited trials per subject for each start position for upright faces, and participants were allowed up to 10 seconds to study each face. In the current study, the first two limitations did not exist, and also participants had a more restricted time (up to 5 seconds) during which they could study the stimuli. With these changes in design, I did find significant ($p < 0.036$, one-tailed) higher discrimination performance for when faces were viewed with a left sided-start position, which corresponds to a right-sided tendency in fixation patterns. When fixating on the right side of a face, most of the face is in the left visual field, thus this result is consistent with a right-hemisphere cortical advantage for face perception and representation. Though the first ordinal fixation tended to fall ipsilateral to the start position, it had a shorter duration relative to later fixations, regardless of distance, and there is evidence that stimulus information is not deeply processed in just the first fixation (Hsiao and Cottrell, 2008; Renninger et al., 2007). Thus I suspect that there was shallow sampling of the side of the stimulus ipsilateral to the start position in the first ordinal fixation, and that this difference in performance is driven by the fixations contralateral to the start position. I did not find any evidence of difference for butterflies, though discrimination performance was overall quite low for butterflies. These data regarding the relationship between eye-movements and behavior are suggestive and preliminary, and so further research is warranted to better characterize how eye-movement patterns relate to visual recognition performance and information use (Samson et al., 2014; Malcolm et al., 2008; Butler et al., 2005; Luh et al., 1994, 1991; Burt and Perrett, 1997), whether such effects are specific to faces (Leonards and Scott-Samuel, 2005), and how such relationships may be subject to individual differences (Mehoudar et al., 2014; Peterson and Eckstein, 2013; Miellet et al., 2011; Levine et al., 1988).

As already stated, I observed a close correspondence between faces and butterflies in the similarities in influences of Distance and Side on spatial fixation patterns across ordinal fixations. I did, however, also observe lower discrimination performance and longer short distance latencies to first saccade for butterflies than faces, suggesting the stimulus information of butterflies required more effort to process and was more difficult to recognize. Additionally, while my similarity measures indicate that the influences of Distance and Side are highly correspondent between faces and butterflies, nonetheless, the fixation patterns for the two stimuli categories are quite distinct, just by virtue of the stimulus categories being different. Though the patterns of information contained within my butterfly stimuli are arguably much more distinct than faces from a computer vision perspective (each butterfly image was of a distinct species of Lepidoptera, not separate individuals within a species), my participants nonetheless seem to have found butterflies more difficult to visually process and discriminate. This likely reflects specialized visual processing mechanisms and expertise for facial recognition.

Methodological implications for eye-tracking studies

My findings can inform the design and analytic considerations of eye-tracking studies of visual perception. The strong influence of Distance in the first ordinal fixation, but not for subsequent fixations, suggests that for eye-movement studies in which the experimental factors of interest are stimulus- or task-related, lateral starting distance can be safely modulated without the danger of strongly confounding visuomotor influences on eye-movements beyond the first fixation. This result, together with the significantly shorter duration of the first ordinal fixation and prior evidence that the visual information is not deeply processed in the first fixation (Hsiao and Cottrell, 2008; Renninger et al., 2007), indicates that when analyzing eye-movements, it may be a good general practice to exclude the first ordinal fixation.

The overall tendency for fixations to fall on stimulus regions contralateral to the starting side (after the first ordinal fixation), regardless of the stimulus category, indicates that there are general visuomotor factors that must be controlled for in the design of studies of eye-movements and considered in the analysis and interpretation of eye-movement data. This contralateral tendency in fixation patterns is strongly present whether the location of the upcoming stimulus is predictable (Arizpe et al., 2012, which is chapter 3) or is unpredictable, as in the current study; therefore, such visuomotor influences cannot be eliminated through modulation of the predictability of the location of stimuli, and must simply be taken into account when interpreting eye-movement data.

My results demonstrate that interpreting the absolute location of fixations in relation to perceptual performance is difficult. A recent study (Hsiao & Cottrell, 2008) reported that two fixations only were sufficient for participants to achieve optimal recognition performance, indicating that only a subset of the information foveated during free scanning is necessary for recognition. Given the characteristic variation in fixation patterns I observed over the first two fixations across start positions, my results suggest that many different fixation patterns are capable of supporting face recognition. However, that I also found differences in recognition performance for faces between left and right start positions is an indication of how important it is to directly relate eye movement patterns with behavioral performance to ascertain their significance for visual information processing. In particular such differential recognition performance as I report further indicates that measured eye-movement patterns do not necessarily correspond to optimal patterns, as may often be assumed in eye-movement studies. Alternative approaches of determining visual information use, such as gaze-contingent paradigms (e.g. Caldara et al., 2010; Foulsham et al., 2011; McConkie and Rayner, 1975) in which the information available at each fixation is systematically controlled, may help overcome some of these difficulties. The addition of converging evidence from other paradigms assessing information use, such as Bubbles (Gosselin and Schyns, 2001) or reverse correlation analyses (Gosselin and Schyns, 2003; Jack et al., 2012) could also help

in clarifying the connection between eye-movements, visual information use, and perceptual performance.

The kind of correlation matrix and discrimination analyses utilized in the present study may, when possible and relevant, be an advantageous set of analysis methods for detecting the independent effects of stimulus- and task-related factors even though potentially confounding visuomotor factors are also present in a study. This is because correlation matrices containing the factors of interest can simply be averaged across the separate matrices for each start position condition. This factors out any potential nuisance visuomotor influences from subsequent discrimination analyses without the artificial regressing of fixation patterns to the mean between start position conditions that would otherwise occur with the common practice of averaging spatial density maps. More broadly though, the additional potential for hypothesis generation and for data-driven approaches from such analysis methods could be of great utility in eye-tracking studies of visual perception.

Many studies investigating eye movements to faces, only test faces themselves, making it unclear whether any effects, where relevant, are specific to faces or not. My finding of influences on eye-movements not only for faces, but also for butterflies, highlights the importance of including control stimuli in eye-movement experiments so that inferences regarding stimulus specificity or generality can be made.

Mechanistic implications for visual perception and further questions

I report that the overall tendency to fixate the left side of the stimulus was not specific to faces, but was also present, and apparently to a greater extent, for my line-symmetric stimulus category, butterflies. Indeed, a significant positive correlation $(r(13) = 0.72, p < 0.0027$, two-tailed) between faces and butterflies on the proportions of spatial density of fixations to the left of midline indicate that my participants' individual differences in the lateral fixation tendency of one stimulus

category directly related to that of the other stimulus category. Thus the extent of the lateral bias in fixations for butterfly stimuli was related to that for faces. Though the left-sided fixation tendency is often noted in face perception, and thought to reflect face specific mechanisms, there is the possibility that this tendency may be general to all other stimulus categories. This notion is consistent with some prior research (Luh et al., 1991, 1994; Levine et al., 1988), and is worth further investigation to elucidate the general mechanisms of visual recognition and the specific mechanisms of face recognition. Visual representation of faces tends to be cortically right-hemisphere lateralized (Yovel et al., 2008; Levy et al., 1972; Sergent et al., 1992b; Benton and Van Allen, 1968; Warrington and James, 1967; De Renzi et al., 1994; Sergent et al., 1992a; Kanwisher and Yovel, 2006; Kanwisher et al., 1997; Chan et al., 2010; Rossion et al., 2003; Campanella et al., 2000; Bentin et al., 1996; Yovel et al., 2003), but there is evidence that representations for other stimulus categories may tend to be right hemisphere lateralized as well (Warrington and Taylor, 1973; Konen et al., 2011; Warrington and James, 1986) and also that perceptual asymmetries may relate to asymmetric hemispheric arousal (Levy et al., 1983), and so the left-sided tendency in fixation may be related to this characteristic functional neuroanatomy.

Relatedly, my recognition performance results indicate a paradox, which reveals that the relationship between lateralized fixation tendency, hemispheric lateralization, and behavioral performance requires much deeper investigation. I found a significantly higher discrimination performance for when faces were viewed with a left sided-start position, which corresponds to an overall right-sided tendency in fixation patterns (after the first ordinal fixation). When fixating on the right side of a face, most of the face is in the left visual field. Thus, improved recognition performance under this condition is consistent with a right-hemisphere cortical advantage for face perception and representation. However if recognition performance is indeed more optimal for right-sided fixation on the faces, then it is puzzling why there is the natural tendency to fixate the left side of the face, as has been ubiquitously reported in prior studies (Mertens et al., 1993; Gallois et al., 1989; Phillips and David, 1997; Saether et al.,

2009; Guo et al., 2012, 2009, 2010; Everdell et al., 2007; Butler et al., 2005; van Belle et al., 2010), and how this relates to the tendency to use the information on the left side of the face during perceptual judgment (Burt and Perrett, 1997; Butler et al., 2005; Luh et al., 1994, 1991; Gilbert and Bakan, 1973). Though recognition performance was overall too low for butterflies to determine if a similar asymmetry in performance existed for butterflies, there is the possibility that such a paradox applies for visual stimulus categories besides faces too. It is unclear what factors may induce eye-movement patterns which are less than optimal for the recognition to be employed during recognition tasks.

Though there was an influence of Side present throughout the first five fixations, the lack of a strong independent influence of Distance past the first fixation is intriguing. It suggests that the first fixation may reflect a simple initial localizing saccade to the stimulus, required before a more stereotyped information sampling program of fixations can be employed. This reveals the limits of the non-stimulus non-task visuomotor influences on eye-movements, and thereby suggests that definite loci on stimuli serve as functional targets for visual information extraction, the visuomotor influences (Distance and Start Position) notwithstanding.

What precisely drives the visuomotor effects that are evident in my results is not clear, but some possibilities can be considered. The contralateral fixation pattern (after the first ordinal fixation) is consistent with a simple sampling strategy in which the observer fixates high contrast (or otherwise highly salient) visual features on the face far from those that have already been sampled, thereby increasing information gained. Counter to this possibility though, some studies suggest that simple information gain alone does not drive eye movements. A study (Renninger et al., 2007) of eye movements to simple geometric contours provides evidence that eye movements during the task were better characterized, not as maximizing total information gained across the stimulus overall or as fixation to salient features as such, but as reducing local uncertainty such that regions about which the observer has most uncertainty are foveated. Further counter to the predictions of global

information gain, another study (Foulsham et al., 2011) reported that when peripheral background information is masked or blurred, eye movements tended to follow intact information near the fovea, rather than projecting into unseen regions. If a perceptual strategy of global information gain cannot explain the visuomotor effects seen in my results, then perhaps some dynamic of directional "inertia" in occulomotor sequence execution could play some role. Given that the face and butterfly stimuli are symmetrical, such occulomotor inertia, operating in concert with a perceptual strategy of reducing local uncertainty, may explain why I observe fixation patterns that overall tend to fall contralateral to the starting position, but which are not strongly modulated by starting distance after the first ordinal fixation.

Conclusion

I investigated the effects of lateral starting distance and side from a face on subsequent eye movement patterns, and whether such effects may generalize to other line symmetrical stimuli (butterflies). I found an increasing undershoot of the midline of the stimulus with increasing distance for the first ordinal fixation, which was not specific to faces. A tendency for later fixations to fall contralateral to the left- or right-lateralized start position was observed as in my previous study (Arizpe et al., 2012) detailed in chapter 3, and this did not depend on the predictability of the location upcoming stimulus. Lastly, I found preliminary evidence for a relationship between left starting position (right-sided fixation pattern tendency) and increased recognition performance for faces that deserves further investigation.

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4.6 - Supplemental Material

Supplemental Figure 1

Supplemental Figure 1. Example Areas of Interest (AOIs). *AOIs are shown in white. These AOIs were used only for determining the initial start position during stimulus presentation and for stimulus alignment during analysis. AOIs were not visible to the participants.*

Supplemental Figure 2

Supplemental Figure 2. Full Screen Example of Stimulus: Start 16° Left (of Face Midline). *Figures showing example stimuli among the main figures showed only portions of the full screen stimuli. Here we show a full screen example of a stimulus presentation, as a participant would have seen it, on a trial displaying a male face for the start 16° Left (of face midline) condition. Immediately prior to stimulus presentation, participants were required to fixate at a dot at the center of the screen.*

Supplemental Figure 3

Supplemental Figure 3. Full Screen Example of Stimulus: Start 4° Right (of Face Midline). *Figures showing example stimuli among the main figures showed only portions of the full screen stimuli. Here we show a full screen example of a stimulus presentation, as a participant would have seen it, on a trial displaying a female face for the start 4° Right (of face midline) condition. Immediately prior to stimulus presentation, participants were required to fixate at a dot at the center of the screen.*

Supplemental Figure 4
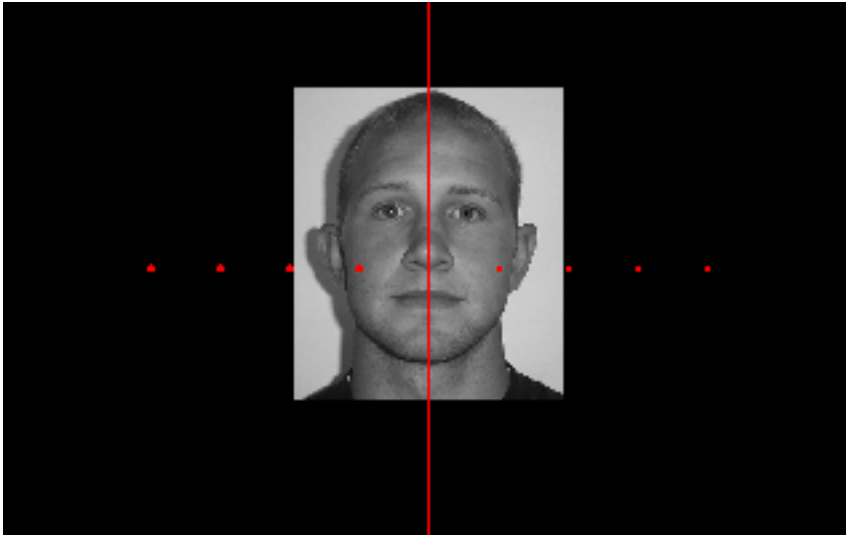
Supplemental Figure 4. Schematic of All Possible Start Positions (Relative to an Example Face). *During the experiment, the locations of the stimuli varied with respect to a fixed central pre-stimulus start position. Here we show a full screen sized schematic, in a stimulus-centered space, of possible start positions relative to an example stimulus. Red dots indicate all of the possible (relative) start positions, and a red line indicates the midline of the stimulus.*

Supplemental Figure 5

Supplemental Figure 5. Full Screen Example of Stimulus: Start 12° Left (of Butterfly Midline). *Figures showing example stimuli among the main figures showed only portions of the full screen stimuli. Here we show a full screen example of a stimulus presentation, as a participant would have seen it, on a trial displaying a butterfly for the start 12° Left (of butterfly midline) condition. Immediately prior to stimulus presentation, participants were required to fixate at a dot at the center of the screen.*

