



Verbal and visual cognition: Individual differences in the lab, in the brain, and in the classroom

Katherine L. Alfred & David J. M. Kraemer

To cite this article: Katherine L. Alfred & David J. M. Kraemer (2017) Verbal and visual cognition: Individual differences in the lab, in the brain, and in the classroom, *Developmental Neuropsychology*, 42:7-8, 507-520, DOI: [10.1080/87565641.2017.1401075](https://doi.org/10.1080/87565641.2017.1401075)

To link to this article: <https://doi.org/10.1080/87565641.2017.1401075>



Published online: 05 Mar 2017.



Submit your article to this journal [↗](#)



Article views: 25



View related articles [↗](#)



View Crossmark data [↗](#)



Verbal and visual cognition: Individual differences in the lab, in the brain, and in the classroom

Katherine L. Alfred and David J. M. Kraemer

Department of Education and Department of Psychological and Brain Sciences, Dartmouth College, Hanover, New Hampshire

ABSTRACT

In many ways, individuals vary in their thought processes, and in their cognitive strengths and weaknesses. Among the findings revealed by individual differences research, one major dividing line highlighted recurrently by decades of experimental studies is that between linguistically-mediated cognitive operations (verbal cognition), versus cognition, which primarily operates on visual – or visuospatial – representations (visual cognition). In this article, we review findings from three research areas—cognitive abilities, working memory, and task strategies—focusing on individual differences in verbal and visual cognition. In each area we highlight behavioral, neuroimaging, and classroom-based findings, bridging the perspectives of these different methodologies.

KEYWORDS

Over the past century of experimental psychology research, there have been numerous attempts to characterize differences in the ways that different individuals think and behave. Most research in the field has tended to treat inter-individual variation as noise to be ignored as “error.” However, the studies that focus on individual differences seek to explain this variation between individuals in terms of psychological constructs that can be measured and used to predict other outcomes.

In this review, we focus on a set of research findings that have emerged from separate lines of investigation, but which when considered together present a coherent picture of an important dimension of individual variation. Toward one extreme of this dimension is “verbal cognition,” which are mental operations that require language either in overt or in covert ways. Verbal cognition is often assessed, for example, by tests of vocabulary or verbal working memory. At the other extreme is “visual cognition,” which includes mental operations that require visual or spatial processing. Visual (or visuospatial) cognition is often assessed by tests that rely on mental rotation, locating embedded figures, or visual working memory.

This dimension—the degree to which cognitive operations require verbal cognition versus visuospatial cognition—accounts for a substantial portion of the variation in individual differences in thought. These differences can be used to predict future success in STEM fields, identify and assist with specific working memory deficits, and account for variance that makes one individual’s neural activity more similar doing two different tasks than two people doing the same task. In this review we present evidence from three areas of research: studies of cognitive abilities, studies of working memory, and studies of task strategies or habits of thought. In each of these areas, we synthesize findings across methodologies, drawing from psychology, cognitive neuroscience, and educational research to better understand this dimension of inter-individual variation.

Most of this work is characterized as basic research (as opposed to applied), and should be taken in the context of *validating a theoretical model of cognition* and *generating hypotheses* for further

studies to test and refine for potential application. Therefore, our aim here is to convey the current state of understanding regarding verbal and visual cognition, not to conclude that the basic research questions are settled and this work is ready for application in classrooms today. Rather, our goal is to highlight meaningful lines of investigation that stretch back decades, that are being pursued in ongoing research programs, and that will continue to provide useful insights into the ways in which cognition varies across the minds of different individuals. These studies draw upon research conducted in the lab and in the classroom, focusing on behavioral, neural, and educational outcomes. Although not the main focus of this review, where it is useful we have noted the findings that appear to be most robust and applicable to classroom education sooner rather than later. Most importantly, however, unifying and presenting these studies within this framework underscores the consistency of the distinction between visual and verbal patterns of cognition across a variety of cognitive domains. These findings convey the importance of this dimension as one that merits further study both on basic and on applied levels of research.

Cognitive abilities

One of the major dividing lines among dimensions of cognitive abilities involves processing verbal (i.e., linguistic) versus visuospatial information (Carroll, 1993). This distinction is reflected in the construction of modern measures of intelligence, such as the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008), in which the General Ability Index score is comprised of two composite index scores: Verbal Comprehension and Perceptual Reasoning. Over a century of research has documented a range of variation on measures of cognitive ability that rely on these cognitive skills. On the population level, verbal and visual cognitive abilities are positively correlated with one another ($r^2 = .4$ to $.7$; Carroll, 1993; Deary, Penke, & Johnson, 2010; Salthouse, 2004). However, these domains of abilities are separable, as can be seen by the high loadings on general cognitive ability (g) by the verbal subtests of the WAIS, “Information” and “Vocabulary” (e.g., g -loadings of $r = .6$ to $.7$), which do not rely greatly on fluid intelligence (Colom, Jung, & Haier, 2006; Lee et al., 2006). Moreover, there is often significant variation within individuals when comparing abilities in one domain versus another.

Separating cognitive abilities into distinct domains has explanatory value when assessing the relationship between intelligence and academic performance. One prominent example of assessing individual differences during cognitive development focused on predictors in childhood of later success in STEM careers. In a large-scale longitudinal study, Wai, Lubinski, and Benbow (2005) measured cognitive abilities of 2,966 precocious 13 year olds with the SAT Math test and followed their progress through grade school and beyond for 20 years. Although the children were all within the top 1% of mathematical ability, the sample was further divided into quartiles to study the differences in quantitative ability within a group already at the top end of the spectrum. The upper quartile was over eight times more likely than the bottom quartile achieve tenure in a STEM field at a highly successful university (Wai et al., 2005). Additionally, the difference between quantitative and verbal abilities on the SAT predicts success in STEM fields when the difference favors stronger quantitative skills (Park, Lubinski, & Benbow, 2007). A further study (Wai, Lubinski, & Benbow, 2009) showed that in 400,000 high schoolers of all ability levels, better visuospatial abilities are important for developing knowledge in STEM fields, and ultimately translate to success in STEM careers. Although the mathematical section of the SAT is not a direct measurement of visuospatial ability, there is evidence to support a link between the two. Visuospatial ability, along with processing speed, predict a significant amount of variance in SAT math scores, even after accounting for variance due to differences in general cognitive abilities (Rohde & Thompson, 2007).

