With high-stakes testing and accountability demands, there has been a major focus in the United States on increasing student achievement, especially in the area of mathematics (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2015). Early mathematics skills are among the strongest predictors of students' later reading and mathematics achievement, as well as their future life success, even after controlling for children's early cognitive ability, behavior, and demographic characteristics (Duncan et al., 2007; Gross, Hudson, & Price, 2009). Given the significant economic and societal impacts of a strong start in quantitative areas, education scholars need a better understanding of the underlying processes involved in children's early mathematical learning and performance.

Previous studies of children's early mathematics performance have typically privileged specific skills, such as number recognition, counting, and magnitude (e.g., Clements & Sarama, 2009; Gunderson, Ramirez, Beilock, & Levine, 2012; Kadosh, Dowker, Heine, Kaufmann, & Kucian, 2013). While these narrow competencies are essential, educators and scholars advocate adopting a broader perspective of school readiness skills that extends beyond explicit academic-focused skills (Le, Kirby, Barney, Setodji, & Gershwin, 2006). Research suggests that other, less traditional academic abilities—also known as domain-general cognitive processes (Welsh, Nix, Blair, Bierman, & Nelson, 2010)—are strongly associated with later outcomes (Heckman, Stixrud, & Urzua, 2006), although they are rarely taught explicitly in classrooms. Two interrelated cognitive processes in particular are critical for children's mathematics achievement: executive functions (EFs) and visuospatial (VS) skills (e.g., Best, Miller, & Naglieri, 2011; Bull & Lee, 2014; Cragg & Gilmore, 2014; de Hevia, Vallar, & Girelli, 2008; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Monette, Bigras, & Guay, 2011; Uttal et al., 2013; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). The role of EFs and VS skills, individually, in the development of mathematics skills is not new; however, their interplay is not as well understood.

We apply a developmental neuroscience perspective to explore how these two cognitive processes and children’s mathematics skills emerge. In addition, examining atypical development can expand our knowledge of the interconnected parts of the developing brain and the domain-relevant processes that underlie the development of children’s mathematics understanding (Karmiloff-Smith, 2007). Thus, for illustrative purposes, we provide evidence of the importance of EFs and VS skills for mathematics learning by examining studies of individuals with autism spectrum disorder (ASD) and Williams syndrome (WS). These groups have distinct cognitive profiles, in both their EFs and VS skills, as
well as their mathematical abilities. By simultaneously considering two cognitive processes that underlie mathematics and linking evidence from multiple fields via a developmental neuroscience perspective, we offer insight into the underlying mechanisms by which EFs and VS skills support the learning and acquisition of mathematics skills. With some concrete examples, this approach also demonstrates how neuroscience research might successfully inform educational practice.

**Early Mathematical Knowledge**

Mathematics competence comprises a variety of skills, including basic numbers knowledge, arithmetic facts, and the capability to follow procedures (Dowker, 1998). The development of these skills progresses hierarchically, so basic math-related concepts and skills provide the foundation for mastering more complex skills (Entwisle & Alexander, 1990). Studies in human neuroimaging, primate neurophysiology, and developmental neuropsychology reveal underlying neuropsychological architectures, meaning that individuals are predisposed to represent, acquire knowledge about, and process numbers (e.g., Dehaene, 1992; Menon, 2010). Moreover, research suggests that numerical abilities are fractionated and include a variety of abilities or subdomains, such as numerosity or approximate sense of number, understanding of numerical symbols, and formal arithmetic, which can be isolated within the brain (Dehaene, Molkko, Cohen, & Wilson, 2004). For instance, when children are first learning numbers, they must connect three separate representations of each number: the quantity “3,” the word “three,” and the Arabic digit “3.” According to the triple-code model—a neuropsychological model of numerical processing (e.g., Dehaene, 1992)—each representation of a number is captured by three codes: the analog magnitude code, the auditory verbal code, and the visual Arabic code. Each of the three codes has distinct functional neuroarchitectures that are associated with observed differences among arithmetic tasks (Dehaene & Cohen, 1995). See Table 1 for a general overview of the triple-code model.