Supplemental Figure 6
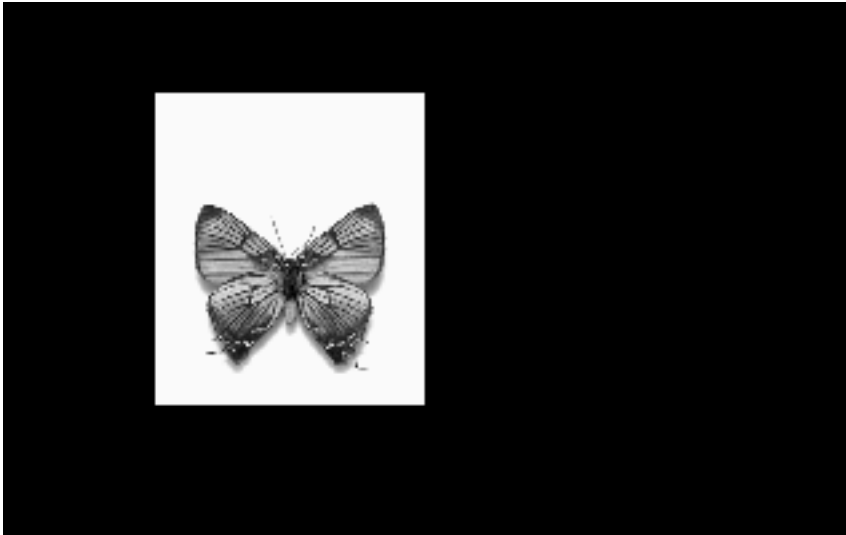
Supplemental Figure 6. Full Screen Example of Stimulus: Start 8° Right (of Butterfly Midline). *Figures showing example stimuli among the main figures showed only portions of the full screen stimuli. Here we show a full screen example of a stimulus presentation, as a participant would have seen it, on a trial displaying a butterfly for the start 8° Right (of butterfly midline) condition. Immediately prior to stimulus presentation, participants were required to fixate at a dot at the center of the screen.*

Supplemental Figure 7
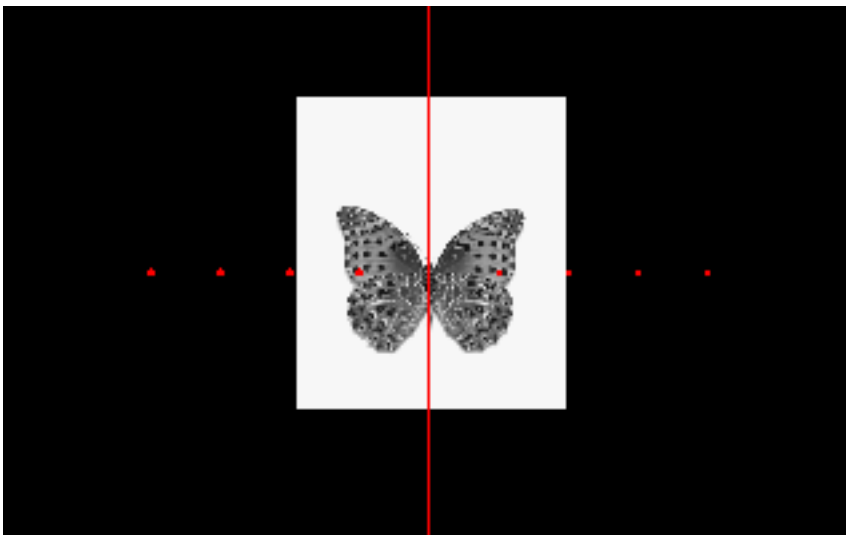
Supplemental Figure 7. Schematic of All Possible Start Positions (Relative to an Example Butterfly). *During the experiment, the locations of the stimuli varied with respect to a fixed central pre-stimulus start position. Here we show a full screen sized schematic, in a stimulus-centered space, of possible start positions relative to an example stimulus. Red dots indicate all of the possible (relative) start positions, and a red line indicates the midline of the stimulus.*

Supplemental Figure 8. Scatterplot of Face versus Butterfly Left Lateral Fixation Density. *Individual differences in proportions of left lateral fixation density correlate between face and butterfly stimuli (r(13) = 0.72, p < 0.0027, two-tailed).*
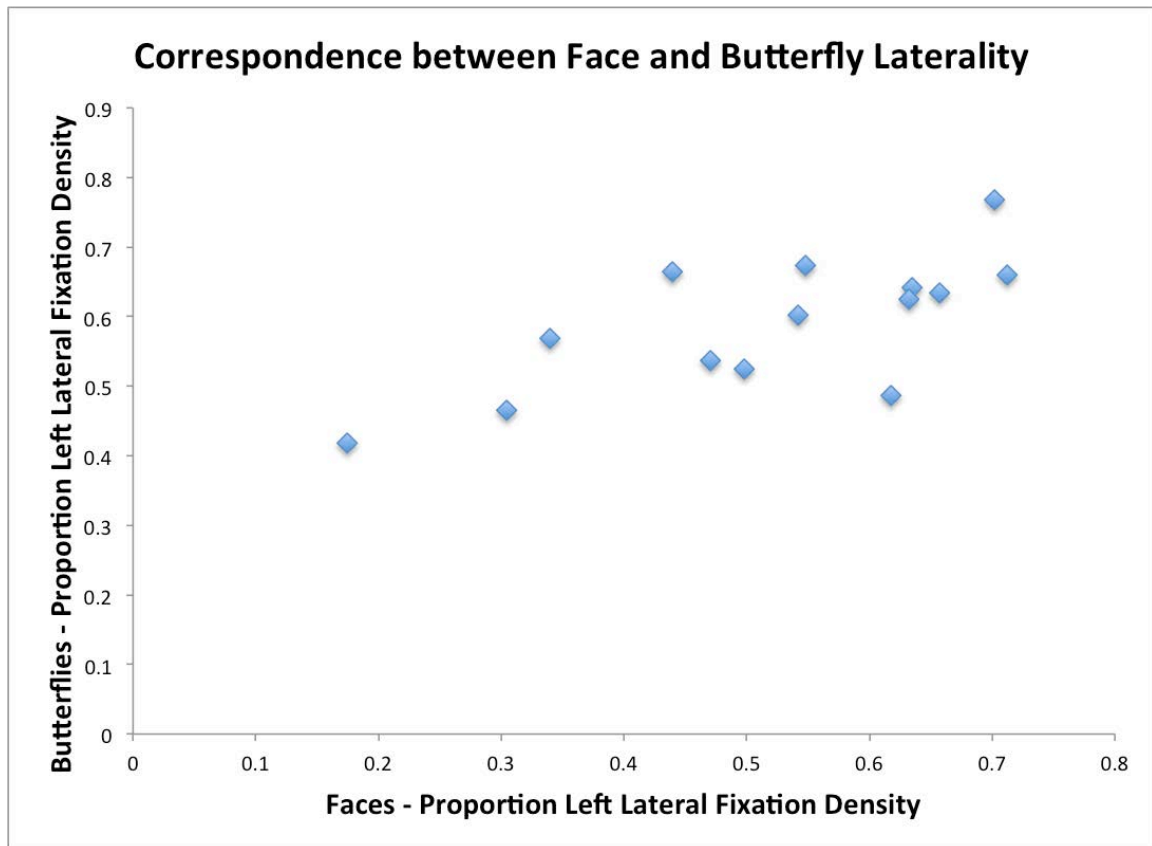
Supplemental Figure 9. Y-dimension profile density plots by stimulus category, starting distance, starting side, and ordinal fixation. *Starting side and distance did not appear to modulate y-dimension profile density, though ordinal fixation did.*
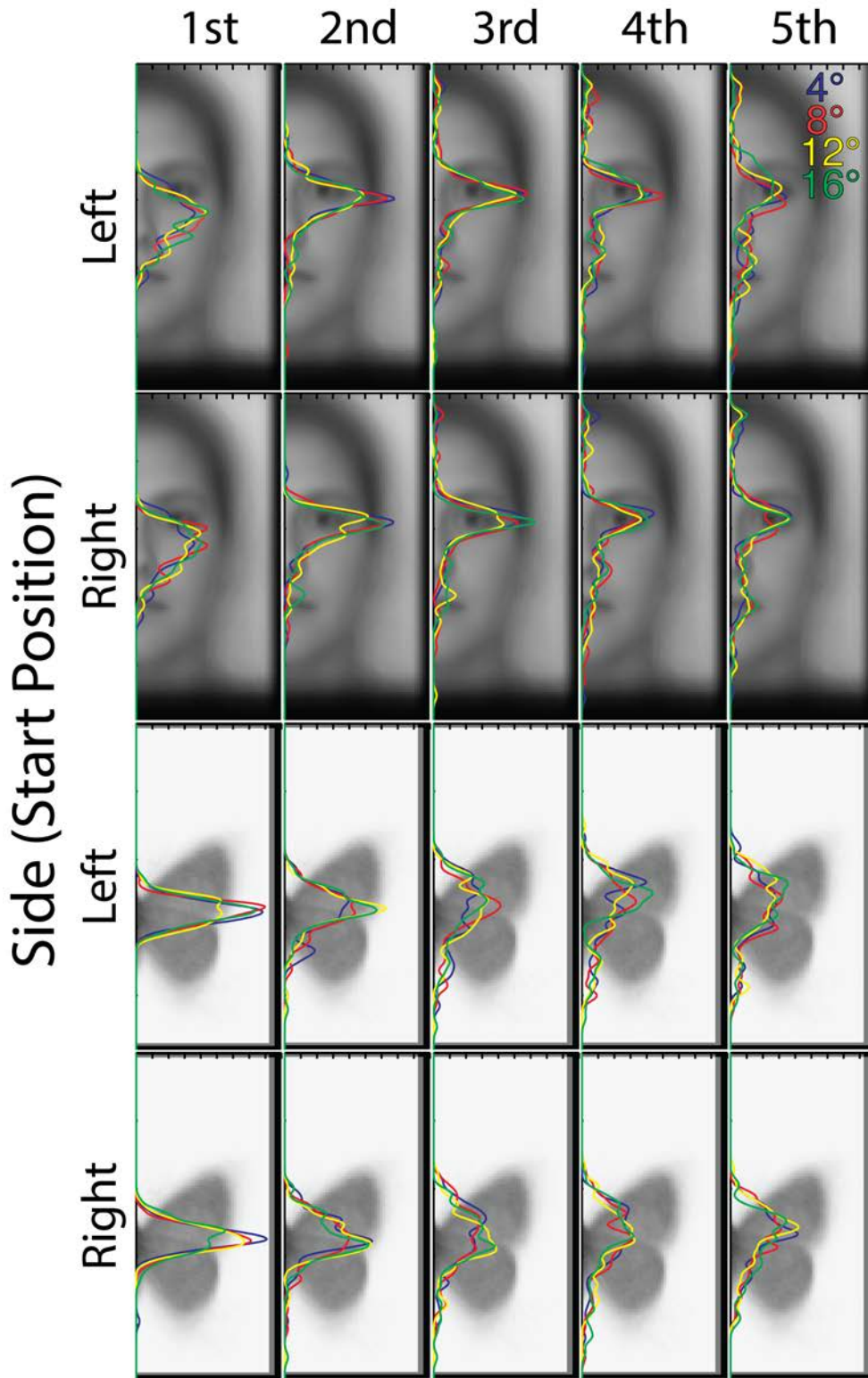
Chapter 5 – Individual differences in eye-movements patterns to faces

5.1 - Introduction

The classic and ubiquitously reported pattern of fixations during face perception is a T-shaped pattern with peak density over the eyes, especially the left eye (from the observer's perspective), and less fixation density over the nose and mouth (e.g. Althoff & Cohen, 1999; Barton, Radcliffe, Cherkasova, Edelman, & Intriligator, 2006; Heisz & Shore, 2008; Janik, Wellens, Goldberg, & Dell'Osso, 1978; Malcolm, Lanyon, Fugard, & Barton, 2008; Yarbus, 1965). Deviations from characteristic spatial or temporal eye-movement patterns to faces have been shown to reflect disorders including autism spectrum disorders (Kliemann, Dziobek, Hatri, Steimke, & Heekeren, 2010; Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Morris, Pelphrey, & McCarthy, 2007; Pelphrey et al., 2002; Pelphrey, Morris, & McCarthy, 2005), schizophrenia (Green, Williams, & Davidson, 2003a, 2003b; Manor et al., 1999; M L Phillips & David, 1997; Mary L. Phillips & David, 1997, 1998; Streit, Wölwer, & Gaebel, 1997; Williams, Loughland, Gordon, & Davidson, 1999), bipolar disorder (Bestelmeyer et al., 2006; E. Kim et al., 2009; P. Kim et al., 2013; Loughland, Williams, & Gordon, 2002; Streit et al., 1997), and prosopagnosia (Schwarzer et al., 2007; Stephan & Caine, 2009; Van Belle et al., 2011), among others (Horley, Williams, Gonsalvez, & Gordon, 2003, 2004; Loughland et al., 2002; Marsh & Williams, 2006), and are thought to relate to the social and perceptual deficits associated with such disorders (e.g. see the relation of eye-region fixations to emotion recognition performance for children with bipolar disorder, but not for healthy control children, reported in P. Kim et al., 2013). However, recent studies have uncovered striking deviations from the classic pattern of fixations even within the healthy population, and that the classic pattern in fact holds largely only when averaging across individual participants' eye-movement patterns (Gurler, Doyle, Walker, Magnotti, & Beauchamp, 2015; Kanan, Bseiso, Ray, Hsiao, & Cottrell, 2015; Mehoudar, Arizpe, Baker, & Yovel, 2014; Peterson & Eckstein, 2013). Such

idiosyncratic eye-movement patterns have been shown to be highly stable even over the course of at least 18 months (Mehoudar et al., 2014), and thus variation in eye-movement patterns among individuals must be regarded as a largely stable dynamic rather than as variance from other sources. Deviation from the classic spatial pattern in the healthy population was not reflected in reduced recognition performance for faces in my prior study (Mehoudar et al., 2014), which is consistent with a prior report showing no difference in the distribution of fixations between high and low face memory groups (Sekiguchi, 2011). Rather, forcing individuals to deviate from their own idiosyncratic fixation patterns has been reported to reduce performance for judgments on faces (Peterson & Eckstein, 2013). Even so, there is also evidence of an association between perception of the McGurk Effect and the degree of an individual's tendency to fixate the mouth of McGurk stimuli (Gurler et al., 2015). Idiosyncratic scanpaths have further been shown to vary across different tasks involving judgment of faces, but to be stable within a given task (Kanan et al., 2015). In addition to these recent findings of idiosyncratic eye-movement spatial patterns to faces, other studies involving temporal measures or other visual perceptual domains have additionally reported individual differences in eye-movements (Andrews & Coppola, 1999; Boot, Becic, & Kramer, 2009; Castelhano & Henderson, 2008; Poynter, Barber, Inman, & Wiggins, 2013; Rayner, Li, Williams, Cave, & Well, 2007). These surprising findings shed light on an intriguing phenomenon of individual differences in eye-movements and raise questions of how these individual differences relate to perceptual mechanisms and performance.

