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REVIEW ARTICLE

Why parametric measures are critical for understanding typical and atypical cognitive development

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Abstract Children's cognitive abilities improve significantly over childhood and adolescence. We know from behavioral research that core cognitive processes such as working memory and mental attention improve significantly across development. Functional magnetic resonance imaging (fMRI) allows for investigating the typically developing, living brain in action. In the last twenty years we have learned a great deal about brain correlates associated with how adults hold and manipulate information in mind, however, neurocognitive correlates across development remain inconsistent. We present developmental fMRI findings on cognitive processes such as working memory and mental attention and discuss methodological and theoretical issues in the assessment of cognitive limitations in the visual spatial and verbal domains. We also review data from typical and atypical development and emphasize the unique contribution parametric measures can make in understanding neurocognitive correlates of typical and atypical development.

Keywords Parametric measures · Cognitive development · Working memory · Mental-attentional capacity · Language impairment · Epilepsy

Mental attention is used when we ride a bike, solve a puzzle, or figure out the cost of an item on sale. Although most of us are fine with doing one thing at a time, it becomes much more challenging when we try to complete several things at once. Such cognitive challenges are in part due to limitations in the amount of information we can effortfully hold and manipulate in mind, which we refer to as mental-attentional capacity. Measurement of mental-attentional capacity can be used to index the type and quantity of items that need to be stored and manipulated within working memory (Pascual-Leone and Johnson 1999, Pascual-Leone and Johnson 2011; Arsalidou et al. 2010). We know that cognitive abilities improve dramatically over the school age years and coincide with a period of drastic brain development. Neuroimaging studies with adults have established a set of brain areas that typically activate to cognitive tasks such as those that require attention and working memory (e.g., Ruchkin et al. 2003; Rottschy et al. 2012). The challenge is to measure these improvements appropriately as typically developing children follow distinct stages of development. This is important because only then can we attempt to quantify similarities and differences in developmental trajectories of children with impairments. This paper will focus on methodological and theoretical issues in assessing capacity of mental attention across development and present measures that can be used concurrently to assess behavioral and neurofunctional performance. Then, we will describe clinical disorders – children with language impairment and children with epilepsy – and highlight the unique contribution that parametric measures can make in this field.

Neuroimaging findings on cognitive tasks

Neuroimaging provides an exciting opportunity to see images of the typically developing, living brain in action. This possibility opened up new ways of investigating ongoing processes

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during problem solving. Core cognitive processes such as attention and working memory have been extensively studied in adults and we know that a standard set of areas repeatedly activates to tasks that engage these processes (Owen et al. 2005; Rottschy et al. 2012). Meta-analyses of functional magnetic resonance imaging (fMRI) data show that adults activate a set of regions, which include the prefrontal cortex in the inferior and middle frontal gyri, the anterior cingulate and parietal cortex in the precuneus, and the inferior parietal lobe (Owen et al. 2005). This set of areas is referred to as the working memory network or the fronto-parietal network.

Several fMRI studies provide evidence about how children's brains activate in response to cognitive tasks, but the findings are inconsistent. An early study showed that, in response to a cognitive task, children and adults elicited activity in very similar regions (Thomas et al. 1999). Other studies showed that children demonstrated more widespread activation compared to adults (Geier et al. 2009) or that children activated a different set of areas compared to areas activated by adults (Ciesielski et al. 2006). Yet another study indicated adults elicited more activity than children in response to solving a cognitive task (O'Hare et al. 2008). Ultimately, a coordinate based meta-analysis (e.g., Laird et al. 2005; Eickhoff et al. 2009) would be very informative, however, inconsistencies across studies in methodology (e.g., age group and task selection) and issues of statistical power (e.g., $n > 100$ foci are recommended for performing an activation likelihood meta-analysis), do not currently allow for such an investigation. Overall, it is clear that there is a relation between development and neurocognitive responses, however we cannot yet specify that relation.

Methodological choices are often identified post-hoc as being the reason for the variable and inconsistent findings in the developmental neurocognitive literature. Unlike adult fMRI studies, where individual rather than developmental differences are the focus, studies with children should involve a multi-group approach that allows comparison across age, performance, and brain response. Many neuroimaging studies with children, however, choose to average performance over large age ranges (e.g., 8 to 13 years; Satterthwaite et al. 2012; Li et al. 2014) when we know from behavioral data that there are significant improvements in performance within these age ranges.

Another important factor for ascertaining developmental variation in neuroimaging findings is task selection. Tasks that are appropriate for one age group may result in ceiling or floor effects (or even chance performance) in another age group. Also, it is important to understand that similar performance levels do not imply similar brain responses. Interpreting brain responses in relation to age and performance levels can be quite complex. Many developmental studies often extrapolate post-hoc from adult findings to explain developmental variation (Crone and Ridderinkhof 2011); however, this approach does not explain the underlying developmental mechanisms that mature as a function of age. These mechanisms can be activated and manipulated by suitably designed, well-controlled tasks. Some have acknowledged that tasks with parametric manipulations in difficulty can be useful in explaining variable performance abilities in neuroimaging studies with children (e.g., Kotsoni et al. 2006). In the following sections we present cognitive tasks with distinct parametric increases in difficulty, which have been designed using developmental theory and have been used for years in developmental psychology. Moreover, we present new tasks that can be used with neuroimaging and are validated developmentally. As such, we propose that these tasks can be valuable tools in developmental cognitive neuroscience.

Typical development: quantifying mental-attentional capacity using parametric tasks

It is ubiquitous that typically developing children progressively perform more complex cognitive tasks. This is in part attributed to the development of core cognitive processes such as mental attention (Pascual-Leone 1970). Mental attention activates task relevant schemes (information bearing units), for a short period of time in the service of working memory. Working memory can be thought of as a mental space where information is held and manipulated. The first quantification of working memory was provided by Miller (1956), who claimed that young adults could hold 7 ± 2 units of information. In an influential paper, Pascual-Leone (1970) outlined a developmental theory that proposed the capacity of mental attention (or mental-attentional capacity) grows by one unit every other year from the age of three until the age of 15 when it reaches seven units, which is also the limit for adults (see Pascual-Leone 1987, for a more detailed discussion). Research with measures that were developed to evaluate mental-attentional capacity has resulted in a substantial body of evidence that supports the proposed growth of mental attention in various domains, including visual spatial and verbal (e.g., Agostino et al. 2010; Im-Bolter et al. 2006; Pascual-Leone and Johnson 2005, 2011). Below we outline data from tasks in these two domains.

Visual spatial domain The Figural Intersection Task is a parametric measure of mental-attentional capacity within the visual spatial domain with well-established replicated results (e.g., Pascual-Leone and Baillargeon 1994). It is an individually administered paper and pencil, self paced task that contains geometric shapes presented separately on the right side of each test page and overlapping on the left side. Children are asked to attend to every discrete shape on the right and then to locate the area of intersection of these shapes in the compound figure on the left. The number of relevant shapes ranges from

2 to 8, which represents the number of schemes that must be kept simultaneously activated by mental attention. Irrelevant shapes are also present in some items, which adds to the mental-demand of the item.