First, the analog magnitude code (i.e., the quantity system) represents numerical quantities on a mental number line, including nonverbal semantic knowledge. The bilateral horizontal segment of the intraparietal sulcus is strongly engaged during many quantity-processing tasks that involve nonverbal representations of numerical quantity, such as relative size (e.g., 2 is smaller than 3) and distance (e.g., 2 is close to 3), as well as relations among numbers (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003). Second, the auditory verbal code is used to verbally process numbers, as well as to retrieve rote arithmetic facts, such as addition and multiplication facts (Gonzalez & Kolers, 1982). The left angular gyrus—specifically, the general language areas of the left perisylvian network and the left basal ganglia and thalamic nuclei—is engaged during the verbal processing of numbers, as opposed to the quantity processing of numbers (Dehaene et al., 2003). Third, the visual Arabic code represents a visual system in which numbers can be encoded and spatially manipulated in the Arabic format (Dehaene & Cohen, 1995). This code engages the posterior superior parietal system—that is, the bilateral inferior ventral occipitotemporal regions associated with the ventral visual pathway—with the left region used for visually identifying words and digits and with the right for simple Arabic numbers (Dehaene, 1992).

While this region plays a role in number processing, it is also central to VS tasks, such as mental rotation, spatial working memory, and eye and attention orienting (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000).

Taken together, neuropsychological evidence indicates that performing different subdomains of mathematics knowledge is associated with activating different areas of the brain (e.g., Butterworth & Walsh, 2011; Dehaene et al., 2004). This evidence in turn suggests differences in the underlying cognitive processes that are needed for distinct mathematics skills (LeFevre et al., 2010), leading us to ask, when are specific cognitive processes such as EFs and VS skills needed for which mathematics skills?

**Two Cognitive Processes Underlying Math: EFs and VS Skills**

Research on the development of mathematics skills at the neural and basic behavioral levels indicate that mathematics performance and achievement rely on “interrelated and interdependent cognitive operations and processes” (Blair, Knipe, & Gamson, 2008, p. 81). Yet, major neuroscientific theories of numerical cognition and mathematics development have not explicitly incorporated cognitive processes into their models until recently. A complementary line of developmental and educational research examines the early cognitive processes that support the development of children’s mathematics skills. Here, we simultaneously consider two cognitive processes that have been robustly linked to mathematics learning: EFs and VS ability. Table 1 provides a synthesis of selectively reviewed literature that discusses the function and brain mechanisms of these two processes, as well as their links to specific mathematics skills. We examine these processes in individuals with ASD and WS. ASD and WS are genetically based neurodevelopmental disorders that present distinct cognitive phenotypes, presumably due to disruptions in normal brain development (Tager-Flusberg, Skwerer, & Joseph, 2006). As such, examining differences in the cognitive profiles of these two groups of children can provide insight into how EFs and VS skills may be differentially implicated in the development of mathematics competence. Figure 1 compares the distinct cognitive profiles of those with ASD and WS to show the relative strengths and weaknesses of their EF and VS skills, described more fully below.

**Executive functions.** EFs refer to multiple distinct higher-order cognitive processes that are involved in adaptive,
# TABLE 1
Overview of Numerical Processing, Executive Functions, and Visuospatial Skills Based on a Synthesis of Selectively Reviewed Research

| Processes: Function (subdomains) | Associated areas of the brain | Links to specific math skills + example |
|---------------------------------|-------------------------------|----------------------------------------|
| **Numerical processing**        |                               |                                        |
| Analog magnitude code (quantity system): Numerical quantities on a mental number line; nonverbal semantic knowledge | Bilateral horizontal segment of intraparietal sulcus | Relative size and distance, relations between numbers, magnitude, representation and manipulation of numerical quantity, nonverbal representations of quantity, calculations. *Example: Quantity “3”* |
| Auditory verbal code (verbal system): Verbal processing of numbers, retrieval of rote arithmetic facts | Left angular gyrus, language areas of left perisylvian network, left basal ganglia, thalamic nuclei | Rote arithmetic facts (addition and multiplication), exact calculations. *Example: Word “three”* |
| Visual arabic code (visual system): Numbers can be encoded and spatially manipulated in the Arabic format | Posterior superior parietal system; bilateral inferior ventral occipitotemporal regions associated with ventral visual pathway with left region, used for visually identifying the words and digits, and the right, used for simple Arabic numbers | Spatial manipulation of numbers, identify words and digits, multidigit calculations, parity judgments, approximation tasks, number comparisons. *Example: Arabic digit “3”* |

