Title: Reason without much language

Abstract

Language is more than a system used for interpersonal communication. Linguistic representations can also form a part of reasoning in other cognitive domains. However, it is unclear whether the role of language in non-verbal domains is a necessary one, or whether it represents an optional resource that is recruited under demanding or highly intentional processing conditions. The possible role of language in categorisation, belief reasoning, calculation and cross-domain integration is explored, together with the various sources of evidence that can inform debates on language-thought relationships. Evidence from comparative and developmental psychology, together with that from neuroscience and 'virtual language impairment' (verbal shadowing) suggests reduced or absent language resource can disrupt performance in non-verbal domains. Similarly results of some investigations of people with developmental or acquired language impairments suggest an association with broader cognitive impairment. However, there is a substantial and growing body of evidence from across experimental fields indicating autonomy between language and reasoning. Residual reasoning in the face of severe aphasia is described, together with possible objections to the evidence from aphasia informing language and thought debates.

Highlights

Different conceptions of the role of language in thought are described, together with domains of cognition that are claimed to be language-mediated. Various sources of experimental evidence are explored. The impact of severe aphasia on reasoning is examined. Reasoning can be preserved despite severe language impairment.

Keywords: Aphasia; Language; Thought; Reasoning

1. Introduction: Lexicon and grammar in thought

The human species is marked out by possession of sophisticated cognition and a similarly elaborate culture, characterised by achievements such as science, religion, arts, and universities. The unique profile of competencies also includes language. Other species show primitive lexical abilities, as observed in the various predator calls of vervet monkeys, or the learning of symbol-meaning associations by some dogs and chimpanzees (Gardner & Gardner, 1969; Seyfarth & Cheney, 2003; Kaminski, Call and Fischer, 2004), and also some sequential processing capacities. For example, Campbell's monkeys systematically combine a small set of calls in order to produce a broader range of signals (Ouattara, Lemasson, & Zuberbühler, 2009), and some songbirds can detect sequential dependencies in novel songs (van Heijningen, de Visser, Zuidema, & ten Cate, 2009). However, these capacities are strictly limited in comparison to those of humans. Signals are characteristically tied to specific contexts and functions, such as calls triggered by the presence of a predator. By contrast, humans use language to achieve a variety of socio-pragmatic functions, referring to absent or abstract entities in syntactically complex constructions (Tomasello, 2008). Given the coincidence of cognitive and cultural complexity together with language, some scientists propose that language is the causal mechanism that has engineered an enhancement of the human mind.

How might language have changed the human mind and what might be the role of the two core linguistic mechanisms – grammar and lexicon – in this proposed augmentation? The lexicon could be the source of symbols that allow the manipulation of abstract concepts or reference to entities or events that are not currently present in the physical context. With an inventory of such terms inferences about the invisible mental states of others become possible. Words such as ‘think’, ‘know’ and ‘remember’ might enable reasoning about what others know and might not know, and perhaps lie at the heart of ability to infer the intentions of others. Clark (1997) points to evidence that only language-trained chimps who had mastered the terms ‘same/different’ were able to solve particular classes of sorting problem (Premack, 1988). Furthermore, possessing a word such as ‘dog’ allows abstraction away from the perceptual level where these creatures present in all different sizes and shapes and with varying behavioural traits, uniting this perceptual diversity into a coherent notion of ‘dogginess’. In this way, words might assist in carving up the complexities of signals from the environment and cue the formation of conceptual categories that are relevant to a particular culture or to humans generally (Whorf, 1956).

Other claims focus on the role of grammar in the augmentation of mind. Initial findings from experiments with non-human species and, in particular, the limited achievements of language-trained chimpanzees in systematically combining symbols (Greenfield & Savage-Rumbaugh, 1990), hinted that grammatical capacity might lie at the core of distinctively human cognition (Carruthers, 1996). The ability to concatenate and embed linguistic expressions might allow increasingly complex forms of thought. For example, long chains of inferences in conditional or causal reasoning might become possible with the availability of sentential forms and their various connectors. Furthermore, grammar might permit the merging of isolated and basic-level knowledge to form unitary higher-order constructs. In the case of forming inferences as to the mental states (such as beliefs) of others (‘theory of mind’ (ToM reasoning), embedded representations of the type ‘[Sally thinks [that the marble is in the basket]]’ might be the substance of sociocognitive reasoning.

A further possibility is that the combined resource of both grammar and lexicon enhance cognition. In the case of reasoning about beliefs, a syntactic mechanism might generate the embedded structure that describes another's mental state, but the predicate governing the subordinate clause is a cognitive verb (Astington & Jenkins, 1999). Isolating components of the language faculty might result in more tractable theoretical and descriptive problems, but in reality these components are closely integrated (e.g., Goldberg, 2006). The rapid emergence of grammatical structure in a new language such as Nicaraguan Sign Language (within two generations of language users) points to the close-coupling of the two systems in phylogeny (Senghas, Kita & Özyürek, 2004), as well as in the acquisition of language by typically-developing children (Tomasello, 2008). With regard to the pathologies of language such as aphasia, although impairments may be categorised by predominant symptoms into syndromes such as agrammatism or anomia (with the focus of impairment on grammatical or lexical systems respectively), careful testing of individual cases reveals disruption of both aspects of language processing (Schuell, Jenkins & Jiménez-Pabon, 1965). If language does enhance cognition, the combined resources of both grammar and lexicon are likely to be necessary for that augmentation.

2. Conceptions of language in thought

Carruthers (1996) describes three conceptions or characterisations as to the role of language in thought. The communicative conception holds that language is predominantly for purposes of interpersonal exchange. By this view, language operates as an input-output mechanism to a central system which undertakes higher-order reasoning. The central system might employ abstract, symbolic representations different from those of natural language – rather those of a 'language of thought' or 'Mentalese' (Fodor, 1983; Pinker, 1994). Alternatively, it might involve visual mental model manipulations (Johnson-Laird, 1983), or operations derived from activations within non-symbolic connectionist architecture (McClelland, 2010).

However, the communicative view is challenged by a body of experimental evidence indicating that language representations do appear to play a mediating role outside of interpersonal exchange (Vygotsky, 1962). For example, Berk (1994) observed that children who used language in support of performance on a non-verbal task, found a solution more rapidly than non-verbalising children. However, Kim (2002) observes that positive effects of verbalisation on non-verbal performance might be culture-specific: American students of East Asian origin displayed interference on a non-verbal reasoning task when required to describe aloud their problem-solving strategies. A series of experiments using the verbal shadowing paradigm show that performance on an apparently non-linguistic task can be disrupted when participants concurrently have to repeat back heard sentences. The demand for verbal shadowing engages language resources, with the result that linguistic representations are not available to the second domain. For the results of such experiments to be convincing, the disruption caused by verbal shadowing must be greater than that elicited by a non-linguistic shadowing task of equal difficulty (e.g., tapping out a rhythm) in order that the source of the interference is not due to general factors such as divided attention or concurrent motor demands. Some experiments employing the verbal shadowing paradigm have shown disruptions in ToM reasoning (Newton & de Villiers, 2007) or cross-domain integration of information in visual searching (Hermer-Vasquez, Spelke, & Katsnelson, 1999). However, other investigations have failed to replicate these results (Learmonth, Nadel, & Newcombe, 2002; Bek, Blades, Siegal & Varley, 2010; Fouget d'Arc & Ramus, 2011; Dungan & Saxe, 2012; Bek, Blades, Siegal & Varley, 2013). Furthermore, Kim (2002) again cautions that there may be culture-specific effects of verbal shadowing/articulatory suppression on performance in non-verbal domains. She reports that while European American students' performance was disrupted by an articulatory suppression task (reciting the alphabet), East Asian American students displayed no significant impairment on a matrix reasoning test when linguistic resources were blocked by the concurrent task.

Carruther's second distinction – a cognitive conception of language – can account for the evidence that language representations appear to be involved in non-language domains. However, this role goes beyond 'involvement'. The claim is that linguistic representations are necessary for, and constitutive of, certain forms of reasoning. Without those representations, particular forms of thought could not be entertained. Carruthers does not suggest that all forms of reasoning necessarily involve language: for example, visuo-spatial problem-solving such as matrix reasoning is less likely to employ linguistic resources. Instead, certain classes of problems, such as ones involving long inference chains, cross-domain integration, embedding, or perhaps a degree of abstraction away from surface properties of stimuli, might mandatorily require the resources of the language faculty.