The Figural Intersection Task was designed by Juan Pascual-Leone in the 1960s (Pascual-Leone 1969). Since then it has been used to assess mental-attentional capacity in school-age children and adults in many countries. To provide a more complete picture of the results based on this task we compiled data from studies that used the Figural Intersection Task and reported mental-attentional capacity scores. First, we searched the literature using standard search engines such as Web of Science (http://www.isiknowledge.com), PsychInfo (http://search.proquest.com/psycinfo) and Google Scholar for key words such as "figural intersection task" and "figural intersection test". This search, which yielded a total of 224 manuscripts, was subjected to two successive exclusion criteria. First, duplicates, citations, and books were excluded. The resulting 119 articles were incorporated into a full text review. To preserve data interpretability, we only considered data from typically developing individuals from studies that used the Figural Intersection Task and reported a mental-attentional capacity score. When possible, we requested mental-attentional capacity scores from authors. Twenty-three studies were either reviews or research reports that mentioned the task somewhere in the text, 57 were studies that did not report mental-attentional capacity scores and nine studies were excluded for other reasons (e.g., mentioned "figural" in an irrelevant context). In the end, 30 published studies met the final selection criteria.

Figure 1 shows data from the 30 studies that report mental-attentional capacity scores on the Figural Intersection Task from a total of 3854 children (as young as 5 years of age) and 1515 adults (up to the age of 45 years). The majority of studies investigated performance on the Figural Intersection Task in North America, however several studies report data collected in South America, Europe, and Australia. It is particularly fascinating to see the graded improvements in mental-attentional capacity as a function of age, regardless of cultural background. This speaks to the cultural-fairness of this test. In parametric tasks, such as the Figural Intersection Task, an item should be solved only when a

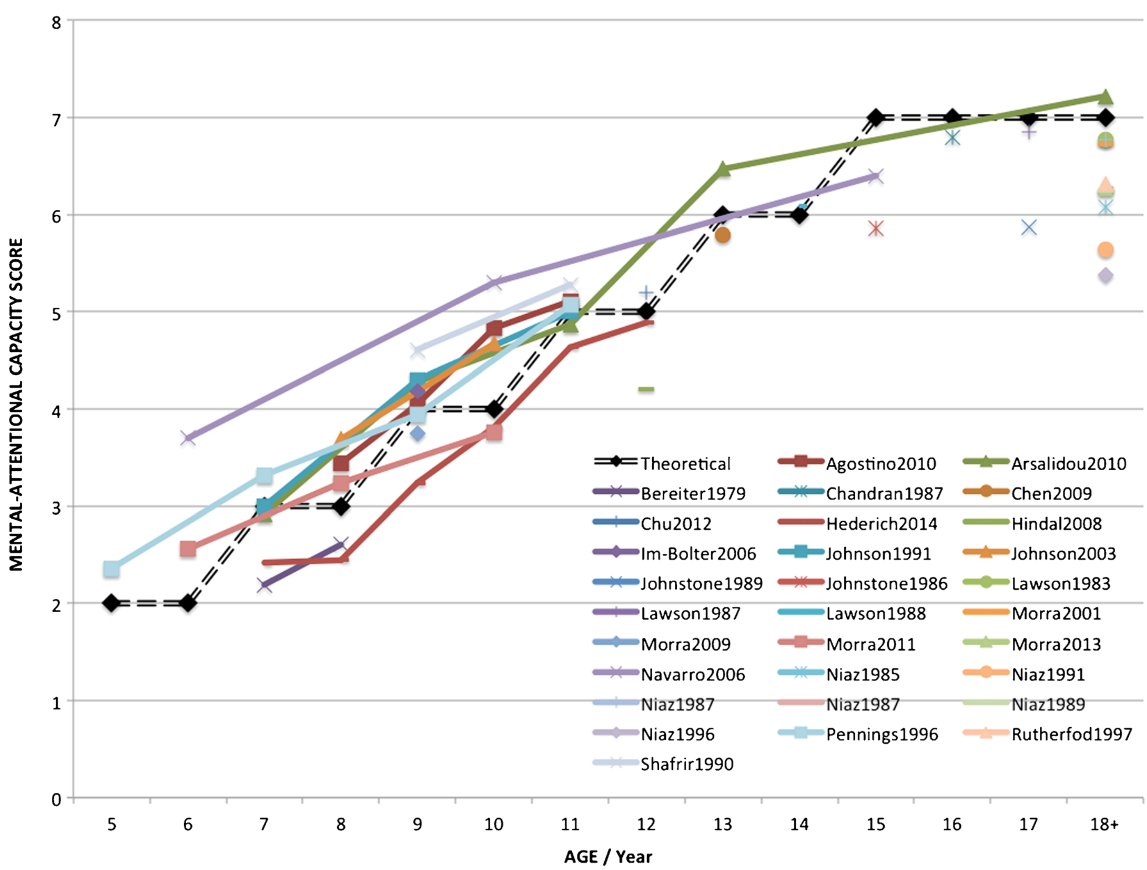

Fig. 1 Summary of mental-attentional capacity scores from the Figural Intersection Task. **Note**: Mental-attentional capacity scores correspond to the highest level of difficulty consistently passed. When grade was reported the earliest age in year was selected to plot the graph (e.g., grade 2 = 7 to 8 years, the score was plotted at 7). When a larger age range was reported the average age was plotted (e.g., for 11 to 13 years, the score was plotted at 12 years). When studies reported the distribution of mental-attentional capacity scores in their sample (e.g., for a total of 30 participants, five scored 4, 20 scored 5, and five scored 6) a mental-attentional capacity score was calculated by adding the scores multiplied by the proportion of participants

child's mental-attentional capacity is equal to or greater than the mental-attentional demand of that item. Quantification of developmental level, using a parametric approach, is particularly meaningful for education as it indicates the cognitive level at which a child needs to be in order to successfully accomplish a task. Indeed, there is a clear association between scores on the Figural Intersection Task and academic performance in areas such as science, chemistry, physics, biology, genetics, and mathematics (see Onwumere and Reid 2008, for a review).

Overall, the Figural Intersection Task is a well-established quantitative measure of mental-attentional capacity across development. Behavioral scores provide important information about age-bound performance levels in children; however, they do not allow for the tracking of ongoing processes as functional neuroimaging does. Although tasks may work well behaviorally they do not always transfer well to neuroimaging protocols due to specific limitations posed by the physical environment of the imaging method (Gaillard et al. 2001; Kotsoni et al. 2006). For instance, during an fMRI experiment a button press is typically required to record performance as it minimizes physical movements that could negatively affect image quality. A task also needs to adhere to time limitations in two ways: (a) trials need to be consistent in terms of presentation intervals so that easy trials are presented for the same amount of time as difficult trials to avoid variable presentation intervals from becoming a confound, and (b) measures should be kept short with frequent breaks particularly when testing younger children to avoid children getting bored and tired.