| Cognitive processes |
|---------------------|
| Executive functions: Multicomponent, distinct higher-order cognitive processes that are involved in adaptive, goal-directed behavior | Prefrontal cortex, left superior temporal gyrus | Applied problem solving. *Example: Tower of London (Shallice, 1982)* |
| Planning: Subcomponents of executive functions are all involved when deliberately planning | Prefrontal cortex | |
| Working memory: Requires effortful mental activity and is involved in maintenance and manipulation of auditory or visual information | Dorsolateral prefrontal cortex | Standardized math tests, early numerical magnitude skills, counting skills; learning new mathematics skills; variability in strategy use; retrieval. *Example: Working memory span tasks (e.g., digit or word span)* |
| Attentional/cognitive flexibility: Shift attention from one stimuli or set of rules to another | Superomedial prefrontal cortex | Problem solving, simple calculations. *Example: Wisconsin Card Sorting Task (Heaton, Chelune, Talley, Kay, & Curtiss, 1993)* |
| Inhibitory control: Allows for the suppression of certain behaviors and activation of new behaviors if needed | Ventral prefrontal cortex | Counting skills. *Example: Stroop task (Ozonoff & Jensen, 1999)* |
| Visuospatial skills: Multicomponent processes broadly composed of synthesizing parts into a whole, constructing and manipulating representations, perceiving and understanding spatial orientations, and reproducing models using fine motor movements | Posterior parietal cortex, intraparietal sulcus, dorsal visual stream | Use adaptive strategies to solve arithmetic problems, spatially represent and interpret numerical information (e.g., learning to count), mental representation of the number line, approximate calculation and estimation, magnitude representation, nonverbal representations |
| Visuospatial construction (e.g., figure copying): Transformation and construction of a visually presented model | Intraparietal sulcus, dorsal cortical stream | *Example: Block design* |

*Adapted from and synthesis of the following literature on triple-code model of numerical processing: Dehaene (1992); Dehaene, Piazza, Pinel, and Cohen (2003); and Gonzalez and Kolers (1982).*
goal-directed behavior. These processes depend on overlapping networks across brain regions, primarily in the prefrontal cortex (PFC), as well as interconnectivity with other brain regions (e.g., left superior temporal gyrus), and they can be impaired by damage to or dysfunction in these areas (Diamond, 2011). Though still under debate, empirical and theoretical work suggests that EFs are characterized by both unity and diversity. This means that EFs comprise distinctly identifiable subcomponents or processes that nonetheless correlate positively with one another and are all involved when deliberate action is needed, as in decision making and planning (Miyake et al., 2000). Three common components are associated with three main convexities of the PFC and can be measured among young children as well as adults:

- **Working memory**, which corresponds to the dorsolateral PFC, requires effortful mental activity and is involved in the maintenance and manipulation of auditory or visual information.

- **Cognitive flexibility or attentional shifting**, which corresponds to the superomedial PFC, allows one to shift attention from one stimulus or set of rules to another depending on the demands of the task.

- **Inhibitory control**, which corresponds to the ventral PFC, allows for the suppression of certain behaviors and the activation of new ones if needed (Garon, Bryson, & Smith, 2008; Miyake et al., 2000; Suchy, 2009; Zelazo, Muller, Frye, & Marcovitch, 2003).

While efforts are ongoing to develop tasks that target individual EF components, other tasks, such as those requiring planning and execution, draw from all three components and, as such, are considered higher-order tasks that tap the general, unitary EF construct (Bull & Scerif, 2001; Miyake et al., 2000).

Consistent with the “unity and diversity” argument, tasks tapping the three components load onto a single factor among young children (Wiebe, Espy, & Charak, 2008; Willoughby, Blair, Wirth, & Greenberg, 2012), whereas from elementary school through adulthood, the best-fitting model includes three components rather than one (Miyake et al., 2000). Although research has postulated that executive processes manipulate the contents of working memory (Miyake & Shah, 1999), even among adults, working memory and EF are virtually indistinguishable and have been proposed to draw from a single resource called executive attention (McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010). This term derives from cognitive neuroscience, and it refers to the deliberate control and management of one’s attentional resources, especially in the presence of distraction or interference (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Posner & Petersen, 1990). Thus, working memory appears to play a special role in EFs.