Success in STEM is not only the result of natural ability, however. Another study compared the experiences and trajectories of success in STEM for both mathematically gifted 13 year olds and top STEM graduate students (Wai, Lubinski, Benbow, & Steiger, 2010). The group of teenagers were followed longitudinally over 25 years to measure their later success in STEM fields, and the researchers detailed the STEM enrichment experiences of the graduate students. In both groups,

people with more STEM opportunities at the pre-collegiate level achieved higher levels of success in STEM fields, indicating that these opportunities—and not skill level alone—are important predictors of later STEM success.

Similarly with verbal ability, Deary and colleagues (Deary, Strand, Smith, & Fernandes, 2007) examined the contributions of g and residual verbal cognitive ability (after controlling for g) to academic achievement of in a group of over 70,000 English students. The researchers measured cognitive abilities of the students at age 11 and followed their progress through their completion of the national public exams taken in multiple subjects at age 16. The results demonstrated a significant contribution of verbal cognitive abilities to academic performance, especially in subjects related to languages and to writing (e.g., English; English literature; French). However, it should also be noted that, while significant, the specific effects of verbal cognitive abilities were much smaller than the overall effects of g in every subject domain (g on GCSE total $\eta^2 = .492$, verbal residual on GCSE total $\eta^2 = .027$; g on English GCSE $\eta^2 = .483$, verbal residual on English GCSE $\eta^2 = .072$). Nonetheless, verbal abilities are significant predictors of academic performance and appear to play a critical role in writing and language abilities. Consistent with this conclusion, in studies of children with subject-specific learning disabilities, verbal abilities underpin reading and spelling achievement, in contrast to visuospatial abilities which correlate with math achievement (Rourke & Finlayson, 1978).

In terms of the neural correlates of intelligence, Jung and Haier (2007) and Deary et al. (2010) have reviewed the literature on functional and structural neuroimaging studies of intelligence. The results point to a frontoparietal circuit in which functional magnetic resonance imaging (fMRI) blood oxygen level dependent (BOLD) activity and white matter integrity in a set of regions (including left anterior prefrontal cortex, angular gyrus, and supramarginal gyrus, left dorsal and ventral anterior cingulate, and bilateral dorsolateral prefrontal cortex) positively correlate with individual differences in intelligence. However, these studies mostly rely on measures of nonverbal fluid or visuospatial intelligence (Lee et al., 2006) and therefore speak more to the neural basis of visuospatial abilities. These studies indicate that visuospatial cognitive abilities correlate with neural activity in prefrontal cortex and parietal regions. General fluid intelligence (as measured with Raven's Advanced Progressive Matrices; Raven, Raven, & Court, 2000) has been shown to predict more parietal and lateral prefrontal activity during a 3-back match/lure task, using both verbal and nonverbal (face) stimuli (Gray, Chabris, & Braver, 2003). Therefore, there seem to be separate neural correlates for general fluid intelligence and visuospatial cognitive abilities when the tasks used to measure general fluid intelligence are comprised of both verbal and visual content.

Brain networks that may underpin verbal cognitive abilities are likely to be brain regions that underlie language production and comprehension. A recent review of neuroimaging studies involving various types of verbal tasks posits a “language network” that, at the highest level, consists of a fronto-temporal network of regions including the posterior inferior frontal gyrus, left medial frontal gyrus, left middle anterior temporal regions, and left middle posterior temporal regions (Fedorenko & Thompson-Schill, 2014). While there is some discussion about what exact sorts of operations “language processing” encompasses, there seems to be a relatively specified network of brain regions, which is engaged during the comprehension of language and not during other tasks (Fedorenko, Behr, & Kanwisher, 2011). Previous neuropsychological studies of language deficits further implicate a subset of this language network – specifically, posterior middle temporal gyrus, anterior superior temporal gyrus, superior temporal sulcus, dorsolateral prefrontal cortex, and inferior frontal gyrus in interpreting semantic content of language and pairing that with visual knowledge of a situation. Damage to these regions resulted in difficulty comprehending the semantic content of spoken sentences when trying to pair them with line drawings, though lesions to Broca's Area and Wernicke's Area did not lead to the same difficulties (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004).

It has also been observed that semantic dementia—which is the impairment of declarative real-world knowledge, such as saying “cat” for a picture of a hamster—is associated with damage to the anterior temporal lobe and ventral temporal cortex (Hodges, Patterson, Oxbury, & Funnell, 1992;

Rogers, Graham, & Patterson, 2015; Rogers, Patterson, & Graham, 2007). These findings are consistent with neuroimaging-based models of semantic knowledge, which highlight the role of temporal regions across various tasks that require semantic processing and also point to the anterior temporal lobe as a possible convergence zone for semantic and perceptual features (Chiou & Lambon Ralph, 2016; Coutanche & Thompson-Schill, 2015; Thompson-Schill, 2003). Between these results on semantic knowledge and the aforementioned studies regarding the language network, it would seem likely that a fronto-temporal network of brain regions underlies individual differences in verbal cognitive abilities. Future work may explore this possibility directly, providing a useful complement to the studies of individual differences in visuospatial cognitive abilities.

Working memory

Working memory is defined as a limited capacity system that temporarily processes and stores information in the service of a specific goal, like splitting a dinner bill and calculating the tip off of your portion (Baddeley, 2003). Variations in working memory capacity are a strong and reliable source of individual differences in performance across a variety of tasks (Engle, Kane, & Tuholski, 1999; Engle, Tuholski, Laughlin, & Conway, 1999; Turner & Engle, 1989), and reduced working memory capacity has been implicated as a limiting factor in comprehension (Gathercole, Lamont, & Alloway, 2006). Under some theories of working memory, domain specific storage is manipulated by domain general processing with slave domain-specific processing subsystems, such as the central executive, served by visuospatial sketchpad and the phonological loop (for review, see Baddeley, 2012). However, some theories of memory predict that visual and verbal processing are separate as well as storage (Friedman & Miyake, 2000; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001).

To examine the separability of resource pools in working memory, Shah and Miyake (1996) developed the “spatial span.” In this task, participants are presented with one letter at a time that might be rotated. Participants are asked to remember the orientation of the letters presented while also deciding if each letter is a mirror image. Spatial span scores were highly correlated with performance on tests of spatial ability, including tests that do not contain mental rotation (rotation arrow span $r(28) = .68$; verification arrow span $r(28) = .65$; simple arrow span $r(28) = .63$). Similarly, a measure of word span was correlated with verbal SAT scores (verification word span $r(28) = .55$; rotation word span $r(28) = .22$; simple word span $r(28) = .44$). Importantly, spatial span scores did not correlate with verbal SAT scores and the reading span score did not correlate with the spatial ability tests. Additionally, there was only a small correlation between the spatial span and reading span scores ($r(28) = .23$), indicating that spatial and verbal working memory are separable. An interference paradigm was used to cross the manipulation component of the task (either mental rotation or sentence verification) with the type of information to be maintained (spatial orientation or two-syllable words). Participants took longer to do the spatial manipulations when the information participants had to maintain spatial information instead of verbal, indicating interference when processing and maintenance share the same modality. These results show that while visual and verbal working memory processing may be correlated, they are ultimately separable.