The Color Matching Task was designed to assess mental-attentional capacity parametrically and be suitable for use with fMRI (Arsalidou et al. 2010, 2013; Vogan et al. 2014). It is a computerized, timed paradigm designed to measure mental-attentional capacity where children see, one by one, a series of items; for each item they must indicate whether relevant colors of the current item match those of the immediately preceding one (Arsalidou et al. 2010). Each trial lasts three seconds, regardless of difficulty. This is similar to the *n*-back task (e.g., Owen et al. 2005); however, the number of intervening items between the current stimulus and the stimulus that is *n* back is not varied. Instead, the number of relevant colors that must be matched is varied from one to six, which together with constant executive demands indexes the mental-attentional demand of the item. Relevant colors are embedded in a figure, which provides consistent interference across levels of difficulty. The Color Matching Task was validated in a study across development with children (7 to 14 years) and adults (Arsalidou et al. 2010). Results showed high correlations with the Figural Intersections Task ($r = 0.65$, $p < 0.001$). A subsequent behavioral study replicated these results with children (7 to 16 years) and adults (Powell et al. 2014) and its applicability with fMRI was validated in children with and without autism (Vogan et al. 2014). Figure 2 shows mental-attentional capacity scores from these two behavioral studies (Arsalidou et al. 2010; Powell et al. 2014) plotted against original predictions of mental-attentional capacity in children (Pascual-Leone 1970).

fMRI data obtained using the Color Matching Task with healthy adults echoes the behavioral findings we see across typical development (Arsalidou et al. 2013). Areas that increase in activity as a function of difficulty are consistent with previous data from adults (e.g., Owen et al. 2005; Rottschy et al. 2012), however results with the Color Matching Task show the linear implication of these areas across six levels of difficulty (Arsalidou et al. 2013). Six levels of difficulty allow for examining the pattern of linearity and of note is that despite significant linear relations with difficulty the pattern of linearity was different between anterior and posterior brain regions.

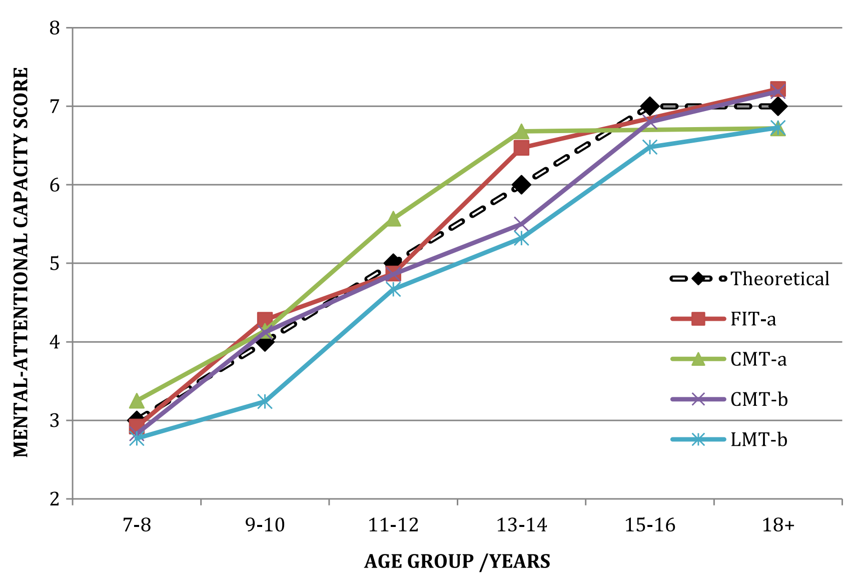

Fig. 2 Summary of mental-attentional capacity scores from visual spatial and verbal tasks. **Note**: Theoretical corresponds to theoretical predictions of mental-attentional capacity given by Pascual-Leone (1970). Figural Intersection Task (FIT) Color Matching Task (CMT) and Letter Matching Task (LMT) from two different studies (*a*; Arsalidou et al. 2010) and (*b*; Powell et al. 2014)

Specifically, prefrontal activity is explained by graded increases in demand for mental-attentional capacity, whereas activity in posterior cortices show bimodal implication with a sharp increase in activity for items with low demand for mental-attentional capacity compared to items with high demand for mental-attentional capacity. We emphasize that performance on the Figural Intersections Task (administered outside the scanner; Arsalidou et al. 2013) was highly correlated with fMRI signal change from prefrontal regions but not posterior regions elicited by the Color Matching Task administered in the scanner; these included right middle frontal gyrus and cingulate gyri bilaterally. This suggests that the variance associated with mental-attentional capacity can be explained in part by activity in these frontal regions.

Overall, the Color Matching Task with its parametric changes in difficulty allows for targeted questions that address brain-behaviour relations in the visual-spatial domain. Although, the Figural Intersections Task and the Color Matching Task may both be considered visual spatial tasks, theoretically mental-attentional capacity is viewed as a domain-general resource for cognition (Pascual-Leone 1970, Pascual-Leone 1987; Pascual-Leone and Johnson 2005, 2011). This is particularly relevant as it has important implications for assessing children with atypical development who are proposed to have domain specific impairments, such as language.

Verbal domain Verbal tasks that have been used to assess working memory capacity, in terms of number of items recalled with and without conflicting information, include the forward and backward digit span tasks. In these tasks the experimenter verbally presents progressively longer series of digits (e.g., 2 to 9 digits) at a rate of one digit per second (e.g., Hester et al. 2004). Participants have to repeat the digits in the order they listened to them (i.e., forward digit span or counting span) or in the reverse order (i.e., backward digit span). Typically, scores correspond to the total number of correct trials, prior to two consecutive incorrect trials at any one span size. In children, 6 to 10 years, significant correlations among the Figural Intersections Task, counting span, and backward word span were observed (Morra 1994). Despite the wide use of the forward and backward span tasks in neuropsychological assessment in children, very little work has been done to examine the brain correlates of these tasks in typically developing children. We have identified two studies, one study with 10-year olds showed that performance on the forward span correlated with activity only in the right angular gyrus, whereas the backward span elicited activity in frontal and temporal gyri as well as the insula (Rossi et al. 2013). The second study, with 7 to 17 year olds, showed that regardless of age the backward digit span was related to brain areas implicated in attention and cognitive control, whereas the forward digit span elicited activity mainly in posterior brain regions (Yang et al. 2015). It should be noted however, both these studies did not record brain activity while participants were performing the digit span tasks; instead, they correlated behavioral performance with brain activity recorded during resting-state scans. This speaks to the difficulty of administering verbal tasks in the MR scanner, as they often require a verbal response, which would cause excessive movement causing in turn image distortions.