**ASD and EFs.** ASD is a heterogeneous group of lifelong neurodevelopmental disorders characterized by impairment in social interaction and communication, as well as the presence of repetitive, stereotyped behaviors and restricted interests (American Psychiatric Association, 2013). Neurobiological evidence indicates anatomical abnormalities in many brain areas of individuals with ASD, including the cerebellum, brain stem, frontal and parietal lobes, hippocampus, and amygdala (Baron-Cohen,
Persons with ASD typically exhibit executive dysfunction, or problems with functions such as planning and cognitive flexibility (Hill, 2004; Ozonoff, Pennington, & Rogers, 1991), due to a form of frontal lobe pathology (Baron-Cohen, 2004). Specifically, both hemispheres of the brain show abnormal activation when shifting attention rapidly among modalities, spatial locations, and object features (Belmonte, Courchesne et al., 1994, Wainwright & Bryson, 1996). In one study, participants with ASD, as compared with typically developing controls, showed significant deficits on attentional functioning that require cognitive flexibility or psychomotor speed, as opposed to accuracy or encoding. In other words, those with ASD seem to have difficulty with focusing and shifting the focus of their attention but not with encoding information and sustaining attention over time (Goldstein, Johnson, & Minshew, 2001). Furthermore, one of the core symptoms of ASD is repetitive, stereotyped behavior, and this behavior also contributes to poor cognitive flexibility and problems shifting to a different task according to changes in a situation (Hill, 2004). Individuals with ASD have difficulty on tasks such as the Wisconsin Card Sorting Task (Heaton, Chelune, Talley, Kay, & Curtiss, 1993), which requires an individual to sort cards first on one dimension (color, number, shape) according to a nonspoken rule and then to shift rules to sort cards on a different dimension. Throughout the task, the test administrator states whether or not the individual has placed the card correctly according to the new rule but does not tell the rule explicitly. Research shows that persons with ASD tend to exhibit perseverative responses; that is, they do not easily shift to sorting cards by the new rule (Ozonoff & McEvoy, 1994).

Individuals with ASD also have problems with planning, which is a complex process that requires constantly monitoring, reevaluating, and updating a sequence of planned actions (Hill, 2004). As compared with age-matched, typically developing individuals, those with ASD struggle on planning tests, such as the Tower of London (Shallice, 1982), where disks must be moved from three pegs to match a goal state from a prearranged sequence (Hill, 2004). This task is particularly difficult for individuals with frontal and parietal lobe abnormalities (i.e., with ASD), especially as the number of subgoals during the problem solving increases (Carpenter, Just, & Reichele, 2000). Interestingly, difficulty in planning and problem solving do not seem to be driven by working memory (Williams, Goldstein, Carpenter, & Minshew, 2005). In fact, although working memory profiles can vary, individuals with ASD are relatively strong in their working memory processes, especially in VS tasks, and do not seem to have trouble simultaneously processing and storing information up to a certain point (Alloway, Rajendra, & Archibald, 2009). Individuals with ASD struggle when information becomes more complex and greater demands are made on the working memory processes. In these cases, neuroimaging studies suggest problems with global working memory processing or deficits in the connections across brain regions, as opposed to a focused deficit in the PFC (Barendse et al., 2013).

Additionally, individuals with ASD generally succeed on tests of inhibitory control, such as the Stroop task (Ozonoff & Jensen, 1999), in which a participant first reads a list of color names written in black ink, then a list of color names written in colored ink that matches the color word (“red” in red ink), and finally, a list of color names written in colored ink that does not match the color word (“blue” in red ink). However, a closer examination suggests that people with ASD tend to have difficulty on the Go/No-Go task, in which an individual responds to the same (“go”) stimulus (either a circle or triangle). In the second, “prepotent inhibition” condition, the “go” stimulus is the opposite of the first condition, and in the final “flexibility” condition, the “go” stimulus changes frequently and the participant must shift from one response pattern to another (Ozonoff & McEvoy, 1994). The Go/No-Go task causes difficulty perhaps because it contains both prepotent inhibition and cognitive flexibility conditions, and individuals with ASD have difficulty with cognitive flexibility. To summarize, individuals with ASD seem to have impairments in majority of the EFs, including cognitive or attentional flexibility and planning; however, it is worth noting that their inhibitory control and generalized working memory processes seem intact when tasks do not also require flexibility.

WS and EFs. WS, a disorder caused by a microdeletion on chromosome 7q11.23 (Ewart et al., 1993), is characterized by relative strength in verbal cognition coupled with impairments in nonverbal cognition (i.e., VS skills and EFs), as well as an unusual personality profile (Mervis & John, 2010; Mervis & Klein-Tasman, 2000). There are structural abnormalities associated with WS that correspond to the distinct phenotype. Structural magnetic resonance imaging (MRI) findings indicate reduced brain size in the areas of the parietal lobe and occipital gray matter; voxel-based morphometry further localizes these gray matter reductions to three regions: the intraparietal sulcus, the region around the third ventricle, and the orbitofrontal cortex (Meyer-Lindenberg, Mervis, & Berman, 2006).