Alloway, Gathercole, and Pickering (2006) used confirmatory factor analysis to test four models of working memory on a comprehensive dataset from children (ages 4–11), covering visual and verbal processing and storage tasks. The first model had two factors for visuospatial and verbal abilities, and the six tests that each factor was designed to capture fully loaded onto those factors (e.g., the verbal factor was associated with all of the verbal tests, and none of the visuospatial ones). The second model again had two factors, for the processing and storage components of working memory, and the tests that each factor was designed to tap into fully loaded onto each of those factors. Neither of those two models were a particularly good fit for the data, indicating that the data cannot be fully explained by just being verbal/visuospatial or by processing/storage in short term memory. The third model tested was the Shah and Miyake (1996) model of working memory, with domain specific storage and domain specific processing, leading to a total of four factors. This model

was a better fit for the data (fit indices higher than 0.90). However, there was a very high correlation between the factor for visuospatial processing and verbal processing ($r = 0.91$, 83% of variance shared). This implies that while the model is a better fit for the data than the first two models, it may not be ideally explained by having fully separate pools for visuospatial and verbal processing. Lastly, a Baddeley model was tested, with separate factors for visuospatial and verbal storage, but only one factor for processing. This model was a slightly better fit for the data (goodness of fit was 0.94), indicating that there may be shared processing for the two domains. Combined, these models indicate that there may be both domain-specific processing as well as some universal processing capacity.

Separate visual and verbal processing and storage is supported by evidence from an fMRI study of delayed match-to-sample and delayed paired associate tasks (Ranganath, Cohen, Dam, & D'Esposito, 2004). In that study, participants learned faces, houses, and face-house pairings. When participants needed to maintain a face as a response to either an earlier face or an associated house, there was increased activity in the fusiform gyrus (fusiform face area) during the delay period. Conversely, when a house would need to be maintained in working memory, there was increased activity in the parahippocampal gyrus. Similar findings are seen with verbal working memory. When words and nonwords needed to be maintained in working memory, an area of inferior temporal cortex was more active when maintaining words compared to nonwords (Fiebach, Rissman, & D'Esposito, 2006). The nonwords were orthographically valid and pronounceable, so the difference in activity can be attributed to a stored knowledge of the semantic content of actual words. Moreover, the activity in the parts of the brain that traditionally process the content of the working memory task is not limited to the maintenance of presented information. Participants generating or evaluating a mental image, showed reproducible and consistent activity in V1 (calcarine sulcus) associated with that mental image (Klein, Paradis, Poline, Kosslyn, & Le Bihan, 2000). These results indicate that the brain regions that support the processing of visual or verbal information are active during working memory tasks that require the processing of information within that domain. Furthermore, this activation is not an artifact of having just seen the stimulus. The brain regions that support to perception of domain-specific information also support the internal generation of information within that domain.

Specific deficits in visual and verbal working memory as well as deficits in working memory broadly can have a strong impact on academic achievement. Impaired working memory affects a student's ability to complete complex tasks. In some cases, overloading working memory can lead to the inability to finish tasks, like writing a sentence (Gathercole & Alloway, 2008; Gathercole et al., 2006). Losing track of an ongoing activity means that the student must guess or stop progress entirely. If there is no compensation for these deficits, the student will fall behind in learning. The more frequently this happens, the further behind the child will fall, and the higher working memory load is necessary to catch up. Working memory ability (independently from IQ) predicted learning in 37 children with learning difficulties across two tests of reading and mathematical ability administered 2 years later (Alloway, 2009)

While many children are diagnosed with broad working memory deficits, there are also specific visual and verbal working memory deficits (Archibald & Alloway, 2008; Archibald & Gathercole, 2006). For reading development in children, Swanson and Howell (2001) found that the phonological loop and central executive were both important for word recognition and comprehension. The two systems operated differently, independently predicting reading performance. Verbal working memory and short term memory are also separable and independently affect reading ability. In children with selective language impairment, 95% of children were found to have an impairment to verbal working memory (both storage and processing), and 70% were had a deficit in verbal short term memory (Archibald & Gathercole, 2006). Deficits in verbal working memory and verbal short term memory seem to be separate, parallel deficits. In children aged 4–8 who had only verbal short term memory deficits (and low-average verbal working memory), those children reached age-appropriate reading ability in 4 years (Gathercole et al., 2005). While verbal working memory has been shown to affect mathematical ability, this seems to be limited to mental arithmetic (Fürst &

Hitch, 2000). In contrast, a study of 9-year-old children with mathematical difficulties showed that they had reduced capacity for visuospatial working memory and executive function compared to controls, but there no significant difference in verbal working memory (McLean & Hitch, 1999).

Studies of children and adolescents with ADHD have also revealed a separation between deficits in the verbal and spatial domains. In a meta-analysis of 26 studies examining working memory deficits in children with ADHD, Martinussen, Hayden, Hogg-Johnson, and Tannock (2005) categorized the existing literature as either testing storage or processing and focusing on either visual or verbal material. They found that the effect sizes for spatial storage and spatial processing (Cohen's *d* of .85 and 1.06, respectively) were larger than the effect sizes for verbal storage or verbal processing (Cohen's *d* of .47 and .43). An additional study of visual and verbal working memory deficits in children with ADHD and language impairment found that while children with ADHD (regardless of comorbidity with language impairment) had deficits in spatial storage and processing as well as verbal processing, only children with language impairment (regardless of ADHD) had additional impairment with verbal storage (Martinussen & Tannock, 2009).