The Direction Following Task measures mental attentional capacity in the verbal domain (Cunning 2003; Im-Bolter et al. 2006; Pascual-Leone and Johnson 2005, 2011). Children are asked to carry out oral directions that vary in terms of mental attentional demand. The task uses tokens of basic shapes, colors, and sizes, as well as a simple repetitive demand ("place X on Y″) to control for extraneous factors (e.g., preposition difficulty, degree of abstractness) that load heavily on experiential learning. Children place the tokens on spaces (on a board) that vary in color and size. Despite the broad differences between the Direction Following Task and Figural Intersection Task, the Direction Following Task correlates well with the Figural Intersection Task and other measures of mental-attentional capacity (Agostino et al. 2010; Cunning 2003; Im-Bolter et al. 2006; Morra et al. 2013; Pascual-Leone and Johnson 2005, 2011), verifying its validity. It has been used to predict performance on children's writing (Balioussis et al. 2012), mathematics (Agostino et al. 2010), and language competence (Im-Bolter et al. 2006). The Direction Following Task has similar limitations as the span tasks and the Figural Intersection Task in terms of fMRI applicability as the child needs to make multiple head and body movements to construct a response.

The Letter Matching Task was designed to be a verbal counterpart of the visual spatial Color Matching Task (Powell et al. 2014), which can be used with children in fMRI (Vogan et al. 2016). It is a computerized, timed paradigm and children have three seconds to indicate whether relevant letters of the current item match those of the immediately preceding one. Similar to the Color Matching Task, the number of relevant letters needed to determine a match range from one to six. Relevant letters are embedded in a pattern, a global-macro letter that looks like an *A*. The macro-pattern *A* is made up of the local, micro relevant and irrelevant letters. Relevant letters include the letter *A*. This pattern provides consistent interference because participants need to ensure that they ignore the large configuration on every trial. The Letter Matching Task was validated in a study with children (7 to 16 years) and adults, showing high correlation with the Color Matching Task ($r = 0.77$, $p < 0.001$; Powell et al. 2014). The Letter Matching Task correlates highly with the Color Matching Task, and although we would expect a high correlation with scores on the Direction Following Task, we do not currently have data to directly confirm this. Results show that mental-attentional capacity scores closely follow theoretical expectations at each age (Pascual-Leone 1970; Powell et al. 2014). Figure 2 illustrates the trajectories of performance on the Letter Matching Task and how it parallels theoretically predicted scores and those from the Color Matching Task.

An fMRI study that examined the brain correlates of the Letter Matching Task in children (9 to 15 years) shows children activate prefrontal and parietal regions as a function of difficulty (Vogan et al. 2016). These include bilaterally the anterior cingulate, middle frontal gyri, and precuneus. These results were consistent with a developmental investigation of the Colour Matching Task that showed that children aged 7 to 13 years also linearly implicate the anterior cingulate and prefrontal cortices and the precuneus, bilaterally as a function of difficulty (Vogan et al. 2014). In addition, solving the Colour Matching Task also implicates the fusiform gyri, which is consistent with adult data (Arsalidou et al. 2013). Commonalities in brain areas observed among tasks support the theoretical assumption of mental-attentional capacity as a domain-general resource. However, a direct task comparison is needed to confirm this.

The Color and Letter Matching Task have the following characteristics in common: (a) multiple, parametrically scaled levels of complexity that capture increases in mental-attentional capacity across development, (b) invariant need for executive control across classes of items to ensure that younger and older children can perform the task, (c) minimal prior knowledge requirements as pre-training is used to ensure that needed information is provided prior to task completion, and (d) minimal language and conceptual requirements. Task properties such as these also allow for culture fair assessment.

Thus far, we have highlighted a parametric approach for assessing trajectories of cognitive growth. Unlike other child task protocols adapted from adult measures to assess neural activity, measures of mental-attentional capacity are paradigms designed and validated within a developmental theoretical framework (Pascual-Leone 1970, Pascual-Leone 1987; Pascual-Leone and Johnson 2005). For instance, with the *n*-back task we cannot predict what performance level we should expect by a specific age group. We know that young children have difficulty with the 1-back but 2-back is difficult even for adults. Tasks with parametric increases in difficulty (that are theoretically based) are lacking in the field and would be particularly useful for developmental cognitive neuroscience (Kotsoni et al. 2006). Quantification of age-related growth of mental-attentional capacity has implications for other fields such as education and clinical practice. Improvements in mental attention with age are related to academic skills such as reading and mathematics (Agostino et al. 2010); cognitive abilities such as executive function (Im-Bolter et al. 2006; Im-Bolter et al. 2015a, b), intelligence (Im-Bolter et al. 2006; Pascual-Leone and Johnson 2005), and language competence (Im-Bolter et al. 2006). Children with different neurodevelopmental disorders often have difficulties with cognitive abilities such as executive function and language and the measurement of mental-attentional capacity can increase our understanding of atypical development. In the following section we focus on two disorders that have in common deficits in language: children with language impairment and children with epilepsy.

Atypical development: understanding limits in mental attentional capacity

A continuing challenge in the study of atypical development is identifying underlying mechanisms when there is a great deal of overlap in terms of the distinguishing characteristics of different disorders. For example, although the etiology of children with language impairment and children with epilepsy is quite different these two groups of children share a common characteristic – a significant deficit in language ability. For children with language impairment, the deficit cannot be explained by hearing loss, low nonverbal intelligence, or neurological damage. Epilepsy, however, is a neurological disorder that involves one or more occurrences of a seizure. Below we present data on how children with language impairment and epilepsy underperform on quantitative measures, which serves to highlight how their cognitive developmental level can be assessed and compared to their typically developing peers.

Language impairment Estimates of language impairment vary widely and range from 2 % to 20 % across preschoolers, kindergarteners, and older children and adolescents (Im-Bolter and Cohen 2007; Law et al. 2000). Language impairment is typically diagnosed during the preschool years but is sometimes not discovered until much later in childhood and early adolescence (Cohen et al. 1998; Im-Bolter and Cohen 2007). Children with language impairment generally are believed to have a primary linguistic deficit; however, they also exhibit nonlinguistic (Finneran et al. 2009; Im-Bolter et al. 2006; Marton 2008) and social cognitive deficits (Andrés-Roqueta et al. 2013; Craig 1995; Farmer 2000; Marton et al. 2005). As a result, it has been suggested that children with language impairment may have reduced cognitive resources that account for their linguistic and nonlinguistic deficits (Bishop 1992; Johnston 1992). We suggest that these reduced cognitive resources may represent deficits in mental-attentional capacity and how mental-attentional capacity is used and controlled.

Compared to hundreds of adult fMRI studies examining language functions, in the past two decades there are only 39 studies examining maturation of language networks in children (see Weiss-Croft and Baldeweg 2015, for a review). Similarly, the number of fMRI studies with children with language impairment is surprisingly small. We could only identify four fMRI studies that examined children and adolescents with language impairment. These studies focused on performance on language tasks (e.g., object naming, Hugdahl et al. 2004; verbal working memory, Weismer et al. 2005; word generation from categories, De Guibert et al. 2011; auditory covert naming, Badcock et al. 2012). Magnetic resonance imaging studies suggest structural brain anomalies in children with language impairment in areas related to executive control (e.g., increased asymmetry in prefrontal areas; Jernigan et al. 1991). Only one study that we know of has used fMRI to examine working memory (with two levels of cognitive load) in adolescents with language impairment (Weismer et al. 2005). Weismer et al. (2005) used a modified listening span task that incorporated sentence encoding and recognition (rather than recall) of final words with adolescents (13 years of age) with language impairment or with normal language. As would be expected, they found that overall performance of the language impairment group was significantly worse than the normal language group. fMRI showed that both groups were comparable with respect to patterns of activation and physiologic response; however, the language impairment group demonstrated hypoactivation in regions associated with attention and memory processes (Weismer et al. 2005). These results are consistent with behavioral data that provide support for the idea that language impairment may be the result of domain general deficits.