The present study principally aimed to estimate the diversity and prevalence of different kinds of individual eye-movement patterns to faces in the healthy population. As in prior studies, I also probed how these patterns relate to recognition performance. Finally, and importantly, as an aid and a reference in informing the design and analysis of future studies of individual differences in eye-movements, I investigated how various experimental factors modulated the relative distinctiveness among and consistency within individual spatial patterns of eye-movements to faces. The experimental factors investigated were Race of Face (Caucasian, African,

Chinese), Face Orientation (upright, inverted), pre-stimulus Start Position (left, right of upcoming face), Phase (study, test), and Time Window (1st -5th seconds). For each of these factors I investigated three aspects of individual differences in eye-movement patterns: i) *Discriminability* at each level of the given factor (i.e. for each level, are participants' individual patterns distinct relative to one another?), ii) *Relative Discriminability* between levels of the given factor (e.g. Are participants' individual patterns more distinct relative to one another for one level than another), and iii) Individual *Consistency Across Levels* of the given factor (i.e. are individual patterns consistent between levels). I quantified these aspects using discrimination index and discrimination accuracy measures, which are conceptually equivalent to those ubiquitously employed in neuroimaging to measure the relative distinctiveness of neural or hemodynamic activation patterns (Haxby et al., 2001; Kriegeskorte et al., 2008), but which have been adapted for eye-movement data (see Methods) similarly to several prior eye-tracking studies (Benson et al., 2012; Borji & Itti, 2014; Greene, Liu, & Wolfe, 2012; Kanan et al., 2015; Mehoudar et al., 2014; Tseng et al., 2013).

I found a strikingly variable distribution of individual differences in the spatial pattern of eye-movements in my participants, which was continuous and thus had no clear data-driven groupings. When I imputed facial feature based categories of eye-movement spatial patterns of my participants, I found that 52% of spatial eye-movement patterns were eye-focused, 31% were nose-focused, 4% were mouth-focused, and 13% did not cleanly fall into any of these categories. As in prior studies, I could not find evidence that individuals' eye-movement patterns related to recognition performance, suggesting that idiosyncratic eye-movements that preferentially deviate from the "classic" T-shaped pattern do not result in impairment in facial recognition. I also found the various influences of the experimental factors that I investigated (i.e. Race of Face, Face Orientation, Start Position, Study/Test Phase, Time Window). I present the influences of these factors with the hope that they may be useful for informing experimental design and analysis in future studies of individual differences in eye-movements so that the influences of these factors on individuals' idiosyncratic eye-movements can be adequately controlled and correctly

interpreted. I also discuss the methodological, theoretical, and ethical implications of my findings.

5.2 - Methods

Ethics Statement

All participants gave written informed consent and were compensated for their participation. The study adhered to the Declaration of Helsinki and was approved by the Institutional Review Board of the National Institutes of Health, Bethesda, Maryland, USA.

Participants

50 individuals, living in the Washington D.C. area, participated.

Of those, 30 (11 male) participated in an experiment in which Race of Face and Start Position were manipulated. From that group, one participant's data was excluded from analysis due to partial data corruption. The remaining 20 individuals (12 male) participated in an experiment in which Face Orientation (upright, inverted) and Start Position were manipulated. From that group, one participant's data was excluded only from analysis requiring test phase eye-movement data or recognition performance data because they did not complete the test phase. All participants were Western Caucasians because eye-movement differences have been reported among different races/cultures of observers (e.g. Blais, Jack, Scheepers, Fiset, & Caldara, 2008, though see Goldinger, He, & Papesh, 2009) and I was interested in individual difference measures that could not be explained by this effect.

Eye-tracking

I used an EyeLink II headmounted eye-tracker (SR Research, Mississauga, ON, Canada), and sampled pupil centroid at 500 Hz. The default nine point calibration

and validation sequences were repeated throughout the experiment. Both eyes were calibrated and validated, but only the eye with the lowest maximum error was recorded for the trials following a particular calibration. Calibration was repeated when maximum error at validation was more than 1° of visual angle. Before each trial, a drift correction was performed. Default criteria for fixations, blinks, and saccades as implemented in the Eyelink system were used.

Stimuli

Grayscale neutral expression frontal-view face images were used in both the Other-Race and Face Orientation experiments. Each face was scaled to have a forehead width subtending 10 degrees of visual angle at presentation and was rotated to correct for any tilt of the head. Images were cropped to remove most of the background, but not the hair or other external features, and all images were equated for overall luminance. At presentation, images were centered on a black background. To eliminate any possible stimulus bias as the source of any laterality effects, half of the faces were randomly left-right flipped across the vertical midline of the image for each participant.

Other-Race Experiment

For the experiment in which Race of Face and Start Position were manipulated, I collected 32 Caucasian-American, 32 African-American, and 32 Chinese face images (16 male and 16 female for each race), for a total of 96 grayscale neutral expression frontal-view face images. All Caucasian faces were taken from the neutral expression 18 to 29 age group of the Productive Aging Lab Face Database established by the University of Texas at Dallas (http://vitallongevity.utdallas.edu/stimuli/facedb/categories/neutral-faces.html) (Minear & Park, 2004). African-American faces were taken from the neutral expression 18 to 29 age group of the Productive Aging Lab Face Database, from the MacBrain ("NimStim") Face Stimulus Set made by the MacArthur Foundation

Research Network on Early Experience and Brain Development (http://www.macbrain.org/resources.htm), and from the Color FERET Database (http://www.nist.gov/itl/iad/ig/colorferet.cfm) (P. J. Phillips, Moon, Rizvi, & Rauss, 2000; P. J. Phillips, Wechsler, Huang, & Rauss, 1998) established by the United States Department of Defense (DOD) Counterdrug Technology Program. All Chinese faces were taken from the CAS-PEAL Face Database (http://www.jdl.ac.cn/peal/index.html) (Gao et al., 2008) established by the ICT-ISVISION Joint Research and Development Laboratory (JDL) for Face Recognition.

The website of the Productive Aging Lab Face Database states: "This [database] contains a range of face of all ages which are suitable for use as stimuli in face processing studies. Releases have been signed by the participants we photographed and the faces may be included in publications or in media events." Development of the MacBrain Face Stimulus Set was overseen by Nim Tottenham and supported by the John D. and Catherine T. MacArthur Foundation Research Network on Early Experience and Brain Development. Please contact Nim Tottenham at tott0006@tc.umn.edu for more information concerning the stimulus set. Portions of the research in this paper use the FERET database of facial images collected under the FERET program, sponsored by the DOD Counterdrug Technology Development Program Office. The research in this paper use the CAS-PEAL-R1 face database collected under the sponsor of the Chinese National Hi-Tech Program and ISVISION Tech. Co. Ltd.

Face Orientation Experiment

For the experiment in which Face Orientation and Start Position were manipulated, I used 80 grayscale neutral expression face images (40 male). These images were of Caucasians between the ages of 18 and 29 again from the Productive Aging Lab Face Database at the University of Texas at Dallas (http://vitallongevity.utdallas.edu/stimuli/facedb/categories/neutral-faces.html). Inverted faces were created by simply reflecting each image around the horizontal

axis.

Areas of Interest (AOIs)

To aid alignment of the face images and positioning relative to the fixation starting position, rectangular areas-of-interest (AOIs) were drawn for each face around the right and left eyes, bridge of nose (i.e. middle of eye region), right and left half of nose, and right and left half of mouth using EyeLink Data Viewer software. These AOIs were never visible to participants during the experiment.

Design

The paradigms of the face orientation experiment and the other-race experiment were highly similar. Each experiment was comprised of two phases: study and test. During the study phase, one face was presented per trial and participants were instructed to remember the faces for later recognition. They were allowed to advance study phase trials in a self-paced manner (up to 10 seconds per trial, self-terminating trials with a button press). The test phase began immediately after the study phase. In each trial of the test phase, participants viewed a face for a limited duration (one second only) and indicated with a button press whether or not they recognized each face as one presented during study (old/new task). Participants were instructed to respond within two seconds following stimulus onset, as soon as they thought they knew the answer.

In both the study and test phases, there were equal proportions of trials for each combination of levels of the factors of stimulus type (race of face or face orientation, depending on the experiment), face gender, and start position (i.e. the pre-stimulus fixation location). The particular subset of faces used in the study phase was randomized across participants. Of the faces presented in both study and test phase, half of the faces were presented with the same start position at study and test and for the other half, the start position on the other side of the face was used

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(e.g. left to right start position between study and test).

I systematically varied the pre-stimulus fixation location ("Start Position") because fixation patterns are affected by visuomotor factors (e.g. start position) in addition to stimulus factors (face), as reported in chapters 3 and 4 (J. Arizpe, Kravitz, Yovel, & Baker, 2012; J. M. Arizpe, Walsh, & Baker, 2015). Further, I were interested in this factor as a potential modulator of individual differences. The start positions of interest were either left of or right of the internal features of the upcoming face stimulus. Coordinates for a given start position were calculated uniquely for each face stimulus to be equidistant from all of the nearest internal facial features. Specifically, this was the unique coordinate that was equidistant from the centers of the nearest eye, nearest half-nose, and nearest half-mouth AOI was calculated numerically for each face. As the data from these experiments were originally collected for different purposes than the present study, there were also other start positions either above, below, or (only in the Face Orientation experiment) centered on the internal features of the upcoming face stimulus throughout the experiment; however, due to the number of comparisons necessary among the start positions and because left and right start position conditions are the most ecological, only left and right start position conditions were ultimately analyzed.

Before the onset of each stimulus, participants fixated at the start position, indicated by a standard Eyelink II calibration target (0.17° diameter black circle overlaid on a 0.75° diameter white circle) on the black screen. Participants initiated the trial by pressing a button while looking at the fixation target. In this action, a drift correction was performed. A colored dot (0.5° diameter) remained after drift correction, and the stimulus appeared only after a participant had fixated at the dot for an accumulated total of 1500 ms. This requirement ensured that drift correction and fixation were stable prior to stimulus onset. If more than 1500 ms of fixation off the start position accumulated before the trial could be initiated, drift correction was repeated. A fixation was considered off the start position if it landed more than 0.5° from the center of the dot. Dot color changed successively from red to yellow to green in

order to signal to the participant that a maintained fixation was successfully detected at the start position.

Other-Race Experiment

In the other-race experiment, I varied Race of Face (Caucasian, African, Chinese) and Start Position across trials. During the study phase, participants viewed 48 faces (16 of each race, 8 male for each race). During the test phase, participants viewed 96 faces (the 48 study phase faces plus 48 new faces).

Face Orientation Experiment

In the face orientation experiment, I varied face Orientation (upright or inverted) and Start Position across trials. For each participant, a random half of the faces were inverted in each phase, with the orientation of a given face being identical in both phases. In the study phase, participants viewed 40 faces (20 male). In the test phase, participants viewed 80 faces (the 40 study phase faces plus 40 new faces).

Analyses

Software

Fixation and AOI data were obtained through EyeLink Data Viewer software by SR Research. Subsequent analyses on these data and behavioral data from the test phase were performed with custom Matlab (The MathWorks, Inc., Natick, MA, USA) code. ANOVAs were performed in SPSS (IBM, Somers, NY).

Behavior

For the purposes of investigating the potential relationship of eye-movement patterns to facial recognition performance, I assessed participants' discrimination

performance on the old/new recognition task in the test phase. For each participant, d' [z(hit rate) - z(false alarm rate)] was computed for discrimination performance for Caucasian faces in the other-race experiment and for upright faces in the face orientation experiment.

Spatial Density Analyses

To measure the individual differences in eye-movement patterns, I first mapped the spatial density of fixations for each participant under various experimental conditions (i.e. Race of Face or Face Orientation, Start Position, Study/Test Phase, Time Window). Except for Time Window analyses, all spatial density maps were produced from all of the valid eye position samples recorded within the first second of the relevant trials. Invalid samples included samples during blinks or after button presses which signaled the end of the trial. For Time Window analyses, spatial density maps were produced from all valid samples within one-second time windows from the first to the fifth second within study phase trials of the other-race experiment. Due to computational constraints, sampling frequency was down sampled to 250Hz just for data from the other-race experiment.

To ensure that summation of fixation maps across different face trials produced spatially meaningful density maps, fixation maps for individual faces were first aligned to a common reference frame using simple translations only. This reference frame was defined by the internal facial features. Specifically, the alignment minimized the sum of the squared differences between the center of the AOIs for each face and the average centers of the AOIs across all faces. Within this common reference frame, samples were then each plotted as Gaussian densities with a mean of 0 and a standard deviation of 0.3° of visual angle in both the x and y dimensions. These density plots were then summed across trials of the relevant experimental condition. When plotting the resulting maps, I used a color scale from zero to the maximum density value observed, with zero values represented in deep blue.

Individual Pattern Characterization

Some prior research (Peterson & Eckstein, 2013), including my own (Mehoudar et al., 2014), has suggested that a proportion of the normal population exhibits mouth-focused fixation patterns without impaired facial recognition performance relative to participants with more eye-focused fixation patterns. Thus I was interested in estimating the proportion of those not principally fixating the eyes in the healthy population with the data from my participant sample. For each participant, spatial density maps were produced from samples during the first second of study phase trials for all upright Caucasian faces and both start position conditions pooled. From these maps, an independent rater unfamiliar with the aims of this study was asked to categorize these fixation patterns into one of three kinds: mouth-focused fixation patterns, eye-focused fixation patterns, and other fixation patterns. Proportions for each of these categories were calculated from these ratings.

Similarity Matrix Analyses

In order to quantify and visualize the degree of similarity between fixation patterns among participants or across different experimental conditions, I computed similarity matrices from the spatial density data. A similarity matrix simply is an organized matrix, in which each cell represents a comparison between given conditions (or in the present study, between given participants), or a given combination of conditions. Each cell contains a value of a specific similarity measure (e.g. correlation value, Euclidean distance, etc) corresponding to that specific comparison, which is specified by its index in the matrix. This class of methods, along with the complementary class of discrimination analyses (see *Discrimination Analyses* subsection below), has become mainstream and ubiquitous in fMRI studies (see Haxby et al., 2001; Kriegeskorte et al., 2008) and has also been used in several prior eye-tracking studies (Benson et al., 2012; Borji & Itti, 2014; Greene et al., 2012; Tseng et al., 2013), including two on face perception (Kanan et al., 2015; Mehoudar et al., 2014).

To produce similarity matrices, I conducted "split-half" analyses in which eye-movement data was first split into two halves, namely, trials from the first and last half of the given phase (i.e. study or test), as each half had equal numbers of trials of all possible combinations of conditions (race of face or face orientation, start position, gender). When including test phase in analyses, I included only those trials in which the observed faces were not present in the study phase. This was done so that the face stimuli that had been seen between the study and test phase for a given participant were equally unfamiliar, thus removing face familiarity as a confound for any modulation in similarity measures I might measure.

Spearman's correlations between corresponding pixels' density values across the split halves of the data were calculated between participants. When correlating within given conditions (e.g. upright faces in the study phase) both halves of the data were of the same conditions, but when correlating between given conditions (e.g. study versus test phase) one half of the data was of one condition and the second half of the other condition.

Discrimination Analyses

Discriminability index. In order to quantify and test the significance of the average distinctiveness ("discriminability") of the patterns of given participants compared to those of the others, I conducted several discrimination analyses using the correlation values from the relevant similarity matrix analyses. I focused in particular on discriminability among participants given certain experimental conditions (i.e. Race of Face or Face Orientation, Start Position, Study/Test Phase, Time Window) or across given conditions (e.g. discrimination of subjects for left start position condition using right start position data). In the similarity matrices, the diagonals always corresponded to the correlation between the two halves of the data for the same participant, and the off diagonal cells to those of non-identical participants. Therefore, discriminability of each participant was quantified as the mean difference

between the diagonal and off diagonals for each row of the given similarity matrix, where rows correspond to each participant's first half of the data, and columns to each participant's second half of the data. Thus a discriminability value existed for each subject, in which greater positive values indicate greater relative discriminability. When discrimination was conducted across different conditions (e.g. discrimination of subjects for left start position condition using right start position data), only the eye-movement data of first half of the first condition and the second half of the second condition were utilized, so that the resulting discrimination measures would be conceptually and statistically comparable to those calculated within given conditions. When testing for statistical significance of average discriminability among participants, a one-tailed, one-sampled t-test of greater than zero was conducted on the discrimination index distribution across participants. A one-tailed test was chosen because only positive discrimination values are interpretable in this context.