If there is separability between visual and verbal working memory, a person with a deficit with one domain might compensate by offloading processing to the other domain. Consistent with this hypothesis, there is some evidence that working memory can be supported in the classroom through the separation of domain specific processing. The "modality effect" in multimedia learning suggests that text that accompanies a picture is better presented in an auditory format. To understand a diagram and its accompanying caption, students need to extract the necessary information from each, hold it in working memory, and integrate it. The need to integrate the same information from multiple sources leads to a working memory load that negatively impacts the ability to learn the material (Sweller, Merriënboer, & Paas, 1998). When presented auditorily, the student can listen to the text while looking at the figure, and can focus attention on the part of the figure being referred to by the caption (Seufert, Schütze, & Brünken, 2009). Further studies showed participants with low working memory capacity performed worse in the visual only condition, though participants with high working memory capacities performed worse in the audiovisual condition (Seufert et al., 2009). This is likely because the high working memory participants had no trouble processing and integrating information, and were possibly suffering from interference in the audiovisual condition. Working memory can be supplemented by using multimedia (specifically audiovisual) material to present figures alongside text, but this effect can disappear and be detrimental when used with high working memory capacity learners. Other studies have shown that low working memory can be aided by restructuring tasks into smaller pieces, and important information should be repeated (Gathercole et al., 2006; Turley-Ames & Whitfield, 2003). However, training working memory through the use of working memory "brain games" does not seem to have a reliable effect (Owen et al., 2010; Shipstead, Redick, & Engle, 2012).

The aforementioned research indicates that visual and verbal working memory have dissociable processing components as well as a unified domain-general processing component. Working memory has some wide-ranging implications for academic success and reduced working memory capacity, both broadly and in terms of specific visual or verbal working memory deficits. Nevertheless, if identified early on, working memory deficits can be supplemented, such as through multimedia figure presentation, to reduce the effects.

Task strategies

Thus far, we have focused our attention on research that investigates variation in task performance and academic achievement related to cognitive abilities and working memory. Now we turn to studies from cognitive neuroscience and neuropsychology that provide insight into the differential recruitment of neural resources that underlie these and other individual differences in cognition. Specifically, fMRI studies of neurotypical individuals, MRI and diffusion tensor imaging (DTI) studies of individuals on the autism spectrum, and neuropsychological studies of individuals with

focal brain lesions have revealed differential usage of verbal and visual brain networks, in some cases leading to dramatically affected task performance on various tasks of reasoning and memory.

In perhaps the most comprehensive investigations to date of individual differences in brain activity, Miller and colleagues (Miller, Donovan, Bennett, Aminoff, & Mayer, 2012; Miller et al., 2009) have quantified the enormous variation in brain activity between individuals performing the same task. For example, (Miller et al., 2012) tested forty-five participants in two fMRI sessions separated in time, in which participants completed a verbal encoding task. During one session, the to-be-remembered word list consisted of imageable nouns, and in the other session the words were non-imageable (abstract) nouns. Instead of focusing on regions more active in encoding imageable compared to abstract nouns, the researchers compared activity between participants, both within the same condition and across conditions. Strikingly, the results demonstrated that the average cross-correlation between any two participants during the same condition was far lower than the average correlation within the same participant at two different scan sessions encoding two different word lists (Miller et al., 2012, 2009). In other words, the assumption that all participants were performing the task in roughly the same way—an assumption that underlies the methodological approach of averaging brain activity across participants—was not borne out by the data. Instead, the results of this study and others (Kirchhoff & Buckner, 2006; David J. M. Kraemer, Rosenberg, & Thompson-Schill, 2009; Miller et al., 2009; 2012) demonstrate that *differences* between participants are often at least as important to consider as the group-level *similarities*.

But what underlies these between-subject individual differences in brain activity? Here too, the study by Miller et al. (2012) provided some insight. In trying to explain the sources of individual variation, they examined many factors, such as anatomical variation, demographic characteristics, and task strategies that participants used during the encoding task. They found that among other factors, task strategies accounted for a significant portion of the variance in brain activity between individuals. Verbal and visual task strategies were measured in two ways: participants were asked about their usage of conscious strategies (e.g., imagining what the objects look like; grouping similar items by their word sounds), and they were also given assessments of cognitive style (e.g., propensity for visuospatial mental imagery; propensity for engaging in language-related activities). Both conscious task strategies and cognitive style (CS) accounted for unique variance in brain activity across brain regions and across participants. Future studies looking at mean differences can better account for individual differences by collecting data with similar measures (e.g. task strategy, cognitive style, working memory capacity, intelligence scales) and determining the amount of variance accounted for by these measures. If significant proportions of variance are accounted for by some of these measures, the data should be analyzed including these differences in the model.

Consistent with these findings, Kirchhoff and Buckner (2006) found that verbal and visual encoding strategies during a picture-based encoding task explained a significant portion of individual variation in brain activity. Similarly, Kraemer et al. (2009) found that verbal and visual CS—thought to reflect propensities for engaging in visual or verbal thought processes (Kozhevnikov, Kosslyn, & Shephard, 2005)—correlated with activity in different modality-selective brain regions while participants performed a working memory task. Further underscoring the role played by individual differences in task approaches, Kraemer and colleagues (Kraemer, Hamilton, Messing, DeSantis, & Thompson-Schill, 2014) used repetitive transcranial magnetic stimulation (rTMS) to disrupt the activity in a language-related brain region thought to underlie the verbal task strategy in the same task they used for the earlier working memory study. They found that when rTMS was applied to the left supramarginal gyrus, participants who rated highly on the verbal CS measure were more impaired at the task, but participants who rated lower on the verbal scale and higher on the visual CS scale were unaffected. Taken together, these studies provide clear evidence that individual differences, including conscious task strategies and self-reported cognitive styles, exert a significant and measurable influence on brain activity as well as task performance.

Several neuroimaging studies have extended our understanding of verbal thinking in general, and the verbal CS in particular, which is characterized by a propensity for using language to encode,

reason, and problem-solve. For example, an fMRI study by Zarnhofer and colleagues (2012) revealed that during a math task that required mental calculation, higher verbal CS was associated with more activity in left-hemisphere regions implicated in language processing, including angular gyrus, inferior frontal gyrus, and Heschl's gyrus. This is consistent with the notion that individuals who score higher on the verbal CS scale are more likely to use verbal task strategies to complete a task. In a different domain, Shin and Kim (2015) used a color-word Stroop conflict task to test the interaction of verbal CS and cognitive control. They found that conflict adaptation—a measure of cognitive control flexibility that assesses performance as a function of previously-experienced conflict—varied by one's verbal style. Participants with higher verbal CS showed greater conflict adaptation effects, responding better to trials that matched the previous trial type, especially when they were congruent. These effects were seen both in the behavioral results (response times) and in the neural data, with left-hemisphere task-related regions such as dorsolateral prefrontal cortex, fusiform gyrus and precuneus showing greater adaptation effects for participants with higher verbal CS scores.