Our research supports this proposal and provides evidence that shows children with language impairment have mental-attentional capacity deficits (Im-Bolter et al. 2006). Moreover, these deficits are not specific to the verbal domain. Compared to their chronological age peers, who performed at theoretically expected levels, children with language impairment performed about half a unit to one unit lower across measures of mental-attentional capacity in the visual spatial and verbal domains (Im-Bolter et al. 2006). Such observations are possible when using tasks with parametric changes in task demand across different domains, specifically the Figural Intersection Task and the Direction Following Task (Im-Bolter et al. 2006). This consistency of performance across domains suggests a domain general rather than domain specific deficit in mental attention. This finding is notable when we consider that the children with language impairment showed no significance difference in nonverbal IQ compared to their same aged peers with typically developing language.

Epilepsy Epilepsy is one of the most common neurological disorders in children. Children with epilepsy often underperform on measures of language and cognitive function (Reilly et al. 2015; Kellermann et al. 2015). Therefore, the presence of language or cognitive impairments is a serious consideration for health care providers and educators. Clinically, however, these language and cognitive difficulties are often under-recognized due to the emphasis placed on the management of seizures. In turn, under-diagnosed language and cognitive impairments result in lower educational achievement, which place these children at risk for adverse psychosocial effects. In fact, studies show that children with epilepsy are at increased risk for academic underachievement with 41 to 62 % of these children meeting diagnostic criteria for at least one type of learning disability (e.g., written expression; Dunn et al. 2010; Fastenau et al. 2008; Lee 2010). Moreover, even with good seizure control and average intelligence, children with epilepsy have a greater risk of developing learning problems compared to their siblings without epilepsy (Bailet and Turk 2000).

The challenge, therefore, is to understand and delineate the relation of cognitive abilities and epileptic phenomenology. For instance, in adults with epilepsy, fMRI studies looking at cognitive abilities show significant reorganization of function attributed to epileptic etiology (Detre et al. 1998; Köylü et al. 2006; Helmstaedter and Kockelmann 2006). Reorganization of function has also been shown in children on tasks of language production and comprehension (Datta et al. 2013). To our knowledge only one study used different levels of difficulty in a task to examine effects of cognitive load in children with frontal lobe epilepsy (Braakman et al. 2013). Braakman et al. (2013) used a verbal task with three levels of difficulty and tested children with and without frontal lobe epilepsy (8 to 13 years). Behaviorally, children with epilepsy scored significantly lower on the verbal task than controls. fMRI showed overall brain responses of children with epilepsy were not significantly different from typically developing children; however, these conclusions are limited since the authors averaged brain responses across all ages and across all difficulty levels. Despite the absence of significant difference in fMRI activity, functional connectivity throughout the entire brain was significantly weaker for children with epilepsy than controls (Braakman et al. 2013). No fMRI study to date has used a parametric approach to distinguish brain response to different levels of task demand in children with epilepsy.

What is the mental-attentional capacity of children with epilepsy? Would a 12 year old with epilepsy show the same mental-attentional capacity as a typically developing peer? How would brain indices differ? Our behavioral data indicate that children with epilepsy not only have significantly worse performance on language tasks compared to children without epilepsy but also significant deficits in their mental-attentional capacity (Im-Bolter et al. 2015b). However, unlike children with language impairment who show comparable mental-attentional capacity across domains, children with epilepsy show disproportionate difficulty on the mental-attentional capacity measure in the language domain. Children with epilepsy were about 1.5 units lower on the visual spatial measure of mental-attentional capacity, but three units lower on the verbal measure of mental-attentional capacity. It should be noted that children with and without epilepsy did not differ with respect to their nonverbal IQ. This suggests that parametric measurement may be more sensitive in detecting such differences, particularly for visual spatial features. Despite the importance of verbal and nonverbal information processing during development, the few fMRI studies in children with epilepsy are restricted mainly to paradigms of language.

Behavioral data provide important information about the psychological functioning of children with atypical development; however, they do not allow for the tracking of ongoing processes as functional neuroimaging does. Therefore, it is important to have tasks that can be used behaviorally and with neuroimaging. This is particularly applicable, for instance, for pre-surgical evaluations of children with epilepsy where fMRI is the most used clinical application (Freilich and Gaillard 2010), as it replaces the need for more invasive options. Tasks such as the Color and the Letter Matching Task that adhere to parametric methodology and can be administered with fMRI lend themselves for assessing cognitive abilities in children with language impairment and with epilepsy.

Benefits of parametric measures: valuable neuroimaging tools

Tasks that work well behaviorally and with neuroimaging, such as the Color and Letter Matching Task, can be valuable tools for assessing brain-behavioral trajectories across typical and atypical development. Having well constructed measures, based on developmental theory, that can be administered behaviorally and with fMRI have a number of benefits that are critical for developmental cognitive neuroscience:

1. Allows for assessment of individuals with variable performance capabilities. Increasing levels of difficulty with invariant executive requirements allows for measuring cognitive limitations across development. Young children can successfully complete easy levels, whereas older children can progressively attain higher levels.
2. Provides the same scaling (e.g., number of difficulty levels, number of trials, trial length) and same metric (i.e., comparable score) across visual spatial and verbal domains. Presentation sequence, difficulty levels, and timing are exactly the same for both the Color and Letter Matching Task. Common scaling and metric eliminates several methodological confounds. This is particularly important for assessing cognitive abilities across specific domains in atypical populations. In principle, children with difficulties in one domain but not another should perform worse only in the domain they have difficulty; however, this may not always be the case. On behavioral tests a child's score reflects the outcome of the interaction between domain-general resources and domain-specific representations. The degree to which a child underperforms may differ across different domains. For instance, a child with problems in the verbal domain may score two levels below children without problems in a verbal task but one level below in a visual spatial task.
3. Offers concurrent collection of behavioral and functional neuroimaging data in populations with restricted capabilities. As time is valuable for children and their families, a single task, such as the Color or Letter Matching Task, can generate interpretable behavioral and neuroimaging indices. For example, the Letter Matching Task can provide an estimate of the child's mental-attentional capacity and brain correlates of mental-attentional capacity when administered with fMRI.
4. Allows for construction of additional difficulty levels in a task with simple manipulations. Parametric task difficulty with constant executive requirements allows for the construction of many graded levels of difficulty. For example, the executive requirement for the Letter Matching Task is to identify whether the letters are the same or different between criterion and target; this does not change regardless of difficulty level. Instead, task difficulty is simply manipulated by varying the number of letters that must be compared.
5. Permits for a variety of statistical analysis options of brain responses as a function of age. Multiple levels of difficulty provide several options of statistically analyzing brain responses. For example:

   a. Brain activity within an age group can be examined as a function of difficulty across six levels. Whether the relation is linear or quadratic may vary on brain regions and performance level.
   b. Brain responses can be assessed based on performance, such as items within the mental-attentional capacity limits of the individual child. If a child who is 9 years old scores a mental-attentional capacity of 4 (as expected theoretically) then only trials with a mental-attentional demand of 4 and lower should be considered in the analyses. If a child who is 9 years old scores a mental-attentional capacity of 3 then only trials with a mental-attentional demand of 3 and lower should be considered in the analyses.
   c. Brain responses can be analysed based on purely theoretical expectations for each age group and across age groups.
6. Provides options for direct contrasts of difficulty levels across domains. For instance, we can examine whether brain responses to difficulty level 4 in the visual-spatial task significantly differ from brain responses of difficulty level 4 in the verbal domain.
7. Allows for comparison of within child performance. Quantification of mental-attentional capacity allows

comparisons to be made to the child's previous performance and to theoretical developmental expectations. Unlike IQ scores that compare an individual's performance to a normative sample, mental attentional-capacity measures parametrically assess cognitive abilities that identify latent differences in performance. Age-appropriate level is provided by theoretical expectation (rather than derived empirically), whereas performance-appropriate level is individualized to a child. For instance, for a child who scores 3 at age 9, which is a unit below the theoretical expectation, any future performance improvements can be gauged by that score. This way, intervention protocols can be customized to each child's developmental level.

Overall, quantitative methodology in parametric designs allows for a better contrast between brain-behavioral relations and can provide new insights into how these mechanisms are compromised in children with developmental difficulties.

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Compliance with ethical standards

Conflict of interest Marie Arsalidou and Nancie Im-Bolter declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

**Articles used for the summary of mental-attentional capacity scores in Figs. 1 and 2 are marked with an asterisk*

*Agostino, A., Johnson, J., & Pascual-Leone, J. (2010). Executive functions underlying multiplicative reasoning: Problem type matters. *Journal of Experimental Child Psychology,* 105(4), 286–305.

Andrés-Roqueta, C., Adrian, J. E., Clemente, R. A., & Katsos, N. (2013). Which are the best predictors of theory of mind delay in children with specific language impairment? *International Journal of Language & Communication Disorders, 48*(6), 726–737.

*Arsalidou, M., Pascual-Leone, J., & Johnson, J. (2010). Misleading cues improve developmental assessment of working memory capacity: the color matching tasks. *Cognitive Development, 25*(3), 262–277.

Arsalidou, M., Pascual-Leone, J., Johnson, J., Morris, D., & Taylor, M. J. (2013). A balancing act of the brain: Activations and deactivations driven by cognitive load. *Brain and Behavior, 3*(3), 273–285.

Badcock, N. A., Bishop, D. V., Hardiman, M. J., Barry, J. G., & Watkins, K. E. (2012). Co-localisation of abnormal brain structure and function in specific language impairment. *Brain and Language, 120*(3), 310–320.

Bailet, L. L., & Turk, W. R. (2000). The impact of childhood epilepsy on neurocognitive and behavioral performance: a prospective longitudinal study. *Epilepsia, 41*(4), 426–431.

Balioussis, C., Johnson, J., & Pascual-Leone, J. (2012). Fluency and complexity in children's writing: The role of mental attention and executive function. *Rivista di Psicolinguistica Applicata/Journal of Applied Psycholinguistics: Special Issue, XII, 3*, 33–45.

*Bereiter, C., & Scardamalia, M. (1979). Pascual-Leone's M construct as a link between cognitive-developmental and psychometric concepts of intelligence. *Intelligence, 3*(1), 41–63.

Bishop, D. V. M. (1992). The underlying nature of specific language impairment. *Journal of Child Psychology and Psychiatry, 33*(1), 3–66.

Braakman, H. M., Vaessen, M. J., Jansen, J. F., Debeij-van Hall, M. H., de Louw, A., Hofman, P. A., et al. (2013). Frontal lobe connectivity and cognitive impairment in pediatric frontal lobe epilepsy. *Epilepsia, 54*(3), 446–454.

*Chandran, S., Treagust, D. F., & Tobin, K. (1987). The role of cognitive factors in chemistry achievement. *Journal of Research in Science Teaching, 24*(2), 145–160.

*Chen, W. C., & Whitehead, R. (2009). Understanding physics in relation to working memory. *Research in Science & Technological Education, 27*(2), 151–160.

*Chu, Y. C., & Reid, N. (2012). Genetics at school level: Addressing the difficulties. Research in *Science & Technological Education, 30*(3), 285–309.

Ciesielski, K. T., Lesnik, P. G., Savoy, R. L., Grant, E. P., & Ahlfors, S. P. (2006). Developmental neural networks in children performing a categorical n-back task. *NeuroImage, 33*(3), 980–990.

Cohen, N. J., Barwick, M. A., Horodezky, N. B., Vallance, D. D., & Im, N. (1998). Language, achievement, and cognitive processing in psychiatrically disturbed children with previously identified and unsuspected language impairments. *Journal of Child Psychology and Psychiatry, 39*(6), 865–877.

Craig, H. K. (1995). Pragmatic impairments. In P. Fletcher & B. MacWhinney (Eds.), *The handbook of child language* (pp. 623–640). Cambridge, MA: Blackwell Publishers.

Crone, E. A., & Ridderinkhof, K. R. (2011). The developing brain: from theory to neuroimaging and back. *Developmental Cognitive Neuroscience, 1*(2), 101–109.

Cunning, S. A. (2003). *The direction-following task: Assessing mental capacity in the linguistic domain*. York University: Doctoral dissertation.

Datta, A. N., Oser, N., Bauder, F., Maier, O., Martin, F., Ramelli, G. P., et al. (2013). Cognitive impairment and cortical reorganization in children with benign epilepsy with centrotemporal spikes. *Epilepsia, 54*(3), 487–494.

De Guibert, C., Maumet, C., Jannin, P., Ferré, J. C., Tréguier, C., Barillot, C., et al. (2011). Abnormal functional lateralization and activity of language brain areas in typical specific language impairment (developmental dysphasia). *Brain*. doi:10.1093/brain/awr141.

Detre, J. A., Maccotta, L., King, D., Alsop, D. C., Glosser, G., D'Esposito, M., et al. (1998). Functional MRI lateralization of memory in temporal lobe epilepsy. *Neurology, 50*(4), 926–932.

Dunn, D. W., Johnson, C. S., Perkins, S. M., Fastenau, P. S., Byars, A. W., deGRauw, T. J., & Austin, J. K. (2010). Academic problems in children with seizures: relationships with neuropsychological functioning and family variables during 3 years after onset. *Epilepsy and Behavior, 19*, 455–461.

Eickhoff, S. B., Laird, A. R., Grefkes, C., Wang, L. E., Zilles, K., & Fox, P. T. (2009). Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: A random-effects approach based on empirical estimates of spatial uncertainty. *Human Brain Mapping, 30*(9), 2907–2926.