Discrimination Accuracy. I also calculated a more stringent index of discrimination that I call discrimination accuracy, which was the accuracy at which the second halves of participant data could be uniquely identified using the first halves. To compute this index, I again utilized the correlation values from the relevant similarity matrix. Every time the diagonal of the similarity matrix (data half 1 correlated with data half 2 for same participant) contained the highest correlation value in it's row (data half 1 of a given participant correlated with data halves 2 of each and every of the participants), then data half 2 of the participant was considered to be correctly identified from data half 1. The discrimination accuracy index is the percent of such correct identifications over all rows (participants). Thus each similarity matrix had a single discrimination accuracy index associated with it. Given random data, the probability that any given participant could be correctly identified is 1/n, where n is the number of subjects (columns) in the matrix. Thus the probability (p-value) that a give discrimination accuracy index was at chance was also calculated using the binomial test.

5.3 - Results

Distribution of peak eye-movement density among participants

I plotted the peak spatial density of eye-movements across 48 participants included in my analyses (Figure 1). From this, it is evident that there is continuous variability in individual differences in eye-movement patterns and that groupings within this distribution are not clear. Further, this distribution of peaks across participants resembles the classic T-shaped pattern frequently reported at the group level in previous studies studies, while also indicating the great diversity in individual patterns.
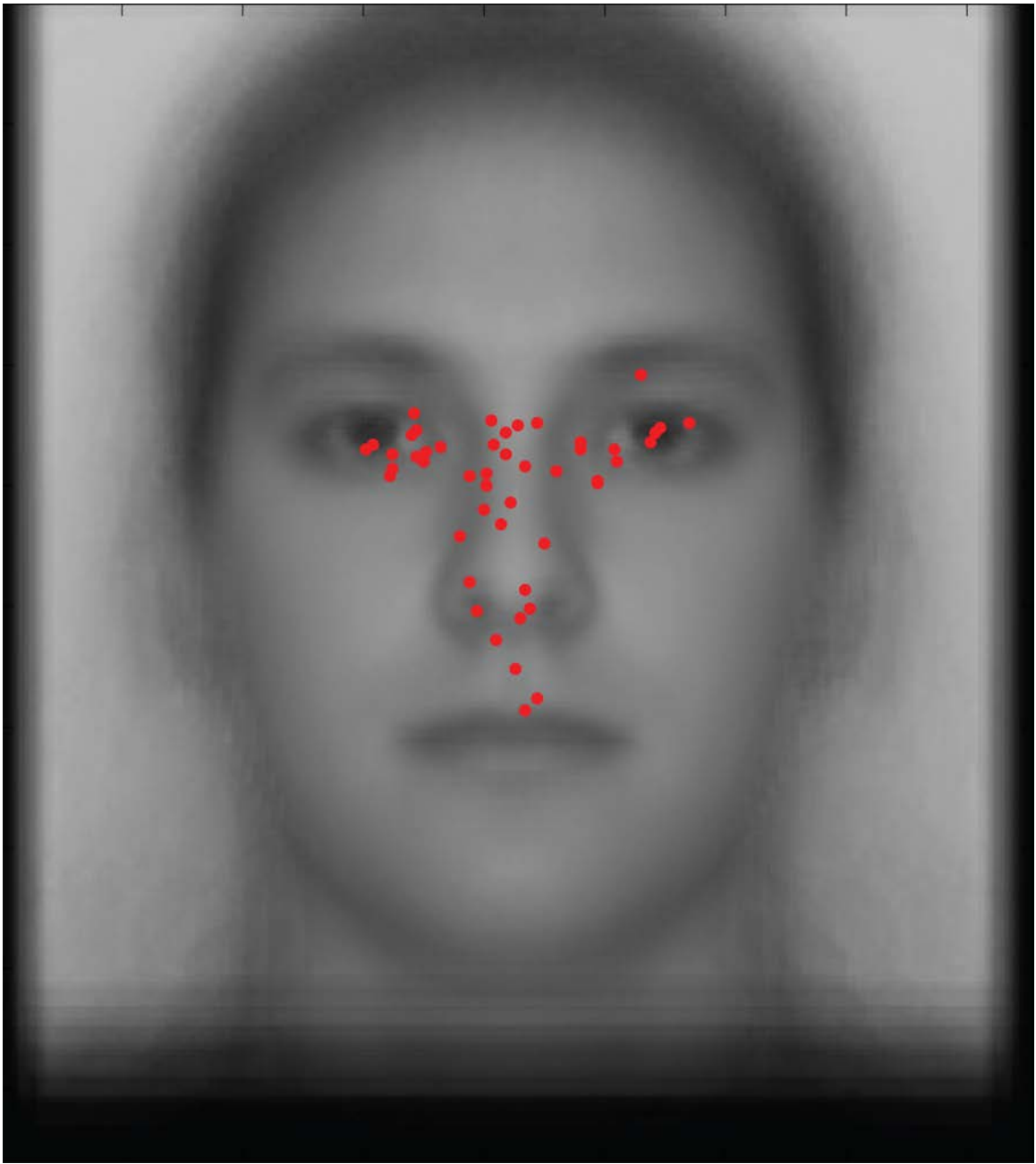
Figure 1. *Distribution of peak eye-movement density among all participants.*

Proportion of non-"eye fixating" observers

I was interested in estimating the proportion of individuals in the healthy population who did not principally focus on the eyes when observing faces. An independent rater imputed facial feature bases categories onto the spatial density maps of my participants into eye-focused, nose-focused, mouth-focused, and other/composite (see Methods). From this, I report that patterns from my participants across both

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experiments were 52% eye-focused, 31% nose-focused, 4% mouth-focused, and 13% other/composite.

Recognition performance versus eye-movement patterns

Given that deviation from the "classic" T-shaped eye-movement pattern to faces has been related to facial processing impairment in clinical populations, but that prior studies have failed to find a similar relationship with respect to idiosyncratic eye-movement patterns in the healthy population (see Introduction), I also investigated whether idiosyncratic eye-movement patterns are related to facial recognition performance. For each experiment, I sorted the individual spatial density maps of my participants according to the participants' facial discrimination performance (Figures 2 and 3). From this, no clear qualitative relationship between eye-movements and recognition performance could be observed. I also plotted both the x- and y-coordinates of the peak fixation density on the face against d-prime performance in each experiment (Figure 4). I failed to find evidence of any correlation (Spearman's correlation) in the x- ($r < 0.38$, $p > 0.12$, both experiments) or the y-coordinates ($|r| < 0.094$, $p > 0.70$, both experiments) to recognition performance.
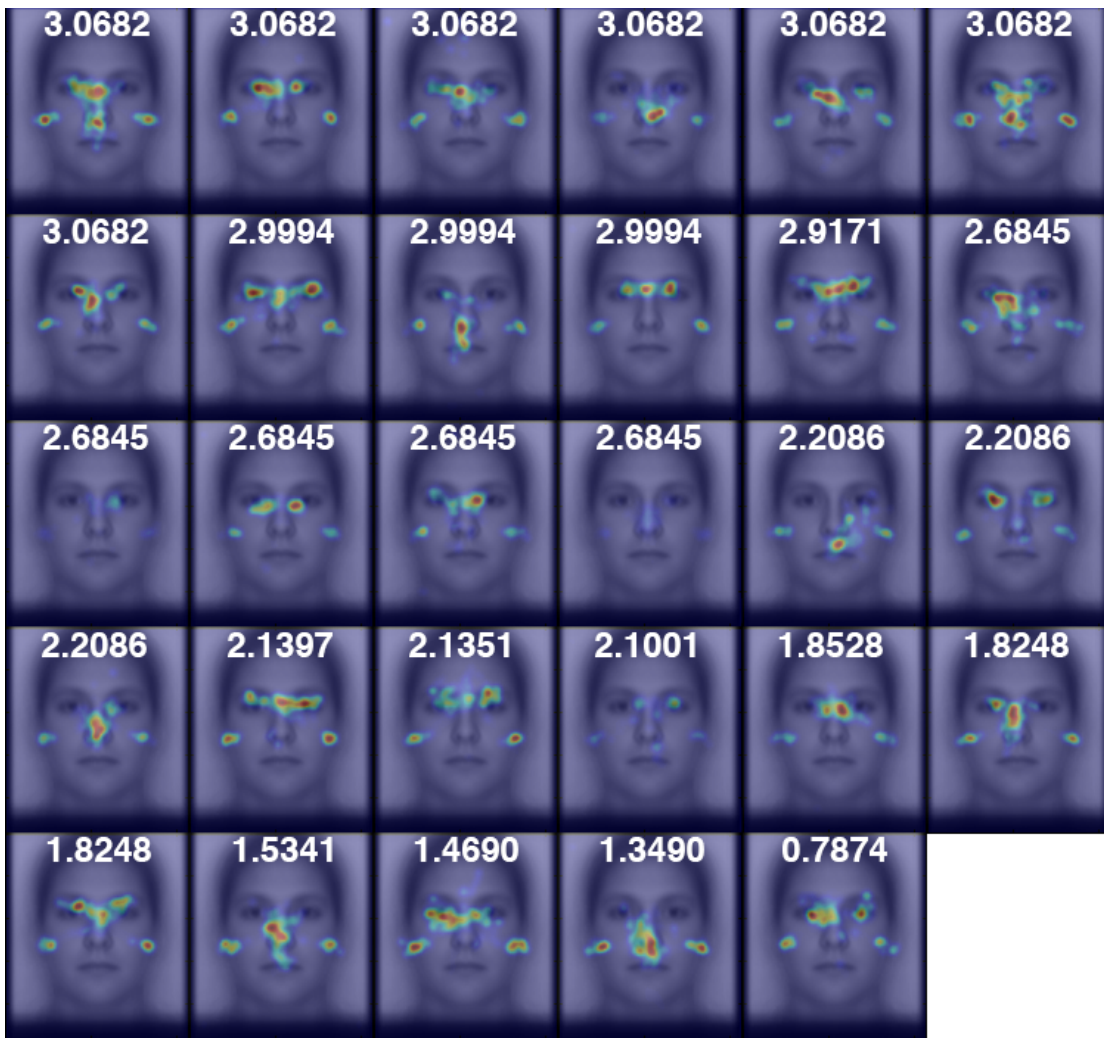
Figure 2. Participants' spatial density maps for Caucasian faces from the Other-Race experiment ordered by facial recognition performance, as measured by d'.
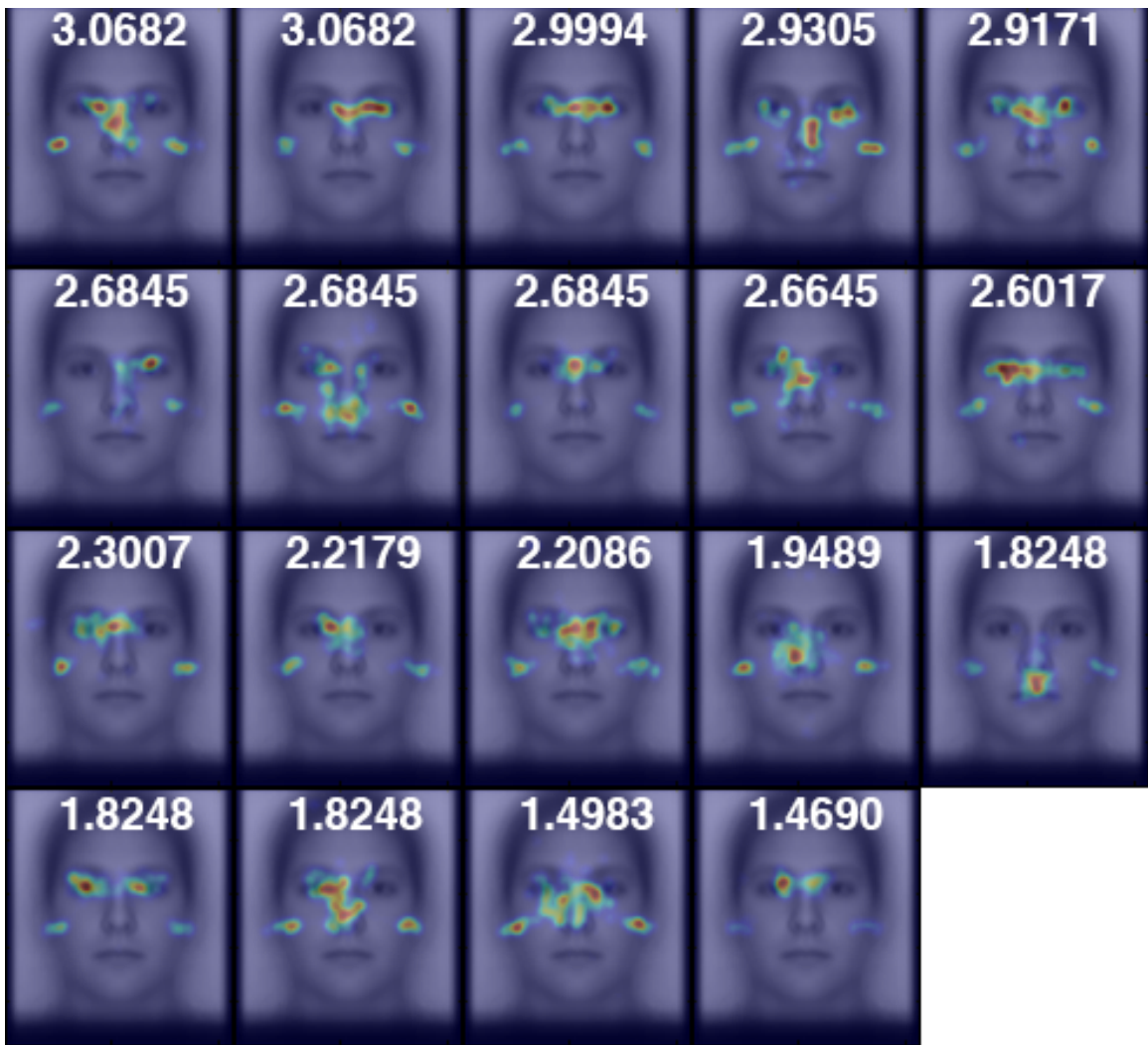
Figure 3. Participants' spatial density maps for upright faces from the Face Orientation experiment ordered by facial recognition performance, as measured by d'.
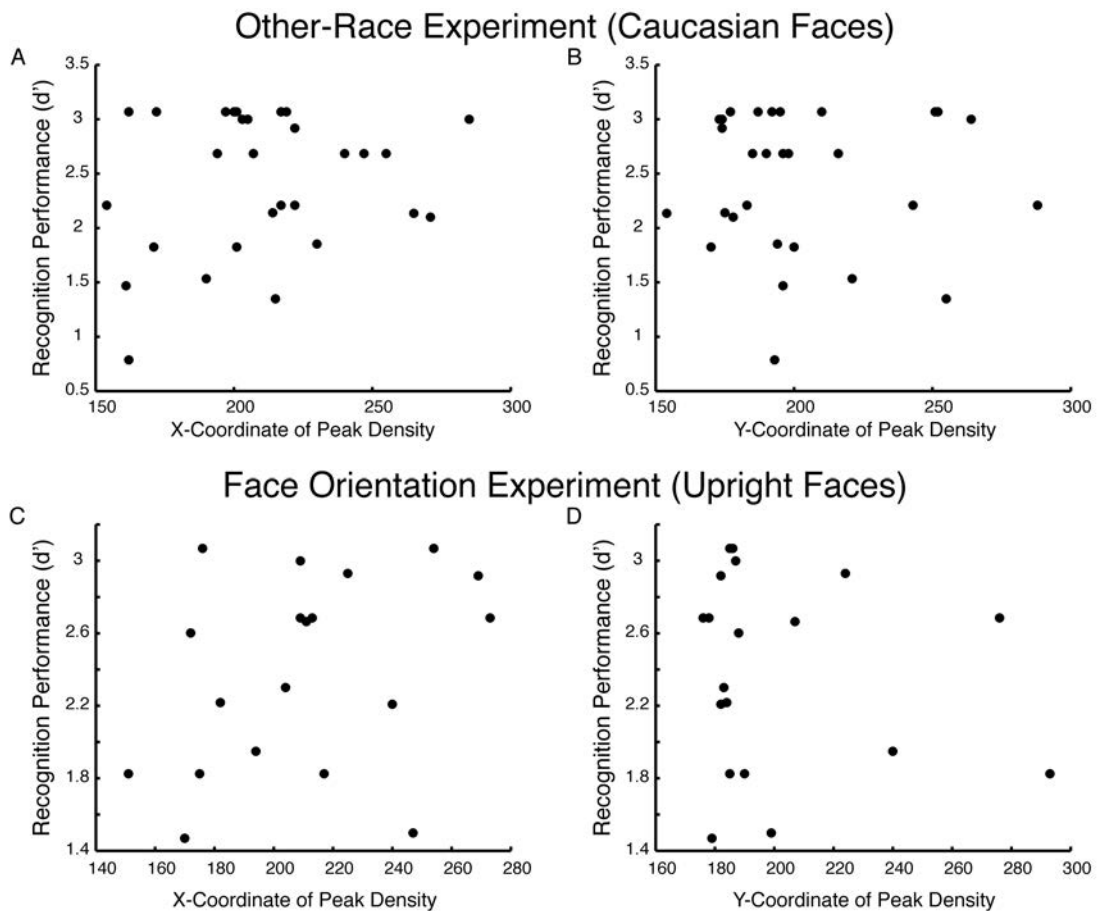
Figure 4. *Scatter plots of peak spatial density coordinates against recognition performance. Participants' x-coordinates (a) and y-coordinates (b) against recognition performance, measured by d' for Caucasian faces in the Other-Race experiment. Participants' x-coordinates (c) and y-coordinates (d) against recognition performance, measured by d' for upright faces in the Face Orientation experiment. For reference, the coordinates (270,175) and (155, 175) correspond to the pupils of left and right eyes, respectively, (213, 240) to the tip of the nose, and (213, 305) to the center of the convergence of the lips on the average face.*