There are a number of ways in which strong claims for language mediation of a particular domain can be tested. The verbal shadowing paradigm might be employed with healthy people in order to create a 'virtual aphasia' and deprive participants of easy access to language resources. Another way of creating a form of virtual aphasia is to apply inhibitory transcranial magnetic stimulation (TMS) to brain structures in the left perisylvian cortex that form the core of the language neural network. Alternatively, the cognitive performances of people with real language disorders – developmental conditions such as specific language impairment (SLI), or aphasia following lesion of cortical language areas – can be explored for insights as to whether they are able to sustain particular forms of thinking (e.g., van der

Lely, Rosen, and McClelland, 1998; Varley & Siegal, 2000; Lupyan & Mirman, 2013). If, for example, representing the mental states of others necessarily requires syntactically-structured language forms, then individuals with severe agrammatic aphasia should not be able to engage in this form of reasoning.

A further test of the cognitive conception of language might come from cross-language studies. In instances where one language divides up perceptual space in a different way to another, do matching differences emerge in non-verbal categorisation of events and attributes described by those words? Cross-language studies largely address the role of the lexicon in thought as claims of radical difference in core grammatical features between languages remain controversial (Everett, 2005). Languages may differ in their colour or number word vocabularies. Some studies of members of the Amazonian Pirahã tribe, whose vocabulary of number words is small, have reported parallel restrictions in numerical cognition (Gordon, 2004). However, Butterworth, Reeve, Reynolds & Lloyd (2008) explored numerical cognition in monolingual speakers of Australian languages with small number vocabularies and found no difference in performance in comparison to a group with access to English number words. A particular difficulty in the interpretation of links between vocabulary and cognition in cross-cultural investigations, especially in contexts where there is radical cultural difference between groups, is that it is unclear as to what is conditioning the association: does absence of vocabulary limit cognition, or does the absence of a particular cultural practice (e.g., trade) limit both number vocabulary and the frequency of reflections on relative quantities and values (Pyers, Shusterman, Senghas, Spelke & Emmorey, 2010)? Cross-language studies in which there are common cultural practices avoid this difficulty. Papafragou, Hulbert and Trueswell (2008) tracked eye movements of Greek and English speakers while they observed animations of motion events. These languages differ in how they encode motion. In English, manner is encoded within the verb and path information by devices such as adverbial phrases. In Greek, the situation is reversed, with path encoded in the verb and manner via various adjuncts. Papafragou et al. observed differences between speakers of the two languages in the phasing of when they looked at path-relevant information in the films, and when they looked to manner-relevant features. However, differential looking patterns only emerged under specific conditions: first, when participants were required to give a verbal account of the event; second, after the film and when awaiting an expected non-verbal memory probe. When participants observed events in real-time with no demand for verbal report or expectation of memory test, no cross-language differences emerged.

A final source of evidence for the cognitive view of language is in investigations of minds with few (pre-verbal infants) or no (comparative psychology) language resources. Experiments with infants using non-verbal methods such as preferential-looking or habitation paradigms provide surprising insights into the competencies of pre-verbal minds. A number of studies have shown emergence of precursors of forms of cognition that are claimed to be language-dependent long before the infant possesses the lexical or grammatical ability to support that reasoning. For example, Wynn (1992) revealed evidence of early and simple numeric competence in 5-month-old infants. Onishi and Baillargeon (2005) showed that 15-month-old children have insights into the mental states of others without competence in cognitive verbs or understanding or use of embedded sentences. Other experiments have replicated and extended these findings. For example, Liszkowski, Carpenter, and Tomasello (2008) showed that 12-month-old children display an ability to attribute knowledge states to others and accordingly communicate differently with informed and uninformed partners.

These findings indicate that the cognitive conception of language – the strongest version of the hypothesis of language-thought dependency – may not hold in the domains of cognition that currently have been explored. Carruthers offers a further and carefully nuanced characterisation of the inter-relationship between language and thought in his 'supra-communicative' view. This suggests that language is primarily for purposes of interpersonal communication, but language representations can scaffold and support other forms cognition without being a necessary component of that reasoning (Siegal & Varley, 2002). Clark (1997) elaborates the supra-communicative position, suggesting a number of ways in which cognition is augmented by language. One possibility is that the encoding of ideas into language makes them concrete and available to scrutiny, discussion, and reformulation. It also permits transmission of culture across generations as novices can benefit from the insights and experience of their forebears through either spoken or written transfer (Vygotsky, 1962). A second example is the effect that verbal labels have on categorisation: if a set of perceptually diverse entities are united by the same label (e.g., dogs, games), a new exemplar might be rapidly assimilated into existing knowledge on the basis of the shared name. Clark also suggests that linguistic encoding allows access to short-term and long-term memory mechanisms and some experimental reports of language-mediation in non-linguistic domains may reflect the mnemonic benefits provided by language.

In the case of short-term memory and mathematical cognition, Klessinger, Szczerbinski, & Varley, (2012) conducted an experiment in which adults were presented with 2 digit + 2 digit addition problems. The experiment was conducted with English-speaking participants and one set of problems contained the number 'seven', which is labelled with a phonologically-long, two-syllable number word in English, while the other sets contained no sevens, resulting in phonologically-shorter problems (i.e., 14 + 17 vs. 12 + 19). The impact of phonological length on calculation times was determined. If calculation employed phonological representations which were maintained and manipulated in phonological working memory, solution times would be longer on the phonologically-long problems. The results indicated that phonological mediation was variable across different participant groups. It was more apparent in less proficient calculators who had generally slower calculation times. This suggests that less able calculators were more likely to call up the resources of the language system to support calculation performance. Older participants (median age 56-years) were generally faster and more accurate than younger calculators (median age 24-years) and showed no influence of phonological factors on calculation. They were likely to have been exposed to educational practices that led to the development of automatized calculation routines, which did not require the scaffolding provided by language.

The cross-linguistic study reported by Papafragou et al. (2008), exploring eye movements in Greek and English-speakers while observing action events, provides further evidence of mnemonic benefits of language. Recall that eye movements differentiated speakers of the two languages when participants were preparing a verbal report of the event, but also when participants were awaiting a non-verbal memory probe. The latter finding suggests that participants were engaged in rich encoding of information, using language forms as well as visual memory, to support subsequent performance on the non-verbal task.

The results of these studies suggest that healthy humans – those with easy access to language resources – will often employ language representations to scaffold performance on intrinsically non-linguistic tasks, particularly where automatic processing requires some degree of augmentation due to task difficulty or a degree of conscious control is directed to performance. Other forms of representational support might also be used in reasoning: a visuo-spatial problem might evoke visual imagery. But language might be used particularly in instances where maintenance of serial information is required. This is illustrated in mathematics where performance in calculation is disrupted to a greater degree by a concurrent verbal task when problems are represented in a horizontal/sequential format rather than a vertical array (Trbovich & LeFevre, 2003). However, a crucial question is whether the use of language is a necessary component of performance - consistent with a cognitive conception - or whether linguistic representations are optional and recruited where additional resource is needed – consistent with a supra-communicative view.

3. Domains of cognition

Even under the strong cognitive view of language, not all forms of thought and reasoning are likely to involve the computations and representations of the language system. The critical cases are domains such as categorisation, where performance might be determined by the availability of word forms, or reasoning that might require the resource of grammar through hierarchical structuring and merging of information (e.g., ToM, mathematics, causal reasoning, cross-domain integration).

3.1 Language and categorisation

A recent example of a categorisation study in the Whorfian tradition is provided by Lupyan and Mirman (2013). They compared the performance of people with relatively mild anomic aphasia to that of healthy controls on a task involving selection of pictured items that belonged to a particular class. Where categorisation could be made on the basis of many shared features (e.g., things which are fruits), aphasic performance was indistinguishable from that of controls. However, when sorting on a criterion based upon fewer shared features and where colour, function, or shape might not overlap (e.g., things made of wood), aphasic participants were impaired relative to controls. Performance was positively associated with degree of naming impairment, suggesting a specific interaction between the lexicon and categorisation. However, aphasic behaviour was compared only to that of healthy controls and so it remains unclear as to whether general limitations stemming from brain damage versus specific lexical impairment are the source of the between-group differences. Although there was a positive correlation between naming scores and categorisation, the results also reveal a strong association with overall aphasia severity and performance. One possibility is that more general issues of brain damage, rather than specific lexical impairment, might explain the differences between groups.