Neuropsychological studies of patients with brain lesions and their associated behavioral deficits have also shed light on the role of verbalization in task strategies across various tasks. Baldo and colleagues (2005) determined that verbalization strategies play an important role even in “non-verbal” reasoning tasks, such as Raven's Progressive Matrices and the Wisconsin Card Sorting Task. They studied the performance of patients with aphasia and found that the severity of the language deficit correlated significantly with performance on these reasoning tasks and did not correlate with control tasks that focused on visuospatial functioning. A follow-up experiment with neurotypical undergraduate students showed a similar impairment when students engaged in articulatory suppression. These results clearly implicate verbalization processes in solving reasoning tasks, including those associated specifically with non-verbal (i.e., visuospatial) processing. Similarly, Oliveri and colleagues (2012) found that lesions to parietal regions correlated with reduced rates for verbal CS, consistent with the findings of Kraemer et al. (2009). In contrast, bilateral subcortical lesions, which preferentially damage visual processing (Oliveri et al., 2012), correlated with increased verbalization rates. The authors conclude that damage to verbal or visual systems—while not ablating that system's function entirely—bias the patient to use the compensatory style afforded by the intact processing system.

Other studies have revealed the neural and behavioral characteristics associated with the visual cognitive style (i.e., a propensity for engaging in visuospatial cognition or focusing on visual features during encoding). Complementing the aforementioned study regarding verbal processing during math problem solving, Zarnhofer and colleagues (2013) showed that higher visual CS is associated with more activity in visual brain areas during mental calculation, whereas higher verbal CS was again associated with greater activity in the left angular gyrus. Another advantage for the visual CS was seen in a task where participants retrieved color information when given object names (Hsu, Kraemer, Oliver, Schlichting, & Thompson-Schill, 2011). Higher visual CS scores were correlated with better performance in the more difficult color retrieval condition. Activity in the lingual gyrus during this condition was also higher for participants with higher visual CS scores, consistent with the use of a more vivid visual imagery strategy to retrieve the color information.

Using event-related potential (ERP) with electroencephalography, researchers have demonstrated that individuals differ in the strategy they use to approach specific tasks. Focusing on an ERP component (the incongruency negativity) that indicates conflict processing, Buzzell, Roberts, Baldwin, and McDonald (2013) gave participants a navigation task in which spatial cues and semantic cues were sometimes in conflict. As in previous studies, the incongruency negativity component reflected the conflict between the types of information being processed, but here this was only observed when participants performed their non-dominant task (e.g., visual navigators attempting to ignore spatial information). In other words, CS was correlated with neural conflict, indicating that different participants were using different information to complete the task, based on their cognitive style. Kraemer, Schinazi, Cawkwell, Epstein, and Thompson-Schill (2016) also found evidence that cognitive style influences the information that participants attend to during a navigation task. They tested memory

for two types of information, landmark memory, which was potentially verbalizable, and judgments of relative direction (JRD), which were not, and found an interaction between task performance and cognitive style. The higher one scored on the visual CS scale, the better that participant performed on the spatial JRD task, and the higher one scores on the verbal CS scale, the better that participant performed on the landmark memory test. Thus, visual and verbal CS again were found to predict differences in task strategies. In a follow-up experiment, however, the authors found that when given specific task instructions for using a verbal or a visual encoding strategy, all participants were able to adopt the new strategy, independent of their cognitive style. As predicted, in this experiment an interaction was seen between the instruction given for task strategy and the type of material to be recalled (Kraemer et al., 2016). Thus, the results support the interpretation that cognitive styles reflect flexible propensities for task strategies, and not entirely immutable habits or abilities.

A few studies have also investigated the neural differences between different types of visual processing. Looking at working memory for visual objects, an ERP study found a distinction between “object” visualizers, who tend to focus on the 2-dimensional shapes of objects and salient visual features, and “spatial” visualizers, who are more focused on the 3-dimensional visuospatial properties of objects and sets of objects in physical space. During a visual working memory task, Li, Gong, Jia, Zhang, and Ma (2011) showed that higher scores on the object dimension than on the spatial dimension predicted better performance across a range of delay periods, whereas scores on the other end of that dimension correlated with attenuated performance at longer delays. This behavioral benefit for the object-oriented style was associated with higher neural efficiency in the 1800–3800 ms stage of processing. Similarly, using an fMRI paradigm with an object processing task, Motes, Malach, and Kozhevnikov (2008) also showed greater neural efficiency for object > spatial visualizers in brain areas that are implicated in object identification including lateral occipital complex.

A related line of studies (Sahyoun, Belliveau, & Mody, 2010; Sahyoun, Soulières, Belliveau, Mottron, & Mody, 2009; Soulières et al., 2009) focused on individuals with forms of Autism Spectrum Disorder (ASD) while solving problems biased toward particular task strategies. One study (Sahyoun et al., 2009) administered a reasoning task to age and IQ matched young adults ($M_{age} = 19$ y-o) with High Functioning Autism (HFA), Asperger’s Syndrome (ASP), and typically-developing controls. The reasoning task was designed with three conditions; two that biased a spatial or verbal strategy, and one that was solvable with either strategy. All three groups had equivalent accuracy, but showed different response time profiles. In the HFA group, tasks that biased or allowed for a visuospatial strategy had the lowest response times. In contrast, the ASP and control groups had the lowest response times for the condition that allowed either strategy, and had slower response times for tasks that biased either strategy. This indicates that participants with HFA seemed to show a preference for the visuospatial strategy for solving the reasoning problems, leading to equally fast response times for both for when the task biased towards a visual strategy or was not biased towards either strategy. In a follow-up study using the same task and comparing HFA children with matched controls, fMRI results indicate greater engagement of posterior visual brain regions, and DTI results indicate weaker connections to frontal language regions (Sahyoun, Belliveau, Soulières, Schwartz, & Mody, 2010). In another DTI study, white matter connections in the parietal and ventral temporal pathways were strongest in the HFA group (Sahyoun et al., 2010), whereas connections between prefrontal cortex and temporal regions were strongest in the control group. Together, these studies show a bias toward visuospatial processing in individuals with HFA, leading to improved performance on tasks that are biased towards or allow visuospatial strategies. This is a clear example of variation in task strategy approaches used by individuals performing the same tasks.

Conclusion

What is apparent from these investigations is that the view of the mind as a set of cognitive mechanisms that are common across all individuals is overly simplistic. Rather, it is critical to consider individual variation in the different ways that participants approach a task, the different

strategies they use to process and recall information, and the different capacities they possess for remembering or reasoning about specific types of stimuli.