In general, individuals with WS exhibit deficits in their EFs, including lapses in attentional flexibility, planning, and inhibitory control (Greer, Riby, Hamilton, & Riby, 2013). One potential explanation for these deficits may be due to amygdala dysfunction and abnormal connectivity within the prefrontal regions (Meyer-Lindenberg et al., 2005), which are associated with EFs. Similar to individuals with ASD, those with WS have poor planning abilities. On the Tower of London (Shalllice, 1982), participants with WS made more errors as compared with typically developing controls; yet,
they did not differ in terms of response time (Menghini, Addona, Costanzo, & Vicari, 2010). In other words, individuals with WS seem to make more impulsive incorrect responses while performing the Tower of London task, which requires planning actions to avoid errors (Menghini et al., 2010; Rhodes, Riby, Park, Fraser, & Campbell, 2010).

Additionally, in a study examining attentional flexibility and inhibition, Greer and colleagues (2013) found that on the Sustained Attention to Response Task (Smilek, Carriere, & Cheyne, 2010), persons with WS had problems with a variety of processes related to inhibitory control and attentional lapse. Sustained Attention to Response Task is a computer-based task in which a participant has to make correct responses by clicking the left mouse button when the digit “4” appears on the screen and the right mouse button otherwise. This task is designed to assess one’s ability to sustain attention and suppress responses to infrequent and unpredictable stimuli during a period of rapid and recurring responding to frequent stimuli. Individuals with WS could not maintain sustained attention performance under conditions of automaticity, due to long streams of nontarget stimuli, and had difficulty with task engagement (Greer et al., 2013).

Interestingly, for individuals with WS, task modality—whether the task is verbal or spatial—seems to be important for specific EFs. For instance, children with WS (4–15 years old) have difficulties in motoric/spatial inhibition tasks (e.g., Detour Box and Pointing/Countering) but not with verbal inhibitory tasks (e.g., Day-Night Stroop Task; Atkinson et al., 2003). Similarly, recent studies suggest that there are impairments in verbal and spatial short-term working memory functioning in WS (Carney, Brown, & Henry, 2013; Rhodes, Riby, Fraser, & Campbell, 2011), although verbal short-term memory is considered to be a relative strength (e.g., Meyer-Lindenberg et al., 2006). However, impairments in executive aspects of working memory processing seem to be selective to spatial tasks, specifically the manipulation of spatial information in memory (Rhodes et al., 2011). Overall, for individuals with WS, deficits in EFs seem to be in all of the main components of EF—namely, attentional or cognitive flexibility, inhibitory control, and planning—which have often been linked to learning and achievement (Best et al., 2011). This pattern of relative strengths (i.e., verbal cognition) and weaknesses associated with WS is unique (Ansari et al., 2003) and suggests modularity in cognitive processes (Bellugi, Bihrlle, Jernigan, Trauner, & Doherty, 1990) that may differentially affect numerical cognition in persons with WS (Ansari & Karmiloff-Smith, 2002).

**VS skills.** VS skills are broadly defined as the ability to observe the visual world, to form mental representations of the visual objects, to mentally manipulate these representations, and to in turn reconstruct aspects of the visual experience (Miyake et al., 2001; Ogawa, Nagai, & Inui, 2010). Thus, like EF, VS ability comprises several subcomponents—such as synthesizing parts into a whole, constructing and manipulating representations, perceiving and understanding spatial orientation, and reproducing models through fine motor movements (Korkman, Kirk, & Kemp, 1998; Mervis & Klein-Tasman, 2000; Newcombe & Frick, 2010)—which place differential demands on the working memory system (Miyake et al., 2001). Success on VS tasks requires cognitive flexibility in shifting back and forth between the parts of the object and the object as a whole (Pani, Mervis, & Robinson, 1999), transforming a visually presented model to the drawing space (Ogawa et al., 2010), and following a pattern to build the object (Meyer-Lindenberg et al., 2004). Because VS tasks are complex and engage various spatial processes, numerous areas of the brain are involved in VS processing, including the posterior parietal cortex, with specific activation in the intraparietal sulcus, which is part of the dorsal visual system (Floyer-Lea & Matthews, 2004; Ogawa et al., 2010; Ungerleider & Mishkin, 1982).