3.2. Inferring the mental states of others

Some of the most interesting claims for the cognitive view of language focus on grammar. The key idea is that grammatical competence and the resulting capacity to generate structured, hierarchical representations has enabled massive enhancement of the human cognitive repertoire (Carruthers, 2002). By this view, thoughts such as representing the beliefs of others, mathematical cognition and cross-domain integration might depend upon the computations and representations of the language system.

In the case of mental state or ToM reasoning, language creates the capacity to embed one proposition within another, as well as providing an inventory of mental state terms. Astington and Jenkins (1999) and de Villiers and Pyers (2002) point to the association between the ability to pass false belief tests and the emergence of complement clauses in children's language, with both occurring between the ages of 3-4 years. They suggest that the ability to represent another's belief depends upon the availability of language representations of the type 'Richard thinks that there are Smarties in the tube'. In subsequent work, Newton and de Villiers (2007) explored the impact on theory of mind reasoning of a temporary 'knock-out' of language in healthy adults through use of a verbal shadowing procedure. Participants shadowed a prose passage while observing a scenario in which one of the characters has a false belief. They reported that prose shadowing disrupted belief reasoning, while concurrent performance on a non-linguistic shadowing task led to no significant loss of accuracy. Subsequent attempts to replicate this finding were not entirely successful. Forgeot d'Arc and Ramus (2011) reported that verbal shadowing diminishes performance on both belief and non-belief reasoning tasks, and that belief attribution remained at an above chance level even when language resources were engaged by a concurrent task. Dungan and Saxe (2012) reveal that ToM performance was disrupted to an equal degree by both linguistic and non-linguistic concurrent tasks. Furthermore, the evidence from studies of preverbal infants show insight into the intentions and beliefs of others long before understanding or use complex sentences containing subordinate clauses (Onishi and Baillargeon, 2005). One solution to the discrepancy between experimental results is to distinguish between automatic (but relatively shallow) processing of mental states, and the explicit (and elaborate) reasoning about beliefs (Apperly & Butterfill, 2009). Preverbal infants might possess the cognitive resources for the former, while the latter might demand extensive interactional experience and integration with other more general reasoning systems.

Cognitive neuroscience studies using functional imaging also provide contradictory evidence with regard to language and mental state inferencing. Early imaging investigations revealed activations in the left temporo-parietal junction (TPJ) regions – part of language cortex – during reasoning about the beliefs of others (Samson, Apperly, Chiavarino, & Humphreys, 2004). Similar findings are reported by Ciaramidaro, Adenzato, Enrici, Erk, Pia, Bara and

Walter (2007), with activation of the left TPJ specifically when interpreting the communicative intentions of others. However, the brain network implicated in mentalising extends beyond language cortex and includes bilateral medial prefrontal cortex, anterior paracingulate cortex, together with parietal lobe structures of the precuneus as well as the right and left TPJ areas (Frith & Frith, 2006; Willems, De Boer, De Ruiter, Noordzij, Hagoort, & Toni, 2010). With regard to the temporo-parietal structures, the results of transcranial magnetic stimulation (TMS) and lesion studies indicate that right TPJ may be a more important processing hub for belief reasoning than the left TPJ. For example, right-sided TMS impaired belief reasoning in healthy participants (Kalbe et al., 2010), while ToM impairments have been described in non-aphasic patients with right hemisphere damage (Siegal, Carrington and Radel, 1996; Happé, Brownell & Winner, 1999).

3.3 Calculation

Language and mathematics share a number of design features. Each employ abstract sets of symbols which are ordered along conventional principles. The number 42 is different from 24, and 'upset' is different from 'set-up'. Similarly 'The dolphin splashed the diver' is different from 'The diver splashed the dolphin', as are the non-commutative mathematic operations of subtraction and division (i.e., 9 minus 6 vs. 6 minus 9). In this regard, Hauser, Chomksy and Fitch (2002) propose that the human mind might uniquely possess a recursive mechanism that allows structure-building operations across a range of cognitive domains, such as language and math.

The results from cross-language/cross-cultural studies provides equivocal evidence for inter-relationship between availability of language forms and numerical cognition, with conflicting findings across studies (Gordon, 2004; Butterworth et al., 2008). Similarly, an exploration of the mathematical abilities of children with developmental language impairment revealed mixed results. Donlan, Cowan, Newton & Lloyd (2007) compared performance in mathematics of children with SLI to that of age- and language-matched controls. Children with SLI showed predictable deficits in comparison to age-matched controls in linguistically-loaded math tasks (e.g., production of number words, completing verbally-presented calculation problems), but they were also impaired on a number magnitude task that did not obviously require speech input or language output (i.e., deciding which of numeral sets 7431 and 7341 is the larger). However, the children in the SLI group were indistinguishable from typically-developing peers on a test of abstract mathematic principles that tapped their understanding of principles of commutative and non-commutative operations across addition and subtraction respectively.

The findings from cognitive neuroscience also show equivocal evidence for inter-relationships of language and calculation. Many functional imaging investigations indicate that non-language right hemisphere parietal cortex lies at the core of number and calculation. Some neuroimaging studies reveal activations of language cortex during exact calculation, although these may reflect retrieval of verbally-encoded rote knowledge in support of addition and multiplication (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Benn, Zheng, Siegal, Wilkinson & Varley, 2012). However, on the non-commutative operation of subtraction in which order of numbers matters, activation of Broca's area is not observed, even though this region is active in processing sequence information in both natural language and artificial grammars (Benn et al., 2012; Bahlmann, Schubotz, Mueller, Koester, & Friederici, 2009). In an important and fine-grained analysis of activation of language cortex by nonlinguistic tasks such as calculation, Fedorenko, Behr and Kanwisher (2011) first localised language regions in individual participants. The response of these individually-defined regions to stimuli from domains such as calculation and music was determined. Fedorenko et al., found no significant response of language zones to mathematical problems, including structure-sensitive inferior frontal regions of the left hemisphere. Overall, there was little evidence of domain-general mediation by language cortex, consistent with either cognitive or supra-communicative conceptions of language, across a range of cognitive processes. Similar findings were reported by Monti, Parsons and Osherson (2012) with regard to hierarchical structure in algebra.

3.4. Cross-domain integration

Another potential cognitive role for language is in integrating otherwise isolated information to form unitary representations. The architecture of mind described by Fodor (1983) proposes a set of innate, special-purpose mechanisms, all with proprietary representations and computations. For example, the module dedicated to processing visual-object inputs is autonomous and encapsulated from that responsible for auditory signals. There are advantages to this design of mind: for example, rapid recognition of inputs is possible as processing systems do not have to compete for computational resources with other informational domains. However, there is also a potential downside. Fodor’s original description of the modular mind restricted this structure to input-output systems. These modules transduce inputs to and from a central and non-modular system. However, others have extended the notion of modularity to include central modules – described as the massive modularity hypothesis (Cosmides & Tooby, 1997). Under this account, much of human cognition is fractionated into specialist mechanisms such as a theory of mind, navigation or ‘cheater detection’ modules. Other characterisations of this fragmentation focus less on processing mechanisms but describe sets of core knowledge – innate, domain-specific representations dedicated to, for instance, number, language, objects or geometry (Carey & Spelke, 1994). However, whether construed in processing terms or domains of knowledge, the fractionation creates the problem of how representations from different domains can be combined or integrated. One proposal is that language provides a mechanism through which to break-out of informational encapsulation (Dennett, 1991; Mithen, 1996).

Spelke and colleagues provide evidence in support of this claim with a demonstration that language resources might be necessary for combining two sources of visual information. Hermer-Vasquez et al. (1999) showed that children who have not mastered spatial language – specifically the ability to produce phrases such as ‘right/left of X’ - are unable to combine visual-landmark with visual-geometric information in a reorientation task. In this seminal experiment, the participant observes an object being hidden in one of the corners of a rectangular chamber. After being blindfolded and disorientated, the participant is asked to locate the object. In one condition, all walls of the chamber are blank and participants typically search at either of the two geometrically appropriate locations (e.g., right of the long wall). When a landmark is provided (one of the short walls of the chamber is coloured blue), adults and older children are able to combine the geometric and the landmark cues (e.g., at the intersection of long wall and the blue wall) in order to locate the hidden object. However, younger children appeared unable to combine the geometric and the landmark information and continued to search at the two geometrically appropriate locations.