What factors modulate individual differences in eye-movements?

I investigated how Race of Face (Caucasian, African, Chinese), Face Orientation (upright, inverted), pre-stimulus Start Position (left, right of upcoming face), Phase (study, test), and Time Window (1st -5th seconds) each influenced the relative distinctiveness and consistency of individual observer's eye-movement patterns of my participant sample. In particular, for each of these factors I investigated three aspects of individual differences in eye-movement patterns: i) *Discriminability* at each level of the given factor (i.e. For each level, are participants' patterns distinct

relative to one another?), ii) *Relative Discriminability* between levels of the given factor (e.g. Are participants' patterns more distinct relative to one another for one level than another), and iii) Individual *Consistency Across Levels* of the given factor (i.e. Are individual patterns consistent between levels) I quantified these aspects using discrimination index and discrimination accuracy (see Methods).

To investigate effects of Race of Face, Start Position, Phase and Time Window I used the Other-Race Experiment data, rather than the Face Orientation Experiment data, because this maximized the amount of data per condition. Orientation was not manipulated in the Other-Race Experiment, so I used the Orientation Experiment data to analyze effects of orientation.

Race of Face

Race of Face did not significantly modulate the distinctiveness of individual eye-movement patterns, and did not strongly modulate individual eye-movement patterns (Figure 5).

Figure 5. *Discrimination indices within- and between- Race of Face (Caucasian, African, Chinese) for the study phase of the Other-Race experiment. Race of Face did not significantly impact discrimination indices. Discrimination index quantifies the average distinctiveness of eye-movement patterns of the given participants compared to those of the others.*

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Discriminability. Using the study phase data from the Other-Race Experiment and averaging correlation matrices from both start positions, I found that discriminability indices (see Methods) were significantly greater than zero for each Race of Face (Caucasian, African, Chinese, all $t(28) > 4.8$, $p < 0.00003$, one-tailed). This means that for each race of face condition, there was significant discriminating information in individual eye-movement patterns. Discrimination accuracy (see Methods) for uniquely identifying individual participants' eye-movement patterns across split halves of data was greater than 24%, and thus significantly greater than chance ($p < 0.00005$), for each race of face.

Relative Discriminability. Notably, discriminability indices did not differ significantly among Caucasian, African, and Chinese face conditions (all three comparisons: paired $t(28) < 0.96$, $p > 0.34$, two-tailed), which suggests that participants were not differentially discriminable for any of these conditions.

Consistency Across Levels. When individual eye-movement patterns in one Race of Face condition were used to discriminate observers in another Race of Face condition (e.g. discriminate individuals' Chinese condition eye-movement patterns from their Caucasian condition patterns), the discriminability indices for the three possible split halves pairings (i.e. 1. Caucasian discriminating African, 2. Caucasian discriminating Chinese, 3. African discriminating Chinese) differed neither from one another (all three: paired $t(28) < 0.61$, $p > 0.54$, two-tailed) nor from the discrimination indices within Race of Face conditions (all comparisons: paired $t(28) < 0.87$, $p > 0.19$, one-tailed). In accord with these results, discrimination accuracy for the three possible split halves pairings were all greater than 27%, and thus still highly significantly above chance ($p < 4.5e-6$). These results suggest that my participants' idiosyncratic eye-movement patterns were consistent across changes in Race of Face.

In light of the lack of evidence for Race of Face modulating my participants'
idiosyncratic eye-movement patterns, I pooled eye-movement patterns across Race
of Face for all remaining analyses involving data from the other-race experiment.

Start Position

Using the study phase data of Other-Race Experiment and pooling all Race of Face
conditions together, I found evidence that pre-stimulus Start Position may have
modulated the distinctiveness of individual eye-movement patterns, and, further, that
the distinguishing information in individual eye-movement patterns differed across
start position conditions (Figure 6).
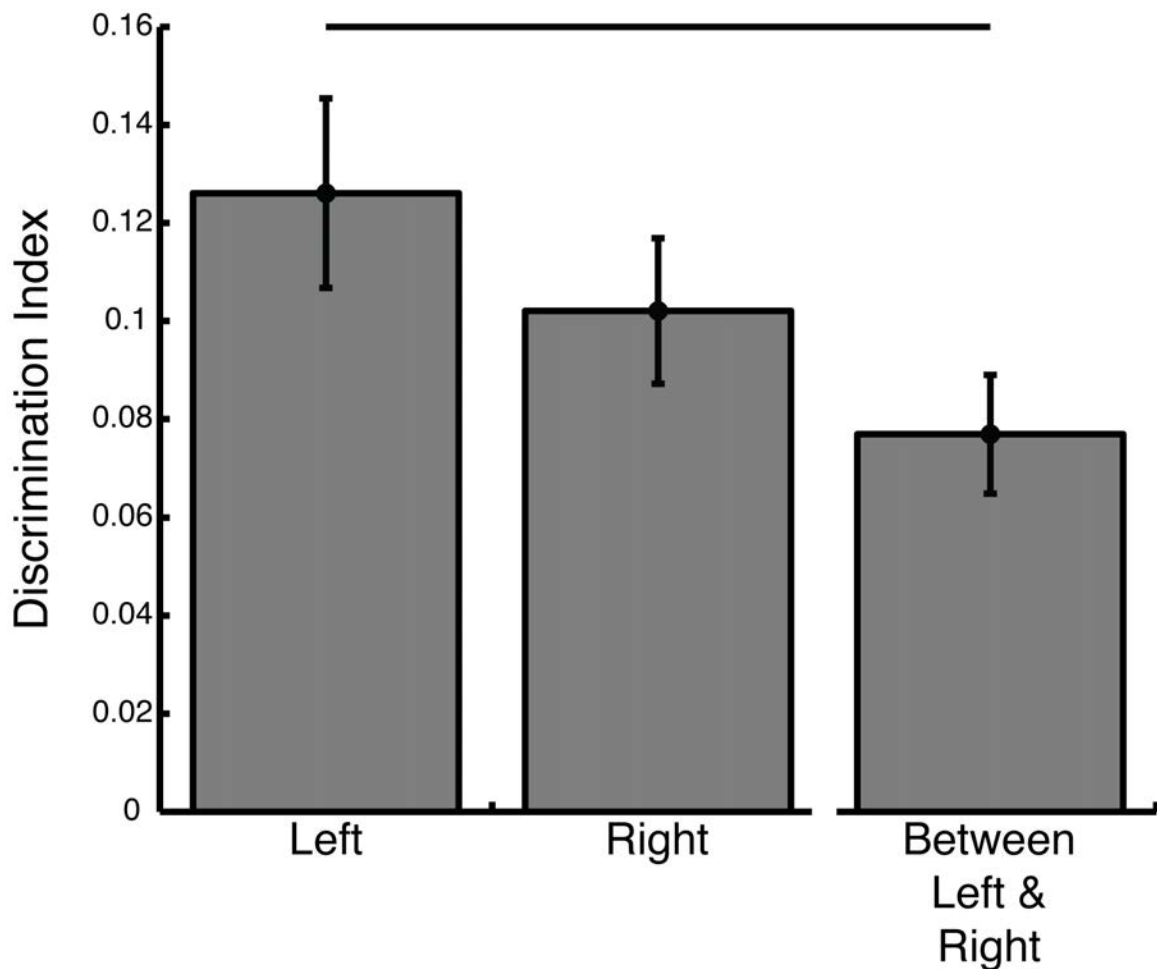
Figure 6. *Discrimination indices within- and between- Start Position (left, right) conditions for the study phase of the Other-Race experiment (all Race of Face conditions pooled). The between- start position discrimination index was significantly lower than that for within left and marginally lower than that for within right.*

Discriminability. Discriminability indices were significantly greater than zero for each Start Position (Left, Right of face both $t(28) > 6.41$, $p < 3.05e-7$). Thus there was significant discriminating information in individual eye-movement patterns for each Start Position condition.

Relative Discriminability. Discriminability indices did not differ significantly between left and right start position conditions (paired $t(28) < 1.098$, $p > 0.28$, two-tailed), suggesting that participants were not differentially discriminable for either condition. Discrimination accuracy was 17.24% for left start position and 48.28% for right start position, both of which are significantly greater than chance ($p < 0.0030$ and $p < 1.59e-13$, respectively). Given the apparent difference in magnitude of

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discrimination accuracy between left and right start position conditions, I conducted a post-hoc test calculating the probability that an accuracy greater or equal to than that the of the right start position could be achieved under the assumption that the true probability of correct individuation is equal to the left start position accuracy. The probability is $p < 0.00012$, suggesting that the discrimination accuracies are different between left and right start position. Compared to discrimination index, discrimination accuracy is a more stringent measure of discriminating information and requires uniquely individuating information to be present in patterns to produce high values, so these results suggest that right start position induced patterns which were more highly uniquely discriminating, while average differences in distinctiveness across individuals was not significantly modulated (see "Methodological considerations" in *Discussion*).

Consistency Across Levels. When individual eye-movement patterns in the right start position condition were used to discriminate individuals in the left start position condition, the discriminability indices were significantly greater than zero contrary to my expectation ($t(28) > 5.52$, $p < 3.4e-6$, one-tailed), and the discrimination accuracy was 10.34%, which is marginally greater than chance ($p < 0.078$). This indicates that discriminating information in eye-movement patterns was at least partially preserved across left and right start position conditions. The between Start Position discrimination index was significantly lower than the within left discrimination index (paired $t(28) > 2.44$, $p < 0.011$, one-tailed) and marginally lower than within right discrimination (paired $t(28) > 1.58$, $p < 0.063$, one-tailed) suggesting that while discriminating information was preserved between left and right start positions, it was degraded. Together, this evidence indicates that my participants' idiosyncratic eye-movement patterns were modulated across Start Position conditions.

In light of the evidence for Start Position modulating my participants' idiosyncratic eye-movement patterns, for all remaining analyses I average the correlation matrices from both start positions before calculating discrimination indices and accuracy, as

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was done in the analysis investigating discriminability across Race of Face conditions.