The results presented in this review can be broadly categorized into three classifications. First, there are several examples in which differences in task strategies led to equivalent outcomes in terms of task accuracy. Even when response times differed significantly between individuals, it can be argued that the main interpretation of these results does not indicate a difference in quality between strategies, but rather indicates that there is more than one way to complete the task. Different individuals approach the task differently, even when there is no clear benefit. The importance of these differences may lie in other contexts; while they may not affect the results of one task, they are indicative of differences in habits of thought or neural processes that may have consequences in other domains. Whether or how these differences will be useful in an educational context remains to be determined. Attempts to match the format of presentation to a student's cognitive style (e.g., illustrations instead of text for a student with visual CS) generally do not yield benefits to learning (Massa & Mayer, 2006; Pashler, McDaniel, Rohrer, & Bjork, 2008; Rogowsky, Calhoun, & Tallal, 2015). Thus, caution is warranted in applying the findings describe here to educational contexts without further basic research to determine when and how these differences are relevant to the learning context within the normal range of variation. Moreover, data from cognitive and neuroimaging studies suggest that propensities for certain task strategies or styles may be beneficial or not depending on the task context and which features the learner must focus on (Fedorenko et al., 2011, 2014; Kraemer et al., 2009, 2016; Ryan & Schooler, 1998).

A second type of finding that emerges from studies of individual differences indicates areas in which a particular deficit, such as reduced verbal working memory, can lead to poor performance in a certain academic area, such as reading comprehension. This information can be useful in correctly ascribing the difficulties that students are having to a specific cognitive source, rather than to a general pattern of disruptive or counterproductive behavior. Such a determination can be useful in generating remediative treatment approaches and compensatory strategies. Ultimately, this may improve the student's capacity for academic achievement and reduce their frustration and lost time and effort spent struggling with seemingly insurmountable tasks. Fast and accurate identification of a student's particular working memory deficits could prevent that student from continually falling further behind.

Lastly, individual differences research on cognitive abilities has pointed us towards indicators of particularly successful outcomes. For instance, decades of longitudinal work (Park et al., 2007; Wai et al., 2005, 2009, 2010) have demonstrated that abilities related to spatial cognition are critical predictors of success in STEM careers. In a similar vein, a recent study has indicated that visual cognitive style is associated with generation of more creative inventions in a lab-based creativity task (Palmiero, Nori, & Piccardi, 2016). These studies focusing on positive outcomes, such as creativity and STEM attainment, highlight important indicators of cognitive differences that can potentially be targeted in educational settings as goals for development. Future work is needed to determine how best to facilitate the development of these cognitive resources.

The studies discussed here clearly indicate that inter-individual variation is more than simply noise in the data. These individual differences form consistent patterns that account for and predict various outcomes across cognitive domains. Even along the visual-verbal dimension of individual differences, research has demonstrated the clear implications for future success in STEM, specific patterns of working memory deficits, and selection of specific task strategies. These differences are so significant that in some cases the brain activity of one person performing two separate tasks is more similar than two people doing the same task. Averaging across these differences discards valuable data that can not only explain variation between individuals, but predict future outcomes. Research on individual differences consists of useful investigations of what make certain individuals struggle or excel at certain tasks, and it teaches us important lessons regarding the human mind.

References

- Alloway, T. P. (2009). Working memory, but not IQ, predicts subsequent learning in children with learning difficulties. *European Journal of Psychological Assessment*, 25(2), 92–98. doi:10.1027/1015-5759.25.2.92
- Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, 77(6), 1698–1716. doi:10.1111/j.1467-8624.2006.00968.x
- Archibald, L. M. D., & Alloway, T. P. (2008). Comparing language profiles: Children with specific language impairment and developmental coordination disorder. *International Journal of Language & Communication Disorders*, 43(2), 165–180. doi:10.1080/13682820701422809
- Archibald, L. M. D., & Gathercole, S. E. (2006). Short-term and working memory in specific language impairment. *International Journal of Language & Communication Disorders*, 41(6), 675–693. doi:10.1080/13682820500442602
- Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, 4(10), 829–839.
- Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, 63(1), 1–29. doi:10.1146/annurev-psych-120710-100422
- Baldo, J., Dronkers, N., Wilkins, D., Ludy, C., Raskin, P., & Kim, J. (2005). Is problem solving dependent on language? *Brain and Language*, 92(3), 240–250. doi:10.1016/j.bandl.2004.06.103
- Buzzell, G. A., Roberts, D. M., Baldwin, C. L., & McDonald, C. G. (2013). An electrophysiological correlate of conflict processing in an auditory spatial Stroop task: The effect of individual differences in navigational style. *International Journal of Psychophysiology*, 90(2), 265–271. doi:10.1016/j.ijpsycho.2013.08.008
- Carroll, J. B. (1993). *Human Cognitive Abilities: A Survey of Factor-Analytic Studies* (1st Edition). Cambridge University Press.
- Chiou, R., & Lambon Ralph, M. A. (2016). The anterior temporal cortex is a primary semantic source of top-down influences on object recognition. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 79, 75–86. doi:10.1016/j.cortex.2016.03.007
- Colom, R., Jung, R. E., & Haier, R. J. (2006). Distributed brain sites for the g-factor of intelligence. *NeuroImage*, 31(3), 1359–1365. doi:10.1016/j.neuroimage.2006.01.006
- Coutanche, M. N., & Thompson-Schill, S. L. (2015). Creating concepts from converging features in human cortex. *Cerebral Cortex*, 25(9), 2584–2593. doi:10.1093/cercor/bhu057
- Deary, I. J., Penke, L., & Johnson, W. (2010). The neuroscience of human intelligence differences. *Nature Reviews Neuroscience*, 11(3), 201–211. doi:10.1038/nrn2793
- Deary, I. J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence*, 35(1), 13–21. doi:10.1016/j.intell.2006.02.001
- Dronkers, N. F., Wilkins, D. P., Van Valin, R. D. Jr., Redfern, B. B., & Jaeger, J. J. (2004). Lesion analysis of the brain areas involved in language comprehension. *Cognition*, 92(1–2), 145–177.
- Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence. In A. Miyake, & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). New York, NY, US: Cambridge University Press. doi:10.1017/CBO9781139174909.007
- Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, 128(3), 309–331. doi:10.1037/0096-3445.128.3.309
- Fedorenko, E., Behr, M. K., & Kanwisher, N. (2011). Functional specificity for high-level linguistic processing in the human brain. *Proceedings of the National Academy of Sciences of the United States of America*, 108(39), 16428–16433. doi:10.1073/pnas.1112937108
- Fedorenko, E., & Thompson-Schill, S. L. (2014). Reworking the language network. *Trends in Cognitive Sciences*, 18(3), 120–126. doi:10.1016/j.tics.2013.12.006
- Fiebach, C. J., Rissman, J., & D'Esposito, M. (2006). Modulation of inferotemporal cortex activation during verbal working memory maintenance. *Neuron*, 51(2), 251–261. doi:10.1016/j.neuron.2006.06.007
- Friedman, N. P., & Miyake, A. (2000). Differential roles for visuospatial and verbal working memory in situation model construction. *Journal of Experimental Psychology: General*, 129(1), 61–83. doi:10.1037/0096-3445.129.1.61
- Fürst, A. J., & Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Memory & Cognition*, 28(5), 774–782. doi:10.3758/BF03198412
- Gathercole, S. E., & Alloway, T. P. (2008). *Working memory and learning: A practical guide for teachers*. Los Angeles, CA: Sage.
- Gathercole, S. E., Tiffany, C., Briscoe, J., Thorn, A. S. C., Team, A., et al. (2005). Developmental consequences of phonological loop deficits during early childhood: A longitudinal study. *Journal Children Psychologist Psychiatry*, 46(6), 598–611.
- Gathercole, S. E., Lamont, E., & Alloway, T. P. (2006). Working memory in the classroom. In *Working memory and education* (pp. 219–240). Elsevier. doi:10.1016/B978-012554465-8/50010-7.

- Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience*, 6(3), 316–322. doi:10.1038/nn1014
- Hodges, J. R., Patterson, K., Oxbury, S., & Funnell, E. (1992). Semantic dementia. *Progressive Fluent Aphasia with Temporal Lobe Atrophy. Brain: A Journal of Neurology*, 115(Pt 6), 1783–1806.
- Hsu, N. S., Kraemer, D. J. M., Oliver, R. T., Schlichting, M. L., & Thompson-Schill, S. L. (2011). Color, context, and cognitive style: Variations in color knowledge retrieval as a function of task and subject variables. *Journal of Cognitive Neuroscience*, 23(9), 2544–2557. doi:10.1162/jocn.2011.21619
- Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behavioral and Brain Sciences*, 30(2), 135. doi:10.1017/S0140525X07001185
- Kirchhoff, B. A., & Buckner, R. L. (2006). Functional-anatomic correlates of individual differences in memory. *Neuron*, 51(2), 263–274. doi:10.1016/j.neuron.2006.06.006
- Klein, I., Paradis, A.-L., Poline, J.-B., Kosslyn, S. M., & Le Bihan, D. (2000). Transient activity in the human calcarine cortex during visual-mental imagery: An event-related fMRI study. *Journal of Cognitive Neuroscience*, 12(supplement 2), 15–23. doi:10.1162/089892900564037
- Kozhevnikov, M., Kosslyn, S., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & Cognition*, 33(4), 710–726.
- Kraemer, D. J. M., Hamilton, R. H., Messing, S. B., DeSantis, J. H., & Thompson-Schill, S. L. (2014). Cognitive style, cortical stimulation, and the conversion hypothesis. *Frontiers in Human Neuroscience*, 8, 1–9. doi:10.3389/fnhum.2014.00015
- Kraemer, D. J. M., Rosenberg, L. M., & Thompson-Schill, S. L. (2009). The neural correlates of visual and verbal cognitive styles. *Journal of Neuroscience*, 29(12), 3792–3798. doi:10.1523/JNEUROSCI.4635-08.2009
- Kraemer, D. J. M., Schinazi, V. R., Cawkwell, P. B., Epstein, R. A., & Thompson-Schill, S. L. (2016). Verbalizing, visualizing, and navigating: The effect of strategies on encoding a large-scale virtual environment. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43(4), 611.
- Lee, K. H., Choi, Y. Y., Gray, J. R., Cho, S. H., Chae, J.-H., Lee, S., & Kim, K. (2006). Neural correlates of superior intelligence: Stronger recruitment of posterior parietal cortex. *NeuroImage*, 29(2), 578–586. doi:10.1016/j.neuroimage.2005.07.036
- Li, S., Gong, D., Jia, S., Zhang, W., & Ma, Y. (2011). Object and spatial visualizers have different object-processing patterns: Behavioral and ERP evidence. *NeuroReport*, 22(17), 860–864. doi:10.1097/WNR.0b013e32834b6d3b
- Martinussen, R., Hayden, J., Hogg-Johnson, S., & Tannock, R. (2005). A meta-analysis of working memory impairments in children with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, 44(4), 377–384.
- Martinussen, R., & Tannock, R. (2006). Working memory impairments in children with attention-deficit hyperactivity disorder with and without comorbid language learning disorders. *Journal of Clinical and Experimental Neuropsychology*, 28(7), 1073–1094.
- Massa, L. J., & Mayer, R. E. (2006). Testing the ATI hypothesis: Should multimedia instruction accommodate verbalizer-visualizer cognitive style? *Learning and Individual Differences*, 16(4), 321–335. doi:10.1016/j.lindif.2006.10.001
- McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology*, 74(3), 240–260. doi:10.1006/jecp.1999.2516
- Miller, M. B., Donovan, C.-L., Bennett, C. M., Aminoff, E. M., & Mayer, R. E. (2012). Individual differences in cognitive style and strategy predict similarities in the patterns of brain activity between individuals. *NeuroImage*, 59(1), 83–93. doi:10.1016/j.neuroimage.2011.05.060
- Miller, M. B., Donovan, C.-L., Van Horn, J. D., German, E., Sokol-Hessner, P., & Wolford, G. L. (2009). Unique and persistent individual patterns of brain activity across different memory retrieval tasks. *NeuroImage*, 48(3), 625–635. doi:10.1016/j.neuroimage.2009.06.033
- Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, 130(4), 621–640. doi:10.1037/0096-3445.130.4.621
- Motes, M. A., Malach, R., & Kozhevnikov, M. (2008). Object-processing neural efficiency differentiates object from spatial visualizers. *NeuroReport*, 19(17), 1727–1731. doi:10.1097/WNR.0b013e328317f3e2
- Oliveri, S., Incorpora, C., Genevini, M., Santagostino, L., Tettamanti, L., Antonietti, A., & Risoli, A. (2012). Clinical investigation of cognitive styles in patients with acquired brain damage. *Neuropsychological Rehabilitation*, 22(3), 362–373. doi:10.1080/09602011.2011.647416
- Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., ... Ballard, C. G. (2010). Putting brain training to the test. *Nature*, 465(7299), 775–778. doi:10.1038/nature09042
- Palmiero, M., Nori, R., & Piccardi, L. (2016). Visualizer cognitive style enhances visual creativity. *Neuroscience Letters*, 615, 98–101. doi:10.1016/j.neulet.2016.01.032
- Park, G., Lubinski, D., & Benbow, C. P. (2007). Contrasting intellectual patterns predict creativity in the arts and sciences: tracking intellectually precocious youth over 25 years. *Psychological Science*, 18(11), 948–952. doi:https://doi.org/10.1111/j.1467-9280.2007.02007.x

- Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning styles: Concepts and evidence. *Psychological Science in the Public Interest*, 9(3), 105–119.
- Ranganath, C., Cohen, M. X., Dam, C., & D'Esposito, M. (2004). Inferior temporal, prefrontal, and hippocampal contributions to visual working memory maintenance and associative memory retrieval. *Journal of Neuroscience*, 24(16), 3917–3925. doi:10.1523/JNEUROSCI.5053-03.2004
- Raven, J., Raven, J. C., & Court, J. H. (2000). *Manual for Raven's Progressive Matrices and Vocabulary Scales. Section 3: The standard progressive matrices*. San Antonio, TX: Harcourt Assessment.
- Rogers, T. T., Graham, K. S., & Patterson, K. (2015). Semantic impairment disrupts perception, memory, and naming of secondary but not primary colours. *Neuropsychologia*, 70, 296–308. doi:10.1016/j.neuropsychologia.2015.01.010
- Rogers, T. T., Patterson, K., & Graham, K. (2007). Colour knowledge in semantic dementia: It is not all black and white. *Neuropsychologia*, 45(14), 3285–3298. doi:10.1016/j.neuropsychologia.2007.06.020
- Rogowsky, B. A., Calhoun, B. M., & Tallal, P. (2015). Matching learning style to instructional method: Effects on comprehension. *Journal of Educational Psychology*, 107(1), 64–78. doi:10.1037/a0037478
- Rohde, T. E., & Thompson, L. A. (2007). Predicting academic achievement with cognitive ability. *Intelligence*, 35(1), 83–92.
- Rourke, B. P., & Finlayson, M. A. (1978). Neuropsychological significance of variations in patterns of academic performance: Verbal and visual-spatial abilities. *Journal of Abnormal Child Psychology*, 6(1), 121–133.
- Ryan, R. S., & Schooler, J. W. (1998). Whom do words hurt? Individual differences in susceptibility to verbal overshadowing. *Applied Cognitive Psychology*, 12(7), S105–S125.
- Sahyoun, C. P., Belliveau, J. W., & Mody, M. (2010). White matter integrity and pictorial reasoning in high-functioning children with autism. *Brain and Cognition*, 73(3), 180–188. doi:10.1016/j.bandc.2010.05.002
- Sahyoun, C. P., Belliveau, J. W., Soulières, I., Schwartz, S., & Mody, M. (2010). Neuroimaging of the functional and structural networks underlying visuospatial vs. linguistic reasoning in high-functioning autism. *Neuropsychologia*, 48(1), 86–95. doi:10.1016/j.neuropsychologia.2009.08.013
- Sahyoun, C. P., Soulières, I., Belliveau, J. W., Mottron, L., & Mody, M. (2009). Cognitive differences in pictorial reasoning between high-functioning autism and asperger's syndrome. *Journal of Autism and Developmental Disorders*, 39(7), 1014–1023. doi:10.1007/s10803-009-0712-9
- Salthouse, T. A. (2004). Localizing age-related individual differences in a hierarchical structure. *Intelligence*, 32, 6. doi:10.1016/j.intell.2004.07.003
- Seufert, T., Schütze, M., & Brünken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude–treatment–interaction study. *Learning and Instruction*, 19(1), 28–42. doi:10.1016/j.learninstruc.2008.01.002
- Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology-General*, 125(1), 4–26.
- Shin, G., & Kim, C. (2015). Neural correlates of cognitive style and flexible cognitive control. *NeuroImage*, 113, 78–85. doi:10.1016/j.neuroimage.2015.03.046
- Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin*, 138(4), 628–654. doi:10.1037/a0027473
- Soulières, I., Dawson, M., Samson, F., Barbeau, E. B., Sahyoun, C. P., Strangman, G. E., ... Mottron, L. (2009). Enhanced visual processing contributes to matrix reasoning in autism. *Human Brain Mapping*, 30(12), 4082–4107. doi:10.1002/hbm.20831
- Swanson, H. L., & Howell, M. (2001). Working memory, short-term memory, and speech rate as predictors of children's reading performance at different ages. *Journal of Educational Psychology*, 93(4), 720–734. doi:10.1037/0022-0663.93.4.720
- Sweller, J., Merriënboer, J. J. G. V., & Paas, F. G. W. C. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, 10, 251–296.
- Thompson-Schill, S. L. (2003). Neuroimaging studies of semantic memory: Inferring “how” from “where”. *Neuropsychologia*, 41(3), 280–292. doi:10.1016/S0028-3932(02)00161-6
- Turley-Ames, K., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language*, 49(4), 446–468. doi:10.1016/S0749-596X(03)00095-0
- Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, 28(2), 127–154. doi:10.1016/0749-596X(89)90040-5
- Wai, J., Lubinski, D., & Benbow, C. P. (2005). Creativity and occupational accomplishments among intellectually precocious youths: An age 13 to age 33 longitudinal study. *Journal of Educational Psychology*, 97(3), 484–492. doi:10.1037/0022-0663.97.3.484
- Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817.
- Wai, J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2010). Accomplishment in science, technology, engineering, and mathematics (STEM) and its relation to STEM educational dose: A 25-year longitudinal study. *Journal of Educational Psychology*, 102(4), 860.
- Wechsler, D. (2008). Wechsler Adult Intelligence Scale–Fourth Edition (WAIS–IV). San Antonio, TX: NCS Pearson, 22, 498.

- Zarnhofer, S., Braunstein, V., Ebner, F., Koschutnig, K., Neuper, C., Ninaus, M., ... Ischebeck, A. (2013). Individual differences in solving arithmetic word problems. *Behavioral and Brain Functions*, 9(1), 28.
- Zarnhofer, S., Braunstein, V., Ebner, F., Koschutnig, K., Neuper, C., Reishofer, G., & Ischebeck, A. (2012). The influence of verbalization on the pattern of cortical activation during mental arithmetic. *Behavioral and Brain Functions*, 8(1), 13.