Farmer, M. (2000). Language and social cognition in children with specific language impairmenet. *Journal of Child Psychology and Psychiatry, 41*(5), 627–636.

Fastenau, P. S., Shen, J., Dunn, D. W., & Austin, J. K. (2008). Academic underachievement among children with epilepsy: Proportion exceeding psychometric criteria for learning disability and associated risk factors. *Journal of Learning Disabilities, 41*(3), 195–207.

Finneran, D. A., Francis, A. L., & Leonard, L. B. (2009). Sustained attention in children with specific language impairment (SLI). *Journal of Speech, Language, and Hearing Research, 52*(4), 915–929.

Freilich, E. R., & Gaillard, W. D. (2010). Utility of functional MRI in pediatric neurology. *Current Neurology and Neuroscience Reports, 10*(1), 40–46.

Gaillard, W. D., Grandin, C. B., & Xu, B. (2001). Developmental aspects of pediatric fMRI: Considerations for image acquisition, analysis, and interpretation. *NeuroImage, 13*, 239–249.

Geier, C. F., Garver, K., Terwilliger, R., & Luna, B. (2009). Development of working memory maintenance. *Journal of Neurophysiology, 101*(1), 84–99.

*Hederich-Martínez, C., & Camargo-Uribe, Á. (2014). Psychometric analysis of the figures intersection test (FIT). *Suma Psicológica, 21*(2), 89–98.

Helmstaedter, C., & Kockelmann, E. (2006). Cognitive outcomes in patients with chronic temporal lobe epilepsy. *Epilepsia, 47*(s2), 96–98.

Hester, R. L., Kinsella, G. J., & Ong, B. (2004). Effect of age on forward and backward span tasks. *Journal of the International Neuropsychological Society, 10*(04), 475–481.

*Hindal, H., Reid, N., & Whitehead, R. (2008). Gender and learner characteristics. *European Journal of Educational Research, 2*(2), 83–96.

Hugdahl, K., Gundersen, H., Brekke, C., Thomsen, T., Rimol, L. M., Ersland, L., & Niemi, J. (2004). fMRI brain activation in a Finnish family with specific language impairment compared with a normal control group. *Journal of Speech, Language, and Hearing Research, 47*(1), 162–172.

Im-Bolter, N., & Cohen, N. J. (2007). Language impairment and psychiatric comorbidities. *Pediatric Clinics of North America, 54*(3), 525–542.

*Im-Bolter, N., Johnson, J., & Pascual-Leone, J. (2006). Processing limitations in children with specific language impairment: The role of executive function. *Child Development, 77*(6), 1822–1841.

Im-Bolter, N., Johnson, J., Ling, D., & Pascual-Leone, J. (2015a). Inhibition: Mental control process or mental resource? *Journal of Cognition and Development, 16*(4), 666–681.

Im-Bolter, N., Owens-Jaffray, K., & Bailey, K. (2015b). Measuring mental-attentional capacity in children with atypical development. In *Paper presented as part of a symposium entitled,* "*Mental-attentional (M-) capacity: Improving measurement of executive attention and working memory*" *at the 45th Annual meeting for the Jean Piaget Society.* Toronto, Ontario: Canada.

Jernigan, T. L., Hesselink, J. R., Sowell, E., & Tallal, P. A. (1991). Cerebral structure on magnetic resonance imaging in language-and learning-impaired children. *Archives of Neurology, 48*(5), 539–545.

*Johnson, J., Im-Bolter, N., & Pascual-Leone, J. (2003). Development of mental attention in gifted and mainstream children: The role of mental capacity, inhibition, and speed of processing. *Child Development, 74*(6), 1594–1614.

Johnston, J. R. (1992). Cognitive abilities of language-impaired children. In P. Fletcher & D. Hall (Eds.), *Specific speech and language disorders in children: Correlates,characteristics and outcomes* (pp. 105–116). San Diego, CA: Singular Publishing Group, Inc.

*Johnstone, A. H., & El-Banna, H. (1986). Capacities, demands and processes – a predictive model for science education. *Education in Chemistry, 23*(3), 80–84.

*Johnstone, A. H., & El-Banna, H. (1989). Understanding learning difficulties. A predictive research model. *Studies in Higher Education, 14*(2), 159–168.

Kellermann, T. S., Bonilha, L., Lin, J. J., & Hermann, B. P. (2015). Mapping the landscape of cognitive development in children with epilepsy. *Cortex, 66*, 1–8.

Kotsoni, E., Byrd, D., & Casey, B. J. (2006). Special considerations for functional magnetic resonance imaging of pediatric populations. *Journal of Magnetic Resonance Imaging, 23*(6), 877–886.

Köylü, B., Trinka, E., Ischebeck, A., Visani, P., Trieb, T., Kremser, C., et al. (2006). Neural correlates of verbal semantic memory in patients with temporal lobe epilepsy. *Epilepsy Research, 72*(2), 178–191.

Laird, A. R., Fox, P. M., Price, C. J., Glahn, D. C., Uecker, A. M., Lancaster, J. L., et al. (2005). ALE meta-analysis: Controlling the false discovery rate and performing statistical contrasts. *Human Brain Mapping, 25*(1), 155–164.

Law, J., Boyle, J., Harris, F., Harkness, A., & Nye, C. (2000). Prevalence and natural history of primary speech and language delay: Findings from a systematic review of the literature. *International Journal of Language & Communication, 35*(2), 165–188.

*Lawson, A. E. (1983). Predicting science achievement: The role of developmental level, disembedding ability, mental capacity, prior knowledge, and beliefs. *Journal of Research in Science Teaching, 20*(2), 117–129.

*Lawson, A. E. (1987). The four-card problem resolved? Formal operational reasoning and reasoning to a contradiction. *Journal of Research in Science Teaching, 24*(7), 611–627.

*Lawson, A. E., & Thompson, L. D. (1988). Formal reasoning ability and misconceptions concerning genetics and natural selection. *Journal of Research in Science Teaching, 25*(9), 733–746.

Lee, G. (2010). *Neuropsychology of epilepsy and epilepsy surgery.* New York: Oxford University Press.

Li, Y., Li, F., He, N., Guo, L., Huang, X., Lui, S., & Gong, Q. (2014). Neural hyperactivity related to working memory in drug-naive boys with attention deficit hyperactivity disorder. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 53*, 116–122.

Marton, K. (2008). Visuo-spatial processing and executive functions in children with specific language impairment. *International Journal of Communication Disorders, 43*(2), 181–200.

Marton, K., Abramoff, B., & Rosenzweig, S. (2005). Social cognition and language in children with specific language impairment (SLI). *Journal of Communication Disorders, 38*(2), 143–162.

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. Psychological Review, 63(2), 81

Morra, S. (1994). Issues in working memory measurement: testing for M capacity. *International Journal of Behavioral Development, 17*(1), 143–159.

*Morra, S. (2001). On the information-processing demands of spatial reasoning. *Thinking & reasoning, 7*(4), 347–365

*Morra, S., & Camba, R. (2009). Vocabulary learning in primary school children: Working memory and long-term memory components. *Journal of Experimental Child Psychology, 104*(2), 156–178.