Study and Test Phase

Phase is a factor that marginally significantly modulated the distinctiveness of individual eye-movement patterns, and significantly modulated individual eye-movement patterns (Figure 7).
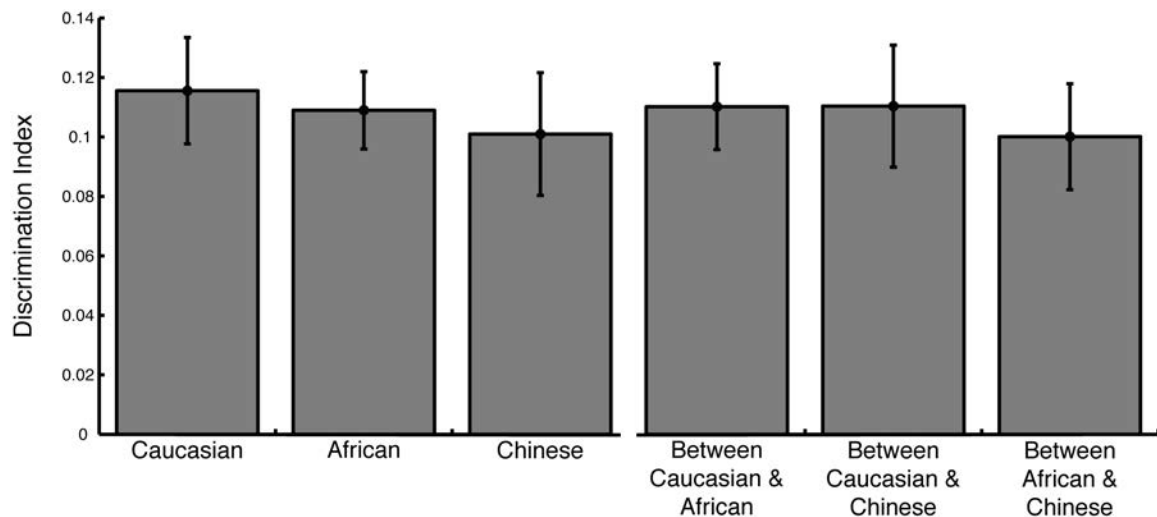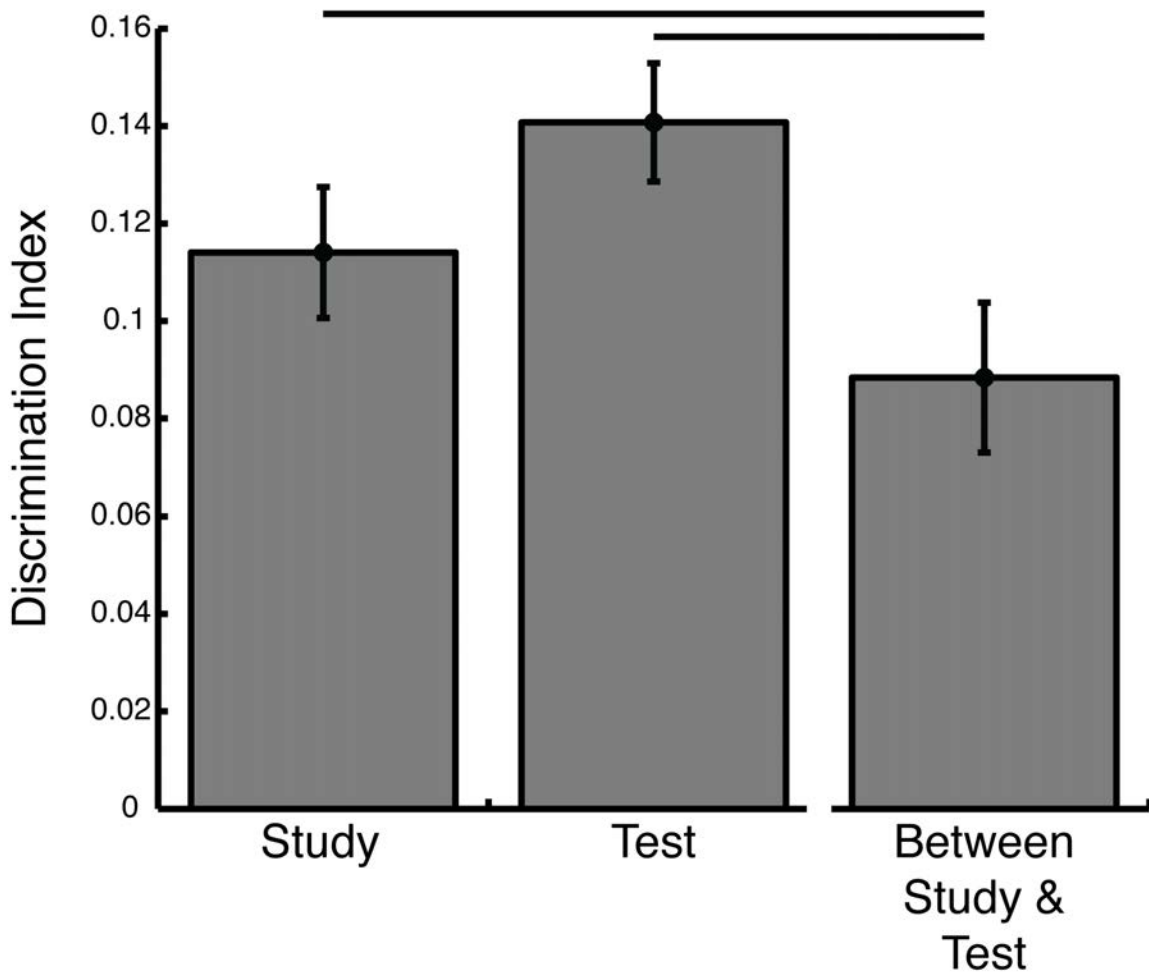

Figure 7. *Discrimination indices within- and between- Phase (study, test) conditions of the Other-Race experiment (all Race of Face conditions pooled and Start Position conditions averaged). The between-phase discrimination index was significantly lower than the discrimination indices within either phase alone, and within-phase discrimination index for study was marginally lower than for test.*

Discriminability. Discriminability indices were significantly greater than zero for both the study and test phases (both $t(28) > 6.75$, $p < 1.2e-7$, one-tailed) in the other-race experiment, and thus indicate significant discriminating information in individual eye-movement patterns in each phase. Discrimination accuracy was greater than 17%, and thus significantly greater than chance ($p < 0.003$), for each phase.

Relative Discriminability. There was a marginally significant difference in the discriminability indices between phases (paired $t(28) > 1.88$, $p < 0.070$, two-tailed), which suggests that participants eye-movement patterns may have been more weakly discriminable in the study phase.

Consistency Across Levels. When individual eye-movement patterns in the study phase were used to discriminate individuals in the test phase, the discriminability index was significantly greater than zero (paired $t(28) > 1.84$, $p < 0.038$, one-tailed) and discrimination accuracy (24.14%) was significantly greater than chance ($p < 0.000046$), but the discrimination index notably was significantly lower than the within-phase discrimination indices (both: paired $t(28) > 1.84$, $p < 0.038$, one-tailed). This suggests that my participants' idiosyncratic eye-movement patterns were modulated across study and test phases.

Given this evidence that my participants' idiosyncratic eye-movement patterns were modulated across study and test phases, and because I cannot rule out that this may have been because of the artificial time restriction to make eye-movements during test phase, I focus only on data from the study phase (which was always self-paced) in all remaining analyses.

Face Orientation

Face Orientation is a factor that did not modulate the distinctiveness of individual eye-movement patterns, while it nonetheless did significantly modulate those individual eye-movement patterns (Figure 8).
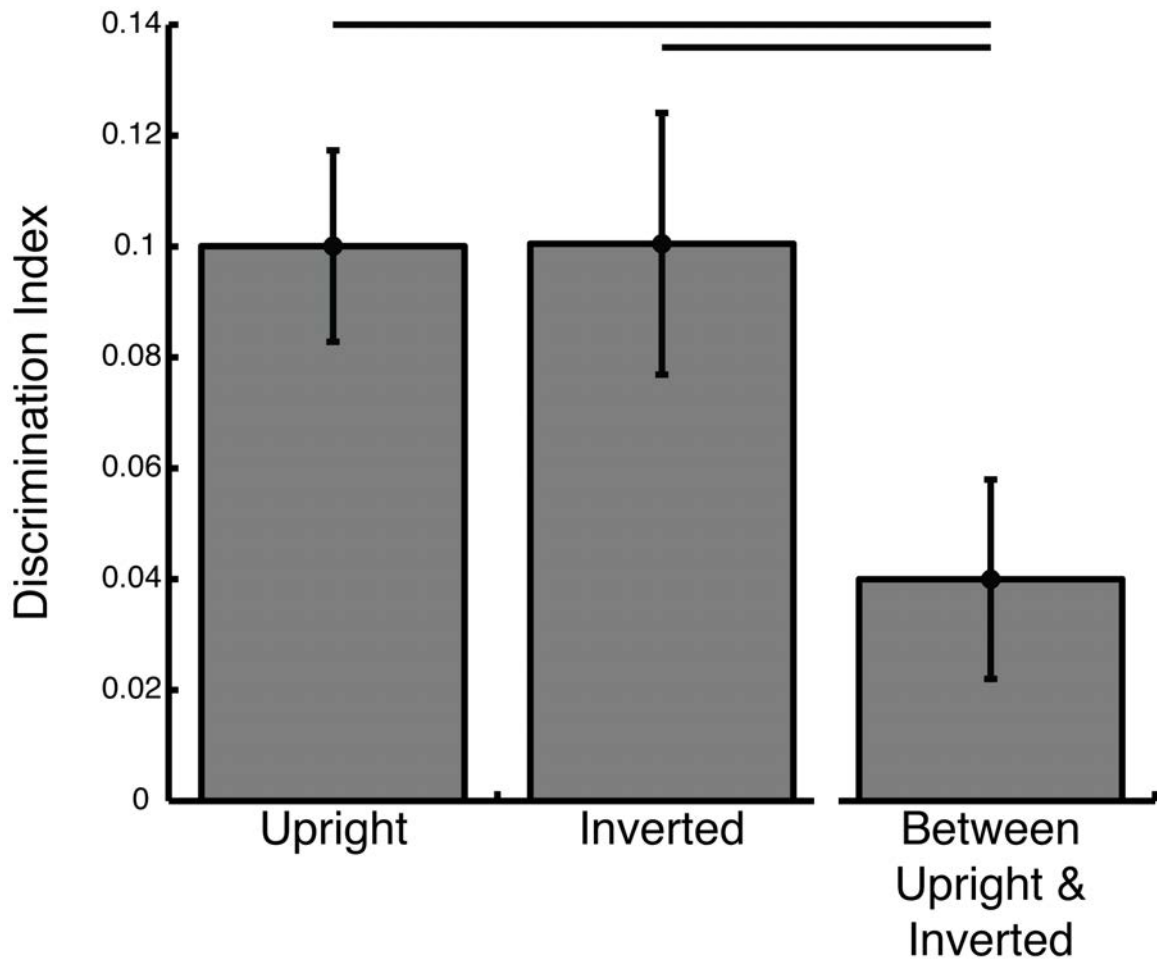
Figure 8. *Discrimination indices within- and between- Face Orientation (upright, inverted) conditions of the Face Orientation experiment (Start Position conditions averaged). The between-orientation discrimination index was significantly lower than either within-orientation discrimination index.*

Discriminability. Discriminability indices were significantly greater than zero for both upright and inverted faces (both $t(19) > 4.15$, $p < 0.00055$, one-tailed) in the face orientation experiment, and thus indicate significant discriminating information in individual eye-movement patterns in each face orientation. Discrimination accuracy was 25% both for upright and for inverted faces, and thus significantly greater than chance ($p < 0.0027$), for each face orientation.

Relative Discriminability. Discriminability indices did not differ between upright and inverted face conditions (paired $t(19) < 0.016$, $p > 0.50$, one-tailed), despite my expectation, which suggests that participants were equally discriminable in both the upright and inverted face conditions.

Consistency Across Levels. When individual eye-movement patterns in the upright face condition were used to discriminate individuals in the inverted face condition, the discriminability index was significantly greater than zero (paired $t(19) > 2.16$, $p < 0.044$, one-tailed) though discrimination accuracy (10%) was not significantly greater than chance ($p > 0.26$). Also, interestingly, the between-orientation discrimination index was significantly lower than both of the within-orientation discrimination indices (both: paired $t(19) > 2.64$, $p < 0.0080$, one-tailed). This suggests that my participants' idiosyncratic eye-movement patterns were modulated across upright and inverted face orientations, though the discriminability did not differ between face orientation conditions.

Time Window

Time Window modulated the distinctiveness of individual eye-movement patterns such that discriminability decreased with later time windows. Also eye-movement patterns were significantly different between time-windows (Figure 9).
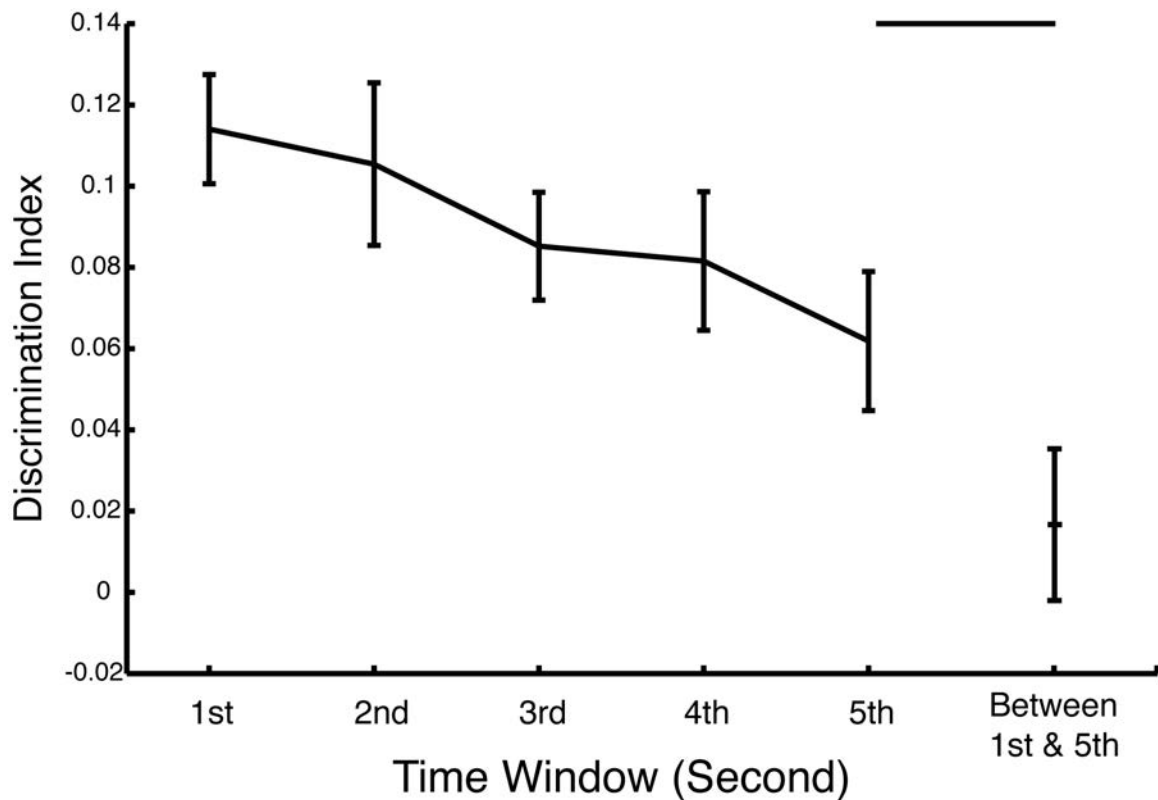
Figure 9. *Discrimination indices within- and between- Time Window (1st – 5th second) for the Other-Race experiment (all Race of Face conditions pooled and Start Position conditions averaged). Discrimination indices within each time window significantly decreased with time. Further, the between- 1st and 5th second discrimination index was not significantly greater than zero and was significantly lower than that for within the 5th second.*

Discriminability. Discriminability indices were significantly greater than zero for each one-second time-window (1st through 5th second, all: $t(28) > 3.54$, $p < 0.0015$, one-tailed) in the other-race experiment, thus indicating significant discriminating information in individual eye-movement patterns in each time-window. Discrimination accuracy was significantly greater than chance (all: $p < 0.017$), for each time window, except for the 3rd second ($p > 0.076$).

Relative Discriminability. Discriminability indices, however, decreased with time. The mean slope of the within-subject regression lines of discriminability index versus time (ordinal second) across participants was negative ($m = -0.0128$) and was significantly less than zero ($t(28) < -2.75$, $p < 0.0052$, one-tailed). This indicates that my participants' idiosyncratic eye-movement patterns became less distinct with time.

Consistency Across Levels. When individual eye-movement patterns in the first second Time Window were used to discriminate individuals in the fifth second Time Window, the discriminability index was not significantly greater than zero (paired $t(28) < 0.88$, $p > 0.38$, two-tailed) and discrimination accuracy (0%) was not significantly greater than chance ($p = 1$). Also, interestingly, the between-time-window discrimination index was significantly lower than the within-time-window discrimination index for the fifth second (paired $t(28) > 2.67$, $p < 0.0063$, one-tailed). This suggests that my participants' idiosyncratic eye-movement patterns were modulated across Time Window.