Hermer-Vasquez et al. explored the hypothesis that language allows creation of unitary representations that combine geometric and object/landmark information. Using a dual-task paradigm with healthy adults, they found that under verbal shadowing conditions, participants revert to searching at the two geometrically plausible but opposite locations even when a landmark cue was present. This effect appeared not to be due to the general demands of dual-task performance as a non-linguistic shadowing task involving tapping out a rhythm did not disrupt reorientation. Other experiments have failed to replicate this result. Learmonth, Newcombe and Huttenlocher (2001) found no effect of verbal shadowing when the dimensions of the experimental room were increased. Bek, et al., (2013) compared performance under two verbal shadowing conditions: repeating back nonsense syllables or meaningful prose. In repeating nonsense syllables, surface ‘inner speech’ mechanisms may be blocked, but core linguistic mechanisms of grammar and lexis may still be available. The two shadowing conditions were closely matched in difficulty, and both forms of verbal shadowing disrupted performance on the reorientation task to the same degree. More problematic still is the evidence from comparative psychology that various non-human species can combine landmarks and geometry in order to reorientate (Gouteux, Thinus-Blanc, & Vauclair, 2001; Sovrano, Bisazza, & Vallortigara, 2003).

4. The problem with correlations

In the review of cognitive domains for which various claims of language mediation have been made, some studies report evidence of association or correlation. For example, loss of language resources through verbal shadowing is associated with impaired mentalising or failure of cross-domain integration. Absence of a particular language form either in early childhood or a whole language community (or a non-human species) is associated with absence of a specific form of reasoning. Similarly, in the case of language pathology, people with SLI or aphasia can display deficits in non-linguistic domains (e.g., Lupyan & Mirman, 2013; Donlan et al., 2007; Baldo & Dronkers, 2007). The difficulty of assuming a causal relationship from a correlation is well-known. The finding that a 4-year-old can solve ToM problems that a 3-year-old cannot might shed little light on language-thought relationships. Developmental studies of this nature are open to a host of 'third factor' accounts of the correlation. A new competency that is evident at age four might be due to a biological factor (such as myelination at the same time of two functionally-independent neuronal assemblies), or experiential factors such as a further year of language learning and interaction with other agents. Unknown third factors might account for some of the reported associations of deficits in neuropsychology. Naturally-occurring brain lesions do not respect functional boundaries and most patients display a constellation of impairments. Some of these stem from organic factors such as damage to neural substrates of systems for movement control, attention, or perception. Others result from the socio-emotional consequences of a brain injury. Social networks become sparse, and depression and loss of motivation post-injury are common. A further crucial factor in experiments with people with severe language impairments is that these individuals do not fully understand verbal task instructions and may not be clear of what is being asked of them.

There are a number of strategies in exploring the factors that drive a correlation. For example, where multiple variables are measured, statistical methods such as structured equation modelling can be employed to explore causal relations. Another strategy is to seek evidence of co-variation: is it possible to identify instances of low (or high) values on one variable, and if so, what is the impact upon the second variable when other plausible candidates for driving the correlation, such as age, are held constant. If the two variables are not yoked together and there is dissociation between them (such as low language capacity but adequate performance on math), this indicates some autonomy between the two processes.

5. Language pathology

Do people with impairments of language display parallel disruptions in other domains of thought, as predicted by a cognitive conception of language, or is it possible to identify dissociations between domains? There are two broad classes of language impairment: developmental and acquired. Developmental language impairment occurs when linguistic abilities do not emerge, or emerge on a slowed or deviant trajectory. It is a broad category: some children display global developmental delay, with slow and restricted attainment across a range of domains; others diagnosed with *specific* language impairment (SLI) have no generalised learning difficulties, significant sensory-perceptual or socio-cognitive impairment, but fail to learn language in a typical way. Despite the label of *specific* impairment, there are reports of associations between atypical language development and impairment in non-linguistic domains such as mathematics (Donlan et al., 2007). But there are also accounts of dissociation, with a normal profile in domains which have been claimed to be language-mediated. An example single case study reported by van der Lely, et al., (1998) explored the ability of AZ, a boy with SLI and a marked and persisting grammatical deficit, on various non-linguistic tasks, including ToM. Despite his linguistic difficulties, AZ was able to make mental state inferences. However, AZ's linguistic difficulties were predominantly in the acquisition of morphology and he was able to construct simple sentences (e.g., 'My dad go to work'). AZ appeared to have sufficient grammatical resources to generate basic clause structures. This highlights a difficulty in using evidence from SLI to explore issues of language and thought. SLI (fortunately) rarely results in the radical impairments of language that can occur in conditions such as aphasia. Children with SLI may have fragmentary linguistic knowledge and inefficient processing, but still possess sufficient linguistic resources to construct a protolanguage, which in turn might support proposed cognitive functions of language.

More severe developmental language impairment is apparent in savant cases. These are individuals with profound learning and socio-cognitive impairments who display remarkable capacity in isolated domains of cognition such as mathematics or music (e.g., Hermelin & O'Connor, 1990; Cromer, 1991; O'Connor, Cowan, & Samell, 2000). Another severe developmental disability - Williams Syndrome - characterised by relatively intact language but low IQ and impairments in cognitive domains such as number, might be argued to represent a reverse dissociation. In this instance, the presence of language appears not to be sufficient for high-order cognition. Karmiloff-Smith, Grant, Berthoud, Davies, Howlin and Udwin (1997) suggest caution in generalising from atypical populations such as William's Syndrome to typical language and cognition. The knowledge and representations that are acquired either in language or a savant island of competence may result from atypical learning strategies such as rote acquisition.

A final group of individuals with developmental language deprivation are people who are profoundly deaf from birth and raised in non-signing environments, with no access to formal sign language. These individuals might develop 'homesign' in order to communicate with those around them, but this signing system lacks the features of full-blown language. Spaepen, Coppola, Spelke, Carey and Goldin-Meadow (2011) describe limits to numerical cognition in four homesigners, although this result was not replicated in a further report of the homesigner IC (Hyde, Winkler-Rhoades, Lee, Izard, Shapiro & Spelke, 2011). IC's mastery of spatial language however was limited and he displayed difficulty in cross-domain integration of geometric and landmark information in reorientation (Hermer-Vasquez et al., 1999).

A second broad category of language pathology is acquired conditions such as aphasia. Aphasia results from damage to the neural substrates of the language system, often as a consequence of a stroke. Patients typically have lesions within left hemisphere perisylvian cortex and associated subcortical structures such as the thalamus. There is a spectrum of deficits within aphasia and the nature and severity of impairments depend on the location and extent of brain damage. While SLI may not result in profound impairment of language capacities, some people with aphasia can display radical excisions of lexical and grammatical capacity. Most aphasic individuals have impairments both of lexicon and grammar, although traditionally aphasic sub-types are characterised by predominant symptoms. Marked lexical impairments are classed as fluent forms of aphasia, such as Wernicke's and anomia. Typical difficulties include word-finding and word comprehension impairment. In other forms of aphasia, grammatical impairment is more noticeable. Broca's aphasia is characterised by simplified syntactic structures in speech and writing and parallel difficulties in deriving semantic/thematic information from sentence structures. Profound disruption of both lexical and syntactic ability occurs in cases of global aphasia with damage usually encompassing both the prefrontal cortical language area (Broca's area) and the superior temporal gyrus (Wernicke's area), together with the tissue between these regions. Individuals with extensive lexical and syntactic impairment allow the opportunity to test claims as to whether language is a necessary resource in cognitive domains such as calculation or cross-modal integration.