*Morra, S., Parrella, I., & Camba, R. (2011). The role of working memory in the development of emotion comprehension. *British Journal of Developmental Psychology, 29*(4), 744–764.

*Morra, S., Camba, R., Calvini, G., & Bracco, F. (2013). Italians do it better? M-capacity measurement and cross-linguistic differences in the Direction Following Task (DFT). *Journal of Applied Psycholinguistics, 13*, 9–24.

*Navarro, J. I., Ramiro, P., Lopez, J. M., Aguilar, M., Acosta, M., & Montero, J. (2006). Mental attention in gifted and nongifted children. *European Journal of Psychology of Education, 21*(4), 401–411.

*Niaz, M. (1987a). Mobility-fixity dimension in Witkin's theory of field-dependence/independence and its implications for problem solving in science. *Perceptual and Motor Skills, 65*(3), 755–764.

*Niaz, M. (1987b). The role of cognitive factors in the teaching of science. *Research in Science & Technological Education, 5*(1), 7–16.

*Niaz, M. (1989). Relation between Pascual-Leone's structural and functional M-space and its effect on problem solving in chemistry. *International Journal of Science Education, 11*(1), 93–99.

*Niaz, M. (1991). Correlates of formal operational reasoning: a neo-Piagetian analysis. *Journal of Research in Science Teaching, 28*(1), 19–40.

*Niaz, M. (1996). Reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity and disembedding ability. *International Journal of Science Education, 18*(5), 525–541.

*Niaz, M., & Lawson, A. E. (1985). Balancing chemical equations: The role of developmental level and mental capacity. *Journal of Research in Science Teaching, 22*(1), 41–51.

O'Hare, E. D., Lu, L. H., Houston, S. M., Bookheimer, S. Y., & Sowell, E. R. (2008). Neurodevelopmental changes in verbal working memory load-dependency: an fMRI investigation. *NeuroImage, 42*(4), 1678–1685.

Onwumere, O., & Reid, N. (2008). Field dependency and performance in mathematics. *European Journal of Educational Research, 3*(1), 43–57.

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping, 25*(1), 46–59.

Pascual-Leone, J. (1969). *Cognitive development and cognitive style: A general psychological integration*. York University: Doctoral dissertation.

Pascual-Leone, J. (1970). A mathematical model for the transition rule in Piaget's developmental stages. *Acta Psychologica, 32*, 301–345.

Pascual-Leone, J. (1987). Organismic processes for neo-Piagetian theories: a dialectical causal account of cognitive development. *International Journal of Psychology, 22*, 531–570.

Pascual-Leone, J., & Baillargeon, R. (1994). Developmental measurement of mental attention. *International Journal of Behavioral Development, 17*(1), 161–200.

Pascual-Leone, J., & Johnson, J. (1999). A dialectical constructivist view of representation: Role of mental attention, executives, and symbols. In I. E. Sigel (Ed.), *Development of mental representation: Theories and applications* (pp. 169–200). Mahwah, NJ: Erlbaum.

Pascual-Leone, J., & Johnson, J. (2005). A dialectical constructivist view of developmental intelligence. In O. Wilhelm & R. Engle (Eds.), *Handbook of understanding andmeasuring intelligence* (pp. 177–201). Thousand Oaks, CA: Sage.

Pascual-Leone, J., & Johnson, J. (2011). A developmental theory of mental attention: its applications to measurement and task analysis. In P. Barrouillet & V. Gaillard (Eds.), *Cognitive development and working memory: A dialogue between neo-Piagetian and cognitive approaches* (pp. 13–46). New York: Psychology Press.

*Pennings, A. H., & Hessels, M. G. (1996). The measurement of mental attentional capacity: A neo-Piagetian developmental study. *Intelligence, 23*(1), 59–78.

*Powell, T. L., Arsalidou, M., Vogan, V. M., & Taylor, M. J. (2014). Letter and Colour Matching Tasks: Parametric Measures of Developmental Working Memory Capacity. *Child Development Research,* 2014.

Reilly, C., Atkinson, P., Das, K. B., Chin, R. F. M., Aylett, S. E., et al. (2015). Cognition in school-aged children with "active" epilepsy: A population-based study. *Journal of Clinical and Experimental Neuropsychology, 37*(4), 429–438.

Rossi, S., Lubin, A., Simon, G., Lanoë, C., Poirel, N., Cachia, A., et al. (2013). Structural brain correlates of executive engagement in working memory: Children's inter-individual differences are reflected in the anterior insular cortex. *Neuropsychologia, 51*(7), 1145–1150.

Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., et al. (2012). Modelling neural correlates of working memory: a coordinate-based meta-analysis. *NeuroImage, 60*(1), 830–846.

Ruchkin, D. S., Grafman, J., Cameron, K., & Berndt, R. S. (2003). Working memory retention systems: A state of activated long-term memory. *Behavioral and Brain Sciences, 26*(06), 709–728.

*Rutherford, M. (1997). Working memory revisited: can we use it to select science students? *International Journal of Science Education, 19*(8), 939–955.

Satterthwaite, T. D., Ruparel, K., Loughead, J., Elliott, M. A., Gerraty, R. T., Calkins, M. E., et al. (2012). Being right is its own reward: Load and performance related ventral striatum activation to correct responses during a working memory task in youth. *NeuroImage, 61*(3), 723–729.

*Shafrir, U., & Pascual-Leone, J. (1990). Postfailure reflectivity/impulsivity and spontaneous attention to errors. *Journal of Educational Psychology, 82*(2), 378

Thomas, K. M., King, S. W., Franzen, P. L., Welsh, T. F., Berkowitz, A. L., Noll, D. C., et al. (1999). A developmental functional MRI study of spatial working memory. *NeuroImage, 10*(3), 327–338.

Vogan, V. M., Morgan, B. R., Lee, W., Powell, T. L., Smith, M. L., & Taylor, M. J. (2014). The neural correlates of visuo-spatial working memory in children with autism spectrum disorder: effects of cognitive load. *Journal of Neurodevelopmental Disorders, 6*(1), 1–15.

Vogan, V. M., Morgan, B. R., Powell, T. L., Smith, M. L., & Taylor, M. J. (2016). The neurodevelopmental differences of increasing verbal working memory demand in children and adults. *Developmental Cognitive Neuroscience, 17*, 19–27.

Weismer, S. E., Plante, E., Jones, M., & Tomblin, J. B. (2005). A functional magnetic resonance imaging investigation of verbal working memory in adolescents with specific language impairment. *Journal of Speech, Language, and Hearing Research, 48*(2), 405–425.

Weiss-Croft, L. J., & Baldeweg, T. (2015). Maturation of language networks in children: A systematic review of 22 years of functional MRI. *NeuroImage, 123*, 269–281.

Yang, Z., Jutagir, D. R., Koyama, M. S., Craddock, R. C., Yan, C. G., Shehzad, Z., et al. (2015). Intrinsic brain indices of verbal working memory capacity in children and adolescents. *Developmental cognitive neuroscience, 15*, 67–82.