5.4 - Discussion

The principal aim of the present study was to estimate the diversity and prevalence of different kinds of individual eye-movement patterns to faces in the healthy population. Additionally, we wanted to probe how these patterns relate to recognition performance, and to investigate how various experimental factors modulate the relative distinctiveness among and consistency within individual spatial patterns of eye-movements to faces. Specifically, I investigated the influence of the factors of Race of Face (Caucasian, African, Chinese), Face Orientation (upright, inverted), pre-stimulus Start Position (left, right of upcoming face), Phase (study, test), and Time Window (1st - 5th seconds) so that knowledge of how these factors modulate the relative distinctiveness among and consistency within individual spatial patterns of eye-movements to faces can inform the experimental design and analysis of future studies of individual differences eye-movement patterns. For each of these factors I investigated three aspects of individual differences in eye-movement patterns: i) *Discrimnability* at each level of the given factor (i.e. For each level, are participants' patterns distinct relative to one another?), ii) *Relative Discriminability* between levels of the given factor (e.g. Are participants' patterns more distinct relative to one another for one level than another), and iii) Individual *Consistency Across Levels* of the given factor (i.e. Are individual patterns consistent between levels). Discrimination index and discrimination accuracy measures (see

Methods), which have had increasingly widespread use in the functional neuroimaging field for investigating the relative distinctiveness of neural or hemodynamic activation patterns under various conditions (Haxby et al., 2001; Kriegeskorte et al., 2008), were adapted for my eye-movement data in order to conduct this investigation.

Diversity and prevalence of individual eye-movement patterns

I plotted the peak spatial density of eye-movements across all 48 participants included in my analyses. From this, it is evident that there is great variability in individual differences in eye-movement patterns. The spatial distribution of these peaks was continuous and thus I could not delineate any natural groupings within this distribution. Similarly, when differences in entire fixation patterns were visualized, no clear groupings among participants' patterns were evident. When I imputed groupings based on the facial features underlying the spatial densities, I observed that 52% of spatial eye-movement patterns were eye-focused, 31% were nose-focused, 4% were mouth-focused, and 13% did not cleanly fall into any of these categories. As my participant population was thoroughly screened for neurological and psychiatric disorders before participation, I estimate that these proportions approximate those found in the eye-movements across the normal healthy population. Given that my participants were all Western Caucasian individuals, and given the prior reports of differences in eye-movement patterns between different cultures/races of observers (e.g. Blais, Jack, Scheepers, Fiset, & Caldara, 2008, though see Goldinger, He, & Papesh, 2009), my findings may not generalize beyond the Western Caucasian population.

Individual eye-movement patterns relationship to recognition performance

Deviation from the "classic" T-shaped eye-movement pattern to faces has been related to facial processing impairment in clinical populations (e.g. P. Kim et al., 2013; see Introduction); however, prior studies of individual differences in eye-

movements have failed to find a similar relationship with respect to the idiosyncratic eye-movement patterns of the healthy adult population (P. Kim et al., 2013; Mehoudar et al., 2014; Peterson & Eckstein, 2013). When fixation patterns were ordered according to recognition performance, there was no evidence that particular eye-movement patterns were associated with higher or lower facial recognition performance. When I correlated peak density in the y- and x-dimensions separately with facial recognition performance (d'), I found no significant correlation for either. This lack of evidence for a relationship between individual differences in spatial eye-movement patterns and recognition performance is consistent with the prior studies that have investigated individual eye-movement patterns to faces.

What factors influenced individual differences?

I investigated the influence of the factors of Race of Face (Caucasian, African, Chinese), Face Orientation (upright, inverted), pre-stimulus Start Position (left, right of upcoming face), Phase (study, test), and Time Window (1st - 5th seconds). Participants' spatial eye-movement patterns were discriminable in each level of each of these factors; however, for most factors, there was evidence that the relative degree of discriminability between levels differed. Race of Face and Face Orientation, the only two stimulus factors I investigated, were the only factors that did not suggest differences in discriminability between levels. Additionally, with the exception of Race of Face, I also found that all factors modulated the individual consistency of eye-movements (i.e. changed individual patterns across levels of the given factor).

In my investigation into the influences of experimental factors, I found that for my Western Caucasian participants, Race of Face (Caucasian, African, Chinese) did not significantly modulate the discriminability of eye-movement patterns among participants (i.e. distinguishability arising from the distinctiveness of participants' patterns relative to those of the others) as individuals were discriminable, and equally so, in each Race of Face condition. Further, individual eye-movement

patterns were consistent among the Race of Face conditions as I failed to find evidence that they differed strongly between Race of Face conditions (though see chapter 3, which is J Arizpe, Kravitz, Yovel, & Baker, 2011).

Start Position (left or right of upcoming face) is a factor that showed evidence of modulation of the discriminability of individual eye-movement patterns. Discriminability indices did not significantly differ between left and right start position, though discrimination accuracy did greatly differ such that discrimination accuracy was lower for left start position. Compared to discrimination index, discrimination accuracy is a more stringent measure of discriminating information and requires uniquely individuating information to be present in patterns to produce high values, so these results suggest that right start position induced patterns which were more highly uniquely discriminating, while average differences in distinctiveness across individuals was not significantly modulated. I additionally found that start position modulated individual eye-movement patterns (i.e. individual consistency was reduced between left and right start position conditions compared to within a start position condition), and thus that discriminating information in individual eye-movement patterns was not invariant across start position conditions. This difference in individual eye-movement patterns between start positions can be attributed to the visuomotor influences induced by the start positions that have been characterized in my prior studies in chapters 3 and 4 (J. Arizpe et al., 2012; J. M. Arizpe et al., 2015).

For Phase (study, test), I observed a trend in my discrimination index ($p < 0.070$, two-tailed) toward higher discriminability in test (i.e. in test, participants patterns were overall more distinct relative to one another). Further, I found evidence that individual eye-movement patterns were modulated between phases, as discrimination between phases was significantly weaker than within phase ($p < 0.038$, one-tailed). Because I cannot rule out that this difference in individual eye-movement patterns between phases may have been due to the artificial time restriction to make eye-movements during test phase, rather than the task difference

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between phases (encoding during study phase, recognition during test phase), this effect warrants further investigation in future studies.

Face Orientation, did not modulate the relative distinctiveness of individual eye-movement patterns ($p > 0.50$, one-tailed), as discrimination indices did not differ between upright and inverted face orientations. This is perhaps surprising as it did nonetheless strongly modulate individual eye-movement patterns (between orientation discrimination was significantly weaker than within orientation discrimination, $p < 0.0080$, one-tailed) as would be expected given prior research (Sekuler, Gaspar, Gold, & Bennett, 2004). Thus while individual patterns were not consistent between upright and inverted faces, individual patterns were nonetheless equally discriminable. This highlights the fact that equal discriminability between conditions does not necessarily imply highly similar patterns in the underlying data between conditions.

Time Window significantly modulated the distinctiveness of individual eye-movement patterns such that discriminability decreased with later time windows (slope was significantly negative, $p < 0.0052$, one-tailed). Also discriminability was further weakened when measured between time windows (1st versus 5th second), compared to within time window (5th second), suggesting that individual eye-movement patterns, not only became less distinct with time into a trial, but also differed between time windows.

Methodological considerations

To conduct my investigation into how various experimental factors modulate the relative distinctiveness among and consistency within individual spatial patterns of eye-movements I employed discrimination index and discrimination accuracy measures (see Methods) adapted for my eye-movement data. These measures have recently become highly utilized in the functional neuroimaging field for investigating the relative distinctiveness of neural or hemodynamic activation

patterns under various conditions (Haxby et al., 2001; Kriegeskorte et al., 2008); however, despite the amenability of eye-tracking data (both spatial and temporal) to be submitted to these kinds of analyses as well as the versatility and utility of these measures in eye-tracking studies, they have been rarely utilized in eye-tracking research (Mehoudar et al., 2014). Among other advantages, such measures can be an effective means of detecting differences in eye-movement patterns, summarizing them within a low-dimensional space, or in conducting data-driven analyses. As is also the case of neuroimaging though, these measures also have their limitations and have particularities in how they may be validly interpreted. Specifically, discrimination indices allow for quantifying the relative distinctiveness in data patterns among conditions overall (or among individual participants overall in the case of the present study). This measure is a global one dependent on the patterns of other conditions, and so does not necessarily imply that a given condition is uniquely distinguishable from others. Rather it can be interpreted as a measure that quantifies the degree to which at least some of the other conditions can be differentiated from the given condition based on data patterns. Discrimination accuracy, as I have employed it in the present study, however, does quantify the degree to which a given condition can be *uniquely* distinguished from other conditions based on data patterns. The advantage of this measure is that it is a more intuitive measure and potentially a more meaningful measure, depending on the context in which it is employed. When applying discrimination accuracy measures in the context of investigations of differences across experimental conditions (rather than in the context of participant individual differences, as in the present study) a distribution of discrimination accuracy values can be produced on which standard means hypothesis testing can be conducted. However, its disadvantages are that it is a highly conservative measure, and thus can lack sensitivity. The relationship between discrimination index and discrimination accuracy is also not, in all cases, necessarily straightforward as it is possible for data to yield a high discriminability index with low discrimination accuracy, or vice versa, under certain circumstances. Given the advantages and suitability of such

discriminability measures to eye-tracking studies, more widespread use of them is strongly advised, along with prudence in how they are employed and interpreted.

Theoretical considerations and questions

Previous research has indicated that deviations from classic spatial and temporal eye-movement patterns to faces reflect psychiatric or perceptual disorders and are thought to relate to the social or perceptual impairments seen in the relevant populations (e.g. P. Kim et al., 2013). However, the findings of the current study along with those of other recent studies (Gurler et al., 2015; Kanan et al., 2015; Mehoudar et al., 2014; Peterson & Eckstein, 2013) reveal that individuals within the healthy population also exhibit idiosyncratic patterns that differ from the classic pattern, in which there are T-shaped eye-movement patterns with peak density over the left eye (observer's perspective). Indeed, the classic pattern emerges strongly only when patterns are averaged across participants, as it appears that most individuals' eye-movement patterns deviate from the classic pattern, at least to some degree. My findings indicate that there may not be discrete categories of eye-movement patterns to faces among healthy observers, but rather suggest a continuous distribution of different patterns among the healthy population. Unlike studies of clinical populations, I found no evidence that deviations from the classic spatial eye-movement pattern in my healthy participant sample related to facial recognition performance, which is consistent with other research (Mehoudar et al., 2014), including a study that indicated that an individual fixating at his or her own idiosyncratic fixation location to a face leads to optimal facial recognition for them (Peterson & Eckstein, 2013).

Such a notion of an optimal fixation location for each individual, though, seems inconsistent with other research, which has reported that increased facial recognition performance was associated with increased fixation to the eyes of faces (Sekiguchi, 2011), and with the evidence in favor of the importance of the visual information in the eyes for accurate and rapid facial recognition (Caldara et al., 2005; Davies, Ellis,

& Shepherd, 1977; Fraser, Craig, & Parker, 1990; Gosselin & Schyns, 2001; McKelvie, 1976; Schyns, Bonnar, & Gosselin, 2002; Sekuler et al., 2004; Vinette, Gosselin, & Schyns, 2004). These are however not necessarily incompatible. While the distribution of specific spatial eye-movement patterns to faces may be continuous across individuals, there is still a bias in the population distribution overall to fixate the eyes, as is apparent in the classic eye-movement pattern commonly observed when participant data is averaged. Thus associations between fixation to the eyes and information use at the group level of an experiment can reflect this bias to fixate the eyes at the population level, even though many individuals do not fixate the eyes much.

Given that fixation location does not necessarily correspond to what or how visual information is processed (Caldara, Zhou, & Miellet, 2010) it remains unclear if the same facial information is used or if the same neural processing is employed during face recognition, regardless of whether an individual's idiosyncratic eye-movement patterns are eye-focused or are focused elsewhere on the face. If we consider racial/cultural differences in eye-movement patterns to faces as a special case of individual differences in eye-movements, then one prior study (Caldara et al., 2010) provides evidence that there is consistency in the facial feature information principally utilized during face identification between groups of participants' whose preferred eye-movement patterns greatly differed. More specifically, though the Eastern Asian participants tended to fixate the center of the face more than the Western Caucasian participants, both the Eastern Asian and Western Caucasian participants utilized the same eye facial feature information to identify faces, suggesting that the Eastern Asian participants preferred to use parafoveal vision to extract that same eye feature information. Future studies of individual differences in eye-movements are needed to confirm the generality (i.e. independent of race/culture) of such a consistency in the diagnosticity of specific facial information across individuals with various idiosyncratic eye-movement patterns. How such diversity in idiosyncratic eye-movement patterns may relate to acquired or inherited

differences in ocular or cortical visual processing (e.g parafoveal acuity or cortical receptive field properties) also warrants investigation in future studies.

Though the differences in idiosyncratic patterns of eye-movements in the healthy population do not seem to be associated with task performance (Blais et al., 2008; Peterson & Eckstein, 2013; Sekiguchi, 2011) as has been often reported in clinical populations (see Introduction), it is possible that some of the mechanisms driving the development of the atypical eye-movement patterns in the clinical population may be at play in driving the diversity in eye-movements in the healthy population, at least for some individuals. At least two studies provide evidence for this possibility. One study (Dalton, Nacewicz, Alexander, & Davidson, 2007) reports that though the unaffected siblings of individuals with Autism did not exhibit the reduced facial recognition performance of their autistic siblings, they nonetheless exhibited reduced fixation duration over the eyes relative to a control group, just as their Autistic siblings had. Further, brain imaging analyses revealed that the unaffected siblings exhibited reduced BOLD signal change in the right posterior fusiform gyrus in response to viewing faces as well as reduced Amygdala volume relative to the control group, just as their Autistic siblings had. A sizable portion of the variance in BOLD signal change in regions of the fusiform gyrus could be accounted for by the variability in looking at the eyes for all groups though; suggesting that the individuals' preferred eye-movement patterns influenced the BOLD signal changes. A second study (Adolphs, Spezio, Parlier, & Piven, 2008) reports that unaffected parents of individuals with autism, whether they exhibited aloof personality traits or not, exhibited an increased use of mouth facial information relative to controls during facial emotion judgment, in much the same way individuals with autism do.

Equally unclear and interesting is whether these individual differences in eye-movements emerge early in development, how heritable they are, and if they are associated with personality, cognitive traits, or developmental abnormalities.   One study (Beevers et al., 2011) reports differences in eye-movements to emotional faces between groups of individuals with different serotonin transporter promoter

region polymorphisms, indicating a link between particular alleles and particular preferred eye-movement patterns.

Practical Considerations

Are there any practical implications for the potential to associate individuals to their eye-movement patterns? With respect to ethical implications within the laboratory, eye-tracking data from experiments, even though anonymized, could, in certain contexts, constitute personally identifiable information, where an eye-tracking pattern, determined from another source, can be associated with a given person. This potential however, could also have useful applications within technological or security domains as individuals' idiosyncratic eye-movement dynamics could serve as biometric signatures. While my findings suggest that the spatial patterns of eye-movements may not alone *uniquely* identify individuals in the majority of instances, even within just my participant sample, incorporating temporal and occulo-motor dynamic information into the individual's eye-movement biometric may enable greater discriminability among individuals. Given the currently expanding prevalence of eye-tracking technology, even within mobile phones, this potential could be exploited in future practical applications.