Some neuropsychological research has reported associations between aphasia and impairments in non-linguistic domains. In addition to the categorisation deficit reported by Lupyan and Mirman (2013), impairments have been described in calculation (Baldo & Dronkers, 2007), and executive function (Baldo, Dronkers, Wilkins, Ludy, Raskin, & Kim, 2005). For example, Baldo et al (2005) report the performance of a group of aphasic patients on the Wisconsin Card Sorting Test (Heaton, Chelune, Talley, Kay, & Curtiss, 1983) which requires categorisation on the basis of shifting criteria. The standard form of the test is introduced by lengthy (for people with severe aphasia) verbal instructions, which might alert the participant that there is something unusual about the test. In the test a previously correct sorting criterion switches to being incorrect and the participant has to deduce the new sorting criterion on the basis of feedback. In both calculation and executive function, Baldo and colleagues report a positive correlation between aphasic and non-language impairment. However, as with all correlations, there is the difficulty in interpreting the source of the association.

Contrary to reports of associated deficits, instances of sometimes dramatic dissociations between language and other cognitive domains can be found. For example, although at a group level Baldo and Dronkers observed an association between language impairment and calculation deficits, within their individual case data there were examples of dissociation between domains. Figure 1 displays the brain scan of a severely aphasic man (SA). Despite extensive damage to left perisylvian cortex, he who is able to drive, play chess and strategic battle games with his computer, and plan and control the family finances (Siegal & Varley, 2002). These informal observations suggest considerable autonomy between non-linguistic cognition and the computations and representations of the language system, and argue against a strong version of the cognitive conception of language, at least in adult cognitive architecture.

INSERT FIGURE 1 ABOUT HERE

6. Reasoning without (much) language

In a series of experimental investigations, we have explored the performance of people with severe aphasia in domains which are claimed to be language-mediated such as mental state inferencing, calculation, and cross-domain integration (Varley & Siegal, 2000; Varley, Siegal & Want, 2001; Varley, Klessinger, Romanowski, & Siegal, 2005; Bek, et al., 2010; Willems, Benn, Hagoort, Toni, & Varley, 2011).The participants in our experiments all have severe and long-standing aphasia as a result of large left hemisphere lesions. In order to explore the possible roles of grammar and lexis in reasoning, we sub-divide patients into those with profound lexical impairment (labelling them as globally aphasic) and those with some residual lexical abilities as displayed in word comprehension and picture naming (labelling them as agrammatic). With regard to standard clinical classifications of aphasia syndromes, all participants would be classified as globally aphasic due to the severity of sentence comprehension problems. Standard agrammatic/Broca's aphasia profiles include sensitivity to word order information and, therefore, correct performance on active sentences (Zimmerer, Dąbrowska, Romanowski, Blank, Varley, 2014). The patients we describe as agrammatic differ in that they perform at chance on the comprehension of canonical active sentences of the type 'The boy kissed the girl/The girl kissed the boy'. Furthermore, while Linebarger, Schwartz and Saffran (1983) reported retained grammaticality judgements in the face of impaired sentence comprehension in agrammatic aphasia, all patients in our studies were impaired on a simple grammaticality judgement task, although some achieved above-chance performances.

6.1. Mental state inferences

Our first investigations into cognition in severe aphasia explored the ability to infer beliefs of others, or ToM reasoning (Varley & Siegal 2000; Varley, et al., 2001). Specifically, we examined whether people with severe grammatical impairments were able to represent the beliefs of others in the absence of capacity to understand or construct simple sentences and, by extension, more complex embedded structures of the type ‘He thinks there are Smarties in the tube’. Two patients (SA and MR) were recruited to these experiments. Our first study with SA involved a standard ToM unexpected contents task: SA was shown a container and the contents were as expected (e.g., a Babushka doll containing smaller Babushkas), or unexpected (a book hollowed out and containing a necklace). SA was asked what was really in the container and what would a third person to whom the contents had not been revealed would think was there. As performances on standard version ToM tasks are heavily dependent upon comprehension of probe questions (Bloom & German, 2000), SA’s understanding of ‘think’ and ‘really’ were trained on a non-ToM task. He was presented with a bag of balls and asked to guess how many balls it contained. At the same time, a flashcard with ‘think’ and a thought bubble icon were shown to him. He then emptied the bag and counted out the balls, and in the presence of a second ‘really’ flashcard, gave a reality answer. Finally, a third person subject of the ‘X thinks _’ construction was trained (SA was asked to guess how many balls another person might estimate). SA’s performance was not perfect on subsequent ToM trials (his understanding of the ‘think/really’ contrast was fragile), but his responses indicated he was able to infer the knowledge state of others, even when these beliefs were false. In a subsequent study, we used a picture ToM test and a second profoundly aphasic participant (MR) also displayed retained belief reasoning. Our findings were replicated by Apperly, Samson, Carroll, Hussain & Humphreys (2006), who described patient PH who, despite severe grammatical and verb comprehension deficits, displayed both first- and second-order belief reasoning (reasoning about what another person is thinking about another person’s beliefs).

The results from investigations of severe aphasia were consistent with those of developmental studies where preverbal infants showed implicit awareness of mental states of others (Onishi and Baillargeon, 2005), as well as investigations with non-human species (e.g., Santos, Nissen & Ferrugia, 2006). They are also consistent with neuroimaging findings that much of the neural 'mentalising network' lies outside of the regions that are typically damaged in aphasia (Willems et al., 2010). One region common to both language and mentalising networks is the left TPJ. However, the evidence from aphasia suggests that this brain region is not at the core of the mentalising system. One possibility is that activations of this structure might reflect the integration of the mentalising core with language, particularly in the case of explicit belief reasoning by healthy adults, and also given that inferences regarding others' beliefs and intentions are often based around their communicative actions (Ciaramidaro, et al. 2007).

In a recent study, we explored the ability of people with severe aphasia to generate and understand the communicative intentions of others using a barrier game where there is an imbalance of knowledge between the two participants (de Ruiter, Noordzij, Newman-Norlund, Hagoort, Toni 2007; Newman-Norlund, Noordzij, Newman-Norlund, Volman, Ruiter, Hagoort, Toni, 2009; Willems, et al., 2011). Two tokens are displayed on a 3x3 grid: one controlled by the sender, the second by the receiver. The sender knows the target location and orientation for both tokens and has to communicate to the naive receiver the position and orientation of her shape. The sender has to develop novel communicative strategies to convey this message through manipulating the movements of his own shape. For example, the sender might move his token to the receiver's location, pause, and then move to his destination. In a similar way, the receiver has to infer from the movements of the sender's token what his communicative intentions might be. In some trials, the message might be relatively easy to convey as the receiver's token matches that of the sender (e.g., both have circles). In others, the communicative task is more difficult (e.g., the sender controls a circle and the receiver's token is a rectangle in horizontal orientation). Aphasic participants adopted the role of both sender and receiver across two experiments. The results indicated that three participants with severe agrammatic aphasia (JCB, SA and PR) and a single participant with global aphasia (ST) were able both to design and interpret novel communicative signals, with performance well above chance level for all participants. For example, success rate in communication for ST in the sender role was 80%, and as a receiver, 79% correct. Success rates fell on the harder trials, but performance remained significantly above chance.

These findings indicate considerable autonomy between language, inferring mental states of others and forming and interpreting communicative intentions when expressed in novel forms. Although one should be cautious in making inferences from adult (aphasic) cognition to the developmental case, the neuropsychological evidence is in alignment with that of developmental studies. Language acquisition rests upon sophisticated socio-cognitive foundations (Tomasello, 2008). When language is lost or profoundly impaired later in life, those socio-cognitive foundations remain in place and people with severe aphasia remain capable of inferring beliefs and intentions of others.

6.2. Calculation in aphasia

Early functional imaging and behavioural investigations suggested that language was implicated in exact calculation (Dehaene, et al., 1999). However, subsequent investigations in healthy participants revealed that language representations may not be necessary for calculation (Fedorenko et al., 2011; Frank & Barner, 2012; Benn et al., 2012; Monti, Parsons & Osherson, 2012). In terms of the neuropsychological evidence, some studies describe association between language impairment and aphasia (e.g., Baldo & Dronkers, 2007), but there are also reports of double disassociations between language and calculation, i.e., individuals who display calculation impairments without aphasia, and those who are aphasic but not acalculic (Butterworth, 1999; Klessinger, Szczerbinski, & Varley, 2007). These cases indicate that, although elements of the two processing networks might overlap, there is likely to be considerable autonomy between the two systems, particularly in core computations.

We examined the possibility of shared resources between language and calculation through identifying syntactic 'homologues' between the two domains (Hauser et al., 2002; Varley, et al., 2005). In particular, we focused on the non-commutative operations of subtraction and division, sensitivity to bracketed structure in mathematical equations, and principles of generativity and discrete infinity in number. Our aim was to determine if profoundly agrammatic individuals were sensitive to these principles when expressed in number. Three men with agrammatic aphasia (SA, SO and PR) took part in the experiment, and each was unable to understand the difference between sentences such as 'The man chased the dog/The dog chased the man'. However, they were able to correctly calculate the difference between 7 – 2 vs. 2 – 7, or 20/5 vs. 5/20. They displayed similar sensitivity to the structural features of embedded equations (e.g., (5 x (6 + 2))), and were able to generate long strings of numbers with values between 1 and 2, reflecting awareness of the potential infinity of numbers. Overall, there was a clear dissociation between the syntactic principles of mathematics, and those of language.

One possibility regarding these discordant neuropsychological findings is that in these chronically aphasic individuals, significant reorganisation of the calculation system may have occurred. In order to compensate for the loss of a necessary resource, new neural networks might have been recruited into the processing complex in order to sustain function. We explored this possibility by examining brain activations during calculation in severely aphasic participants (Benn et al., 2013). Typical changes that might occur if a system was degraded and needing additional neurocognitive resources would be up-regulation of prefrontal zones, reflecting greater demand on executive or controlled processing. Only two patients (PR and JCB) were able to be scanned and functional imaging indicated no wholescale reorganisation of the neural network for calculation or remapping to new cortical sites. Other neuroimaging studies examining activations during the processing of structured mathematical information in healthy participants provide convergent evidence that our patient findings do not represent exceptional results. Monti et al. (2012) required participants to judge the equivalence of two sentences or algebraic equations and observed distinct profiles of activation across the two forms of representation. While linguistic expressions were associated with activation of typical left hemisphere sites (e.g., inferior frontal gyrus, superior and middle temporal gyri), algebraic judgments evoked bilateral parietal activations (e.g., intraparietal sulcus). Similar findings were reported by Maruyama, Pallier, Jobert, Sigman, and Dehaene (2012), who found that judgements of nested bracket equations resulted in activations outside of the language network and centred in lateral occipital and posterior fusiform regions, with greater activation in the right hemisphere.

6.4 Cross-domain integration

In the experiments described above, we observe retained abilities within single representational domains in people with severe aphasia. In exploring cross-domain integration in these patients, we adopted the reorientation paradigm of Hermer-Vasquez et al. (1999). Five men took part in the experiment: three had severe agrammatic aphasia (SA, PR, JCB) and two global aphasia (ST, JB). The global patients had greater difficulty in understanding spatial terms such as ‘left’ and ‘right’ than the agrammatic cases, but all the aphasic participants were impaired in understanding sentences encoding spatial information (Bek et al., 2010). Despite these linguistic impairments, the aphasic participants were indistinguishable from age-matched healthy controls in combining geometric with object/landmark information. This was the case in non-shadowing conditions, but also in a condition when they attempted a simplified word shadowing task (repeating back concrete nouns) in order to block any residual lexical resources. Given the severity of their aphasias, their ability to verbally shadow was impaired. However, even with intermittent verbal shadowing, they continued to integrate the two sources of visual information, suggesting that in established/adult cognition access to language was not required for this task. Our results are consistent with those of a number of other experiments, including those exploring performance in non-human species (Gouteux, et al., 2001; Sovrano, et al., 2003).

7. Limits to the evidence from aphasia

There are a number of good reasons to object to the evidence from aphasia in informing debates on the relationship between language and thought. Our studies involve small numbers of patients (these individuals are difficult to recruit and have a host of comorbid deficits that make the design and implementation of experiments challenging). Our results are not always replicated by other neuropsychological investigations, some of which describe associations between aphasic language impairment and disruption of other cognitive domains. The identification of associations and constellations of impairments is important in clinical diagnostics (if A is reported to co-occur with B, if you identify A, you would be wise to check for B). But the contribution of associations to theory-building in cognitive neuroscience is more limited. Observed associations might result from lesions extending across the substrates of many processing systems. In the case of aphasia, they may also result from an individual not understanding what is required of them, either in general tasks instructions or specific item probes. The results from our case series investigations converge with those of some experiments with healthy adults, preverbal infants, non-human species and functional neuroimaging. Taken together, there is a robust and growing body of evidence of considerable autonomy between language and the cognitive domains investigated to date.

A second and legitimate objection to the evidence from aphasia is that as an acquired impairment, it tells us nothing about the role of language in the development of a characteristically human mind. Aphasia usually occurs later in life and the person who becomes aphasic usually had full access to language before brain injury. If language has a role in configuring reasoning systems, this initial language-driven canalisation has taken place. Returning to the claim that words might influence perception and categorisation, loss of the linguistic label in later life is unlikely to result in wholescale re-engineering of conceptual knowledge. The evidence of aphasic dissociations can inform debates as to the role of language in ongoing, adult cognition but there is a need for caution in making inferences from an aphasic mind to questions of acquisition.

A third objection to the evidence from aphasia is more problematic. Chomsky (2007) writing with regard to the debate as to the relationship between language and mathematics, claims:

> "Speculations about the origin of the mathematical capacity as an abstraction from linguistic operations are familiar, as are criticisms, including apparent dissociation with lesions and diversity of localization. The significance of such phenomena, however, is far from clear. They relate to the use of the capacity, not its possession; to performance, not competence." (p. 7).

This is a familiar claim made regarding aphasic deficits. The key idea is that only the mechanisms involved in relaying linguistic information to and from a central competence are impaired in aphasia and that competence remains intact. This claim is supported by evidence that some aphasic people (but not those in our studies) despite sentence comprehension difficulties retain the ability to perform grammaticality judgements across of range of complex syntactic stuctures (Linebarger et al., 1988). However, the claim that competence is untouched by aphasic brain damage is perplexing to those from a biological tradition. Whitaker (1971) captures this difficulty:

> "If brain damage cannot affect competence, then competence is not a property of the brain" (p.16).

The patient SA, whose brain scan is displayed in Figure 1, has massive damage across the left hemisphere perisylvian cortical network. The lesion area encompasses sites that are invariably active in processing linguistic information in functional neuroimaging studies. Lexical processing is underpinned by multiple neural sites, reflecting the distributed nature of semantic-conceptual knowledge, although the key linguistic input/output hubs to this network lie within the perisylvian region. Syntactic processing is more focally organised within the brain with left hemisphere Brodmann's areas 44 and 45 (Broca's area) often activated by tasks that require sequential processing (Bahlmann et al., 2009). All these key regions are lesioned in SA's case. If the core computations and representations that are at the heart of linguistic competence do not lie within the lesioned area, then where are they?

Those of a Chomskian-generativist persuasion might suggest that competence theory is an abstraction, or in terms of Marr's hierarchy of explanations within cognitive science, a Level One explanation (Marr, 1982). Psycho- and neurolinguistic research addresses Levels Two and Three, attempting to describe the nature of representations and the algorithms involved in processing and the neurobiological mechanisms that instantiate language. All this is fine and dandy: there is no issue in working up a theory to the point at which it is fit for experimental testing at Levels Two and Three. However, proponents of competence theories make predictions regarding phylogenetic, ontogenetic and biological mechanisms (e.g., Hauser, et al., 2002) and if a theory is relevant to Level Two/Three questions, then it must be responsive to empirical data and not retreat to an inviolate theory of competence when experiments fail to confirm its predictions.

8. Conclusions

Single factor accounts, such as possession of language, in the enhancement of the human mind are attractive. However, in the domains explored here, the evidence does not support a cognitive conception of language. The convergence of findings from a variety of experimental methods forms a robust body of evidence against a strong cognitive view. The human brain/mind differs from those of other species not only in its possession of language and there are many factors cumulatively and in their interactions that may create uniquely human cognition.