Conclusion

I found a strikingly variable and continuous distribution of individual differences in the spatial pattern of eye-movements in my participants. Imputed facial feature based categories of eye-movement spatial patterns of my participants indicated that 52% were eye-focused, 31% were nose-focused, 4% were mouth-focused, and 13% did not cleanly fall into any of these categories. I also found that the experimental factors that I investigated (Race of Face, Face Orientation, pre-stimulus Start Position, study or test Phase, and Time Window) variously influenced the relative distinctiveness among and consistency within individual spatial patterns of eye-movements to faces.

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Chapter 6 – Conclusion

6.1 – Summary and Conclusion

Summary

I have investigated eye-movement patterns as a window into the cognition of visual information processing during facial recognition. The course of this investigation also notably led to the discovery of multiple robust influences on eye-movement patterns beyond cognitive (stimulus and task) factors, including visuomotor dynamics (arising from the starting position of the eyes relative to the stimulus) and striking individual differences across observers that must be considered when interpreting eye-movement data.

The first study investigated the Other Race Effect (ORE), which is the robust and well-established finding that one is generally poorer at facial recognition of individuals of another race than of one's own race. Research on the ORE has been conducted for over four decades because understanding the origin of the ORE is expected to elucidate fundamental face processing mechanisms and the influence of experience on such mechanisms. Several recent studies of the ORE in which the eye-movements of participants viewing own- and other-race faces were tracked have, however, reported highly conflicting results regarding the presence or absence of differential patterns of eye-movements to own- versus other-race faces. This discrepancy, of course, has lead to conflicting theoretical interpretations of the perceptual basis for the ORE. In particular, two highly conflicting views have emerged from prior eye-tracking studies of the ORE, namely (i) that face processing depends on the culture of the observer, but is equivalent by race of face observed (Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Caldara, Zhou, & Miellet, 2010; Hills, Cooper, & Pake, 2013; Hills & Pake, 2013; Kelly, Jack, et al., 2011; Kelly, Liu, et al., 2011; Miellet, Lao, Zhou, He, & Caldara, 2012; Miellet, Vizioli, He, Zhou, & Caldara, 2013; Rodger, Kelly, Blais, & Caldara, 2010; Tan, Stephen, Whitehead, &

Sheppard, 2012), and (ii) that face processing differs by own- vs. other-race face (Brielmann, Bülthoff, & Armann, 2014; Fu, Hu, Wang, Quinn, & Lee, 2012; Hu, Wang, Fu, Quinn, & Lee, 2014; Nakabayashi, Lloyd-Jones, Butcher, & Liu, 2012), but does not differ by race of observer (Goldinger, He, & Papesh, 2009; Or, Peterson, & Eckstein, 2013). I report that there are indeed subtle spatial differences in fixation patterns to own- (Caucasian) versus other-race (African and Chinese) faces of my Caucasian participants. Notably though, I additionally provide evidence that the prior conflicting reports can be accounted for by the differences in the statistical sensitivity of the analysis methods employed across studies, such that Area of Interest (AOI) analyses are more sensitive at detecting the subtle differential fixation patterns than spatial density (heatmap) analyses. Because fixation patterns for both Chinese and African faces differed from those of own-race Caucasian faces, but recognition performance was reduced only for Chinese faces, these results are consistent with an account of the basis for the ORE that lies both in differential employment of attention to specific facial features between races of faces and also in differential diagnostic value of facial features for different races. The strengths of these eye-movement differences were weak however, suggesting that own- versus other-race differences for other perceptual mechanisms beyond just featural processing more strongly contribute to the ORE and require further investigation. Also requiring further investigation is the basis for the conflicting reports regarding the presence of an influence of the culture of the observer on eye-movements to faces as my study only included one culture/race of observers.

In the study of eye-movements during visual perception more generally, as was the case in the ORE experiment above, a key assumption is that fixation patterns reflect cognitive processing and, thus, index the most informative stimulus features for task performance. During face recognition, initial fixations near the center of the nose have been taken to indicate this location is optimal for information extraction. However, the use of fixations as a marker for information use rests on the assumption that fixation patterns are predominantly determined by stimulus and task. Because evidence that visuomotor factors (pre-stimulus start position) strongly

modulated subsequent eye-movement patterns was observed in the eye-movement data of the ORE experiment, I conducted an additional experiment to specifically investigate these visuomotor influences on eye-movement patterns. In this second experiment, I tested the effect of starting position (left of, right of, above, below, and centered upon the internal features of the upcoming face) on subsequent fixation patterns during a face recognition task with upright and inverted faces. While I observed differences in fixations between upright and inverted faces, likely reflecting differences in cognitive processing, there was also a strong effect of start position. Over the first five saccades, fixation patterns across start positions were only coarsely similar, with most fixations around the eyes. Importantly, however, the precise fixation pattern was highly dependent on start position with a strong tendency toward facial features furthest from the start position. For example, the often-reported tendency toward the left over right eye was reversed for the left starting position. Further, delayed initial saccades for central versus peripheral start positions suggest greater information processing prior to the initial saccade, highlighting the experimental bias introduced by the commonly used center start position. Finally, the precise effect of face inversion on fixation patterns was also dependent on start position. These results demonstrate the importance of a non-stimulus, non-task factor in determining fixation patterns. The patterns observed likely reflect a complex combination of visuo-motor effects and simple sampling strategies in addition to cognitive factors. These different factors are very difficult to tease apart and therefore reveal that great caution must be applied when interpreting absolute fixation locations as indicative of information use, particularly at a fine spatial scale.

A third experiment extended the investigation into these visuomotor factors that robustly and characteristically influence eye-movement patterns to faces. In this experiment, I manipulated lateral starting side and distance from the midline of face and control (butterfly) stimuli in order to further investigate the nature and generality of such visuomotor influences. First, I found that increasing starting distance from midline (4, 8, 12, 16 degrees of visual angle) strongly and proportionately increased

the distance from midline of the first ordinal fixation, which tended to fall on the half of the face nearest the starting side for all distances. I did not find influences of starting distance on subsequent fixations though, suggesting that eye-movement plans are not strongly affected by starting distance following an initial orienting fixation. Further, I replicated my prior effect of starting side (left, right) to induce a spatially contralateral tendency of fixations following the first ordinal fixation. However, I additionally established that these visuomotor influences did not depend upon the predictability of the location of the upcoming stimulus, and were present not only for face stimuli but also for my line-symmetrical control stimulus category (butterflies). Finally, for faces, I found a relationship between left starting side (right sided fixation pattern tendency) and increased recognition performance, which likely reflects a cortical right hemisphere (left visual hemifield) advantage for face perception.

Finally, extensive additional analyses were applied to the data of the first two experiments to investigate individual differences in eye-movement patterns to faces. The spatial pattern of eye-movements to faces considered typical for neurologically healthy individuals is a roughly T-shaped distribution over the internal facial features with peak fixation density tending toward the left eye (from the observer's perspective). However, a prior study on which I collaborated (Mehoudar, Arizpe, Baker, & Yovel, 2014) and another recent study (Peterson & Eckstein, 2013) have indicated that striking deviations from this classic pattern are common within the population and are highly stable over at least several month, thus revealing that this classic pattern reflects the average of the various idiosyncratic eye-movement patterns across individuals. Thus in my fourth study, I analyzed the spatial patterns of eye-movements for 48 participants from the first two experiments to estimate the diversity and prevalence of different kinds of individual eye-movement patterns to faces in the healthy population. I found that approximately 52% of my participants exhibited eye-focused, 31% exhibited nose-focused, 4% exhibited mouth-focused, and 13% exhibited other/composite eye-movements. I did not find a relationship of particular idiosyncratic eye-movement patterns with recognition performance. Finally

I examined how various experimental factors (Race of Face, Face Orientation, pre-stimulus Start Position, study or test Phase, and Time Window) modulated the relative distinctiveness among and consistency within individual spatial patterns of eye-movements to faces. I suggest that the discrimination index and discrimination accuracy measures employed in this study on individual differences have advantages as measures in eye-movement studies more broadly as means of summarizing complex relationships and differences in eye-movements in a low dimensional space and as a means of data-driven analysis. However, I also caution that correct interpretation of these measures requires an understanding of the relative natures of these measures and the different statistical sensitivity of each. These findings, along with others that indicate that idiosyncratic patterns are individually optimal for facial recognition (Peterson & Eckstein, 2013), raise interesting questions regarding whether and how such differential eye-movement patterns may relate to individual differences in information utilization and neural processes underlying the cognitive processing of faces and, indeed, all visual stimuli.

Factors potentially decoupling fixation location from visual information use

As discussed above, the results of chapters 3 and 4 identify visuomotor factors that explain why absolute fixation locations do not necessarily indicate the most important information for or the information actually used during a perceptual task; however, it is interesting to consider that the results of the other empirical chapters are consistent with the existence of other factors that can effect a similar decoupling of fixation location from visual information use. The results of chapter 2 are, specifically, consistent with a role of experience and familiarity with a category of stimulus in how eye-movements are employed, regardless of the actual information important for or actually used in the perceptual task. The results of chapter 2 revealed, for example, that though small differences in fixation pattern were observed between Caucasian and African faces, African faces nonetheless elicited fixation density predominantly over the eyes. Given the evidence from other studies (Hills et al., 2013; Hills & Pake, 2013) that fixation at the nose leads to better

identification of African faces than fixation over then eyes, the peak in fixation over the eyes seen in my participants perhaps does not correspond to the most relevant information for the recognition task. Because my participants resided in Washington, D.C. their perceptual exposure to African faces, and thus their familiarity with the African facial physiognomy may have enabled them to adequately extract nose and mouth information, even though eye-movements patterns were only weakly different from the patterns to own-race Caucasian faces. Further, though some evidence (Caldara et al., 2010; Miellet et al., 2012, 2013) suggests that the diagnostic facial information does not differ between Caucasian and Chinese faces, my participants nonetheless employed slightly different eye-movement patterns between own-race Caucasian and other-race Chinese faces. Thus, the lack of familiarity with Chinese faces as such, rather than any substantial difference in the location of the diagnostic visual information associated with the physiognomy of Chinese faces, perhaps drives these differences in eye-movements.

Additionally, the individual differences in eye-movements observed in Chapter 5 considered along with evidence for the importance of the eye information in facial perception (Sekiguchi, 2011) are consistent with the possibility that even though a given participant may employ their idiosyncratic fixations away from the eyes, the eye information is what is nonetheless utilized. If so, it is possible that there can be preferred retinal loci other than central foveal for the extraction of certain visual information, and that such loci can be idiosyncratic for given individuals. This state of affairs would constitute a clear decoupling between fixation location and visual information use that may not be consistent in nature or degree among individuals.

Race of observer eye-movement differences a special case of individual differences?

The precise mechanisms underlying such idiosyncratic eye-movement patterns as detailed in chapter 5 remain to be elucidated, though it is perhaps helpful to conceptualize the differences in eye-movements to faces for different races of

observers discussed in chapters 1 and 2 as a potential special case of individual differences in eye-movements. Particularly because the kind of explanations proposed for the differences in fixation patterns to faces among different race observers may also underly the individual differences in eye-movements such as reported in chapter 5. Specifically, influences of culture, cognitive style, genetics, and personal experience may also be relevant explanatory factors in the diversity of eye-movement patterns in the healthy population, independent of the race of the observer.

Assuming that the race of observer differences in visual perception could indeed elucidate individual differences in eye-movements more generally, other prior studies (Caldara et al., 2010; Miellet et al., 2012, 2013) provides evidence that there is consistency in the facial feature information principally utilized during face identification between groups of participants' whose preferred eye-movement patterns greatly differed. More specifically, though the Eastern Asian participants tended to fixate the center of the face more than the Western Caucasian participants, both the Eastern Asian and Western Caucasian participants utilized the same eye facial feature information to identify faces, suggesting that the Eastern Asian participants preferred to use parafoveal vision to extract that same eye feature information. An explanation proposed for this racial difference in visual processing is the supposed differences in cognitive style associated with differences in Eastern and Western culture such that Eastern individuals generally tend to assume a more holistic and Westerners a more analytic cognitive style. Thus the hypothesis that idiosyncratic cognitive styles relate more generally to idiosyncratic eye-movement patterns, independently of the race of the observer, may be worth future investigation. Given that such inter-individual cognitive style differences must correspond to differences in neural processing, how such diversity in idiosyncratic eye-movement patterns may relate to acquired or inherited differences in ocular or cortical visual processing (e.g parafoveal acuity or cortical receptive field properties) also warrants investigation in future studies.

Along similar lines, given that genetic factors partially define race and that there are race of observer differences in eye-movement patterns to faces, this perhaps also indicates that genetic diversity not only across races, but also within a given race, could influence indiosyncratic eye-movement patterns more generally. In accord with this notion, one study (Beevers et al., 2011) reports differences in eye-movements to emotional faces between groups of individuals with different serotonin transporter promoter region polymorphisms, indicating a link between specific alleles and specific preferred eye-movement patterns.

Finally, the clear role of experience with other-race individuals in the magnitude of the Other Race Effect and the eye-movement differences reported among different race observers, as discussed in chapter 1, suggest that perceptual and/or social experience drives preferred eye-movement patterns more generally. If so, there is a potential role of individual experience in the development of the kind of individual differences in eye-movements to faces as I reported in chapter 5. While experience-dependent awareness for racially-specific diagnostic facial information (Hills et al., 2013; Hills & Pake, 2013) and experience connected with culture (Blais et al., 2008) have been proposed as experiential factors potentially underlying race of observer differences in eye-movement patterns to faces, such specific factors do not seem to apply in the case of individual differences more broadly. This is because in my participant sample from chapter 5, the cultural context for the observers did not ostensibly differ and the faces being observed were all own-race Caucasian faces. Therefore, precisely how individual experience could more broadly shape idiosyncratic eye-movements to faces is unclear.

Conclusion

In this thesis, I have investigated factors influencing eye-movement patterns during face perception and the relationship of eye-movement patterns to facial recognition performance. The basis of the other-race effect was investigated in chapter 2 and differences in eye-movement patterns during recognition of own- versus other-race

(African, Chinese) faces were found for Caucasian participants. However, these eye-movement differences were subtle and their detection was analysis-dependent, indicating that the discrepancy in prior reports regarding the presence or absence of such differences are due to variability in statistical sensitivity of analysis methods across studies. Visuomotor influences, specifically pre-stimulus start position and distance, were investigated in chapters 3 and 4. I found that visuomotor factors strongly influence subsequent eye-movement patterns during face perception. In particular, an overall bias in fixation patterns to the opposite side of the face induced by start position and an increasing undershoot of the first ordinal fixation with increasing start distance were found. These visuomotor influences were not specific to faces and did not depend on the predictability of the location of the upcoming stimulus. These findings highlight the relevance, not only of stimulus and task factors, but also robust and characteristic visuomotor factors, in the interpretation of eye-movements as indices of visual attention. The final study (chapter 5) investigated individual differences as a factor in eye-movements to faces. The prevalence of different kinds of patterns and the impact of various stimulus, task, and visuomotor factors on the discriminability and consistency of individual eye-movement patterns were measured. Together the findings reported in this thesis uncover neglected factors important to the interpretation of eye-movement patterns in studies of visual cognition, including factors that go beyond cognitive (stimulus and task) factors, namely visuomotor dynamics (arising from the starting position of the eyes relative to the stimulus) and striking individual differences across observers.

6.2 - References

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