A supra-communicative view of language – that language supports thought and reasoning in other domains – is consistent with a multifactorial approach. In healthy people language resources may often be deployed to scaffold performance on a range of problems without being a mandatory component of that reasoning. In particular, verbal encoding enables access to short- and longer term memory mechanisms. It also supports reasoning on sequential problems that require long chains of inferences. Under a supra-communicative view, the person with severe language impairment will not have easy access to a resource that not only enables interpersonal exchange, but which also enhances thinking and allows rapid assimilation of new information. It may be for this reason that some studies identify deficits in both language and non-language cognition. However, in the cognitive domains explored to date, the evidence points to autonomy of thought and language.

References

Apperly, I.A., Butterfill, S.A. 2009. Do humans have two systems to track beliefs and belief-like states? Psychological Review 116 (4), 953-970.

Apperly, I.A., Samson, D., Carroll, N., Hussian, S., Humphreys, G., 2006. Intact first- and second-order false belief reasoning in a patient with severely impaired grammar. Social Neuroscience 1 (3-4), 334-348.

Astington, J.W., Jenkins, J.M., 1999. A longitudinal study of the relation between language and theory-of-mind development. Developmental Psychology 35 (5), 1311-1320.

Bahlmann, J., Schubotz, R.I., Mueller, D., Koester, A.D., Friederici, A.D., 2009. Neural circuits of hierarchical visuo-spatial sequence processing. Brain Research 1298, 161-170.

Baldo, J.V., Dronkers, N.F., Wilkins, D., Ludy, C., Raskin, P., Kim, J.Y., 2005. Is problem solving dependent on language? Brain and Language 92 (3), 240-250.

Baldo, J.V., Dronkers, N.F., 2007. Neural correlates of arithmetic and language comprehension: A common substrate? Neuropsychologia 45 (2), 229-235.

Bek, J., Blades, M., Siegal, M., Varley, R., 2010. Language and spatial reorientation: Evidence from severe aphasia. Journal of Experimental Psychology: Learning, Memory and Cognition 36 (3), 646-658.

Bek, J., Blades, M., Siegal, M., Varley, R., 2013. Dual-task Interference in Spatial Reorientation: Linguistic and Nonlinguistic Factors. Spatial Cognition & Computation 13 (1), 26-49.

Benn, Y., Wilkinson, I.D., Zheng, Y., Cohen Kadosh, K., Romanowski, C.A., Siegal, M., Varley, R., 2013. Differentiating core and co-opted mechanisms in calculation: the neuroimaging of calculation in aphasia. Brain & Cognition 82 (3), 254 - 264.

Benn, Y., Zheng, Y., Siegal, M., Wilkinson. I.D., Varley, R., 2012. Language in calculation: a core mechanism? Neuropsychologia 50 (1), 1-10.

Berk, L., 1994. Why children talk to themselves. Scientific American 1994 (November), 78-83.

Bloom, P., German, T.P., 2000. Two reasons to abandon the false belief task as a test of theory of mind. Cognition 77 (1), B25-B31.

Butterworth, B., 1999. The Mathematical brain. Macmillan, London.

Butterworth, B., Reeve, R., Reynolds, F., Lloyd, D., 2008. Numerical thought with and without words: evidence from indigenous Australian children. Proceedings of the National Academy of Sciences 105 (35), 13179-13184.

Carey, S., Spelke, E., 1994. Domain-specific Knowledge and Conceptual Change. In: Hirschfeld, L., Gelman, S. (Eds.), Mapping the Mind. Cambridge University Press, Cambridge, pp. 169-200.

Carruthers, P., 1996. Language, thought and consciousness: An essay in philosophical psychology, Cambridge University Press, Cambridge.

Carruthers, P., 2002. The cognitive functions of language. Behavioral and Brain Sciences 25 (6), 657-726.

Chomsky, N., 2007. Approaching UG from Below. In: Sauerland, U., Gaertner, H. (Eds.), Interfaces = Recursion = Language? Mouton de Gruyter, Berlin.

Ciaramidaro, A., Adenzato, M., Enrici, I., Erk, S., Pia, L., Bara, B.G., Walter, H., 2007. The intentional network: how the brain reads varieties of intentions. Neuropsychologia 45 (13), 3105–3113.

Clark, A., 1997. Being there: putting brain, body and world together again. MIT Press, Cambridge, Mass.

Cosmides, L., Tooby, J., 1997. The Modular Nature of Human Intelligence. In: Scheibel, A., Schopf, J.W. (Eds.), The Origin and Evolution of Intelligence. Jones and Bartlett Publishers, Sudbury, MA, pp. 71-101.

Cromer, R.F., 1991. Language and thought in normal and handicapped children. Blackwell, Oxford.

de Ruiter, J.P, Noordzij, M.L, Newman-Norlund, S., Hagoort, P., Toni, I., 2007. On the origin of intentions. In: Haggard, P., Rossetti, Y. Kawato, M. (Eds.), Sensorimotor Foundations of Higher Cognition. Oxford University Press, Oxford, pp. 593-610.

de Villiers, J.G., Pyers, J.E., 2002. Complements to cognition: A longitudinal study of the relationship between complex syntax and false-belief-understanding. Cognitive Development 17 (1), 1037-1060.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., Tsivkin, S., 1999. Sources of mathematical thinking: Behavioral and brain-imaging evidence. Science 284 (5416), 970-974.

Dennett, D., 1991. Consciousness explained. Little Brown, Boston.

Donlan, C., Cowan, R., Newton, E.J., Lloyd, D., 2007. The role of language in mathematical development: evidence from children with specific language impairments. Cognition 103 (1), 23-33.

Dungan J., Saxe R., 2012. Matched false-belief performance during verbal and nonverbal interference. Cognitive Science 36 (6), 1148-1156.

Everett, D.L., 2005. Cultural constraints on grammar and cognition in Piraha. Another look at the design features of human language. Current Anthropology 46 (4), 621-646.

Fedorenko, E., Behr, M., Kanwisher, N., 2011. Functional specificity for high-level linguistic processing in the human brain. Proceedings of the National Academy of Sciences 108 (39), 16428-33.

Fodor, J., 1983. The Modularity of mind. MIT Press, Cambridge, MA.

Fouget d'Arc, B., Ramus, F., 2011. Belief attribution despite verbal interference. Quarterly Journal of Experimental Psychology 64 (5), 975–990.

Frank, M.C., Barner, D., 2012. Representing exact number visually using mental abacus. Journal of Experimental Psychology: General, 141 (1), 134-149.

Frith, C.D., Frith, U., 2006. The neural basis of mentalizing. Neuron 50 (4), 531-534.

Gardner, R.A., Gardner, B.T., 1969. Teaching sign language to a chimpanzee. Science 165 (3894), 664-672.

Goldberg, A.E., 2006. Constructions at work: The nature of generalization in language. Oxford University Press, New York.

Gordon, P., 2004. Numerical cognition without words: evidence from Amazonia. Science 306 (5695), 496-499.

Gouteux, S., Thinus-Blanc, C., Vauclair, J., 2001. Rhesus monkeys use geometric and nongeometric information during a reorientation task. Journal of Experimental Psychology: General 130 (3), 505–519.

Greenfield, P.M., Savage-Rumbaugh, E.S., 1990. Grammatical Combination in *Pan paniscus:* Processes of learning and invention in the evolution and development of language. In: Krasneor, N.A., Rumbaugh, R.L., Schieflelbusch, R.L., Studdert-Kennedy, M. (Eds.), Biological and Behavioral Determinants of Language Development. Lawrence Erlbaum, Hillsdale, N.J., pp. 235-258.

Happé, F.G.E., Brownell, H. Winner, E., 1999. Acquired 'theory of mind' impairments following stroke. Cognition 70 (3), 211-240.

Hauser, M.D., Chomsky, N., Fitch, W.T., 2002. The faculty of language: what is it, who has it, and how did it evolve? Science 298 (5598), 1569-1579.

Heaton, R. K., Chelune, G.J., Talley, J.L., Kay, G.G., Curtiss, G., 1983. Wisconsin card sorting test. Psychological Assessment Resources, Odessa.

Hermelin, B., O'Connor, N., 1990. Factors and primes: a specific numerical ability. Psychological Medicine 20 (1), 163-169.

Hermer-Vazquez, L., Spelke, E.S., Katsnelson, A.S., 1999. Sources of flexibility in human cognition: Dual-task studies of space and language. Cognitive Psychology 39 (1), 3-36.

Hyde, D.C., Winkler-Rhoades, N., Lee, S.A., Izard, V., Shapiro, K.A., Spelke, E.S. 2011. Spatial and numerical abilities without a complete natural language. Neuropsychologia 49 (5), 924-936.

Johnson-Laird, P.N., 1983. Mental models: Towards a cognitive science of language, inference, and consciousness. Cambridge University Press, Cambridge.

Kalbe, E., Schlegel, M., Sack, A.T., Nowak, D.A., Dafotakis, M., Bangard, C., Brand, M., Shamay-Tsoory, S., Onur, O.A., Kessler, J., 2010. Dissociating cognitive from affective theory of mind: a TMS study. Cortex 46 (6): 769-80.

Kaminski, J., Call. J., Fischer, J., 2004. Word learning in a domestic dog: evidence for 'fast mapping'. Science 304 (5677), 1682-1683.

Karmiloff-Smith, A., Grant, J., Berthoud, I., Davies, M., Howlin, P., Udwin, O., 1997. Language and Williams Syndrome: How Intact Is "Intact"? Child Development 68 (2), 246-262.

Kim, H.S., 2002. We talk, therefore we think? A cultural analysis of the effect of talking on thinking. Journal of Personality and Social Psychology 83 (4), 828–842.

Klessinger, N., Szczerbinski, M., Varley, R., 2007. Algebra in a man with severe aphasia. Neuropsychologia 45 (8), 1642-1648.

Klessinger, N., Szczerbinski, M., Varley, R., 2012. The role of number words: the phonological length effect in multidigit addition. Memory & Cognition 40 (8), 1289-1302.

Learmonth, A.E., Nadel, L., Newcombe, N.S., 2002. Children's use of landmarks: Implications for modularity theory. Psychological Science 13 (4), 337–341.

Learmonth, A.E., Newcombe, N.S., & Huttenlocher, J., 2001. Toddler's use of metric information and landmarks to reorient. Journal of Experimental Child Psychology 80 (3), 225-244.

Linebarger, M.C., Schwartz, M.F., Saffran, E.M., 1983. Sensitivity to grammatical structure in so-called agrammatic aphasics. Cognition 13 (3), 361-392.

Liszkowski, U., Carpenter, M., Tomasello, M., 2008. Twelve-month-olds communicate helpfully and appropriately for knowledgeable and ignorant partners. Cognition 108 (3), 732-739.

Lupyan, G., Mirman, D., 2013. Linking language and categorization: Evidence from aphasia. Cortex 49 (5), 1187-1194.

Marr, D., 1982. Vision: a computational investigation into the human representation and processing of visual information. New York: Freeman.

Maruyama, M., Pallier, C., Jobert, A., Sigman, M., Dehaene, S., 2012. The cortical representation of simple mathematical expressions. Neuroimage 61(4):1444—1460.

McClelland, J. L., 2010. Emergence in cognitive science. Topics in Cognitive Science 2, 751-770.

Mithen, S., 1996. The Prehistory of the mind. Thames & Hudson, London.

Monti M.M., Parsons L.M., Osherson D.N., 2012. Thought beyond language: neural dissociation of arithmetic and natural language. Psychological Science 23(8), 914-922.

Newman-Norlund, S.E., Noordzij, M.L., Newman-Norlund, R.D., Volman, I.A., Ruiter, J.P., Hagoort, P., Toni, I., 2009. Recipient design in tacit communication. Cognition 111 (1) 46-54.

Newton, A. M., de Villiers, J. G., 2007. Thinking while talking: Adults fail nonverbal false-belief reasoning. Psychological Science 18 (7), 574-579.

O'Connor, N., Cowan, R., Samella, K., 2000. Calendric calculation and intelligence. Intelligence 28 (1), 31–48.

Onishi, K. H., Baillargeon, R., 2005. Do 15-month-old infants understand false beliefs. Science 308 (5719), 255-258.

Ouattara, K., Lemasson, A., Zuberbühler, K., 2009. Campbell's monkeys concatenate vocalizations into context-specific call sequences. Proceedings of the National Academy of Sciences. 106 (51), 22026-22031.

Papfragou, A., Hulbert, J., Trueswell, T., 2008. Does language guide event perception? Evidence from eye movements. Cognition 108 (1), 155-184.

Pinker, S., 1994. The Language instinct. Allen Lane, Penguin Press, London.

Premack, D., 1988. Minds with and without Language. In: Weisenkrantz, L. (Ed.), Thought without language. Oxford University Press, Oxford, pp. 46-65.

Pyers, J.E., Shusterman, A., Senghas, A., Spelke, E., Emmorey K., 2010. Spatial language supports spatial cognition: Evidence from learners of an emerging sign language. Proceedings of the National Academy of Sciences, 107 (27), 12116-12120.

Samson, D., Apperly, I.A., Chiavarino, C., Humphreys, G.W., 2004. The left tempero-parietal junction is necessary for representing someone else's belief. Nature Neuroscience 7 (5), 449–500.

Santos, L.R., Nissen, A.G., Ferrugia, J.A., 2006. Rhesus monkeys, Macaca mulatta, know what others can and cannot hear. Animal Behaviour 71 (5), 1175–181.

Schuell, H., Jenkins, J.J., Jiménez-Pabon, E. 1965. Aphasia in adults. Hoeber, New York.

Senghas, A., Kita, S., Özyürek, A., 2004. Children creating core properties of language: Evidence from an emerging sign language in Nicaragua. Science 305 (5691), 1779-1782.

Seyfarth, R.M., Cheney, D.L., 2003. Signalers and receivers in animal communication. Annual Review of Psychology 54, 145-173.

Siegal, M., Carrington, J., Radel, M., 1996. Theory of mind and pragmatic understanding following right hemisphere damage. Brain and Language 53 (1), 40-50.

Siegal, M., Varley, R., 2002. Neural systems involved in 'theory of mind'. Nature Reviews Neuroscience 3 (6), 463-471.

Spaepen, E., Coppola, M., Spelke, E.S., Carey, S., Goldin-Meadow, S., 2011. Number without a language model. Proceedings of the National Academy of Sciences 108 (8), 3163-3168.

Tomasello, M., 2008. Origins of human communication. MIT Press, Cambridge, Mass.

Trbovich, P. L., LeFevre, J. A., 2003. Phonological and visual working memory in mental addition. Memory & Cognition 31 (5), 738-745.

van der Lely, Rosen, S., McClelland, A., 1998. Evidence for a grammar-specific deficit in children. Current Biology 8 (23), 1253-1258.

van Heijningen, C.A.A., de Visser, J., Zuidema, W., ten Cate, C., 2009. Simple rules can explain discrimination of putative recursive syntactic structures by a songbird species. Proceedings of the National Academy of Sciences, 106 (48), 20538-20543.

Varley, R., Klessinger, N., Romanowski, C., Siegal, M., 2005. Agrammatic but numerate. Proceedings of the National Academy of Sciences 102 (9), 3519-3524.

Varley, R., Siegal, M., 2000. Evidence for cognition without grammar from causal reasoning and 'theory of mind' in an agrammatic aphasic patient. Current Biology 10 (12), 723-726.

Varley, R., Siegal, M., Want, S., 2001. Severe impairment in grammar does not preclude theory of mind. Neurocase 7 (6), 489-493.

Vygotsky, L., 1962. Thought and language. MIT Press: Cambridge, Mass.

Whitaker, H.A. 1971. On the representation of language in the human brain. Linguistic Research Incorp, Edmonton.

Whorf, B.L., 1956. Language, thought and reality: Selected writings of Benjamin Lee Whorf. MIT Press, Cambridge, Mass.

Willems, R.M., Benn, Y., Hagoort, P., Toni, I., Varley R.A., 2011. Communication without a functioning language system. Neuropsychologia 49 (11), 3130-3135.

Willems, R.M., De Boer, M., De Ruiter, J.P., Noordzij, M.L., Hagoort, P., Toni, I., 2010. A cerebral dissociation between linguistic and communicative abilities in humans. Psychological Science 21 (1), 8-14

Wynn, K., 1992. Addition and subtraction by human infants. Nature 358 (6389), 749-750.

Zimmerer, V., Dąbrowska, E., Romanowski, C., Blank, C., Varley, R., 2014. Preservation of the passive in a patient with primary progressive aphasia. Cortex 50, 7-18.