**ASD and VS skills.** Individuals with ASD tend to show various signs of heightened VS abilities, as compared with typically developing individuals (e.g., Caron, Mottron, Berthiaume, & Dawson, 2006; Mitchell & Ropar, 2004). Of the various VS tasks, the most replicated task is the block design task, in which the participant needs to reproduce a two-dimensional design using a set of blocks. Those with ASD complete the task more quickly and with fewer mistakes as compared with typically developing individuals (A. Shah & Frith, 1993). Persons with ASD also excel at the embedded figures task, in which the participant locates a target hidden within a more complex figure, and this finding is robust across different samples (e.g., A. Shah & Frith, 1993). During the embedded figures task, functional neuroimaging shows unusually high activation in ventral occipital areas and abnormally low activation in prefrontal and parietal areas; furthermore, MRI morphometry shows a volume deficit in the parietal lobe, which translates to focused VS attention but decreased higher cognitive processing during the task (Baron-Cohen, 2004; Townsend & Courchesne, 1994). In other words, superiority in these tasks may be due to the fact that individuals with ASD have an aptitude for detail-focused processing, good segmentation skills, and the ability to combine separate features into a coherent whole; yet, perhaps because of this hyperfocus on detail, they may have difficulty shifting attentional focus (Caron et al., 2006).

**WS and VS skills.** In contrast to ASD, one of the most robust characteristics of the diagnosis is that individuals with WS exhibit significant delays, relative to overall level of intellectual ability, in tasks that require VS skills, such as drawing or copying a figure (Bellugi et al., 1990; Bellugi, Lichtenberger, Jones, Lai, & St. George, 2000; Mervis &
Overlap between EFs and VS skills. EF and VS skills are central cognitive abilities that are highly related (Diamond, 2000; Miyake et al., 2001; P. Shah & Miyake, 1996). Completing VS tasks, such as maintaining a mental image, places a heavy demand on central executive functioning, specifically working memory processes, further supporting the idea that EF and VS skills are closely tied (Baddeley, 1996). Although seemingly simple, VS tasks require a complex multistep sequencing of mental manipulations that considerably engage EFs to encode and analyze the problem at hand (e.g., mentally manipulating spatial designs), temporarily store VS information, plan a strategy for solving the problem, monitor performance, shift attention (i.e., cognitive flexibility) back and forth from the provided image to one’s own design, and adapt the strategies during performance (Miyake et al., 2001).

Neuroimaging studies consistently indicate specific links between EFs and VS skills as well. There are dynamic changes in prefrontal and parietal cortex activation associated with improvements in performance on VS-like tasks, which suggests a close interrelation between EFs and VS skills (Floyer-Lea & Matthews, 2004). For example, the development or learning of VS skills requires functional networks in the intraparietal cortex (part of the dorsal visual system for spatial information processing; Ungerleider & Mishkin, 1982) that overlap substantially with the prefrontal circuit that underlie cognitive and EF skills, including attentional control, self-regulation, working memory, and inhibitory control (Floyer-Lea & Matthews, 2004). Likewise, tasks that activate the PFC activate areas of the brain that are necessary for motor and VS processing, such as the cerebellum and basal ganglia (Diamond, 2000). Abnormalities in both the cerebellum and the PFC show that these areas are interconnected and that a dysfunction in one component of the system can affect the other components (e.g., Diamond, 2000).

Furthermore, automaticity theory suggests that the ability to accurately perform a motor-related task without exerting one’s full attention allows attentional resources to become available, which makes simultaneously performing a second attention-demanding (and therefore EF-demanding) task easier (Floyer-Lea & Matthews, 2004). There is more activation in the cerebellum and PFC for both EF and VS tasks that have not yet been automated (Hua & Houk, 1997). After the tasks are automated, however, activation levels in the PFC decrease, suggesting that EF plays an important role in regulating learning overall (Diamond, 2000). In other words, EF is necessary for learning new tasks but becomes less relevant as tasks are automated, thereby freeing attentional resources for more complex demands, such as learning mathematical competencies (Berger, 2010).

EFs and VS Skills Support Early Mathematics Learning

Education researchers are acknowledging the importance of examining how cognitive skills work together to influence academic outcomes (e.g., Assel, Landry, Swank, Smith, & Steelman, 2003; Blair et al., 2008; Cameron, Cottone, Murrah, & Grissmer, 2016; Kim, Duran, Cameron, & Grissmer, in press). EFs and VS skills are considered to be foundational for learning mathematics in general, with specific associations emerging for subdomains of mathematics, such as calculation and problem solving (Ansari et al., 2003; Cragg & Gilmore, 2014). See Table 1 for a summary of the links between EFs and VS skills to mathematics, based on a synthesis of the literature described below.

EFs and overall math. Numerous studies show that EF is a good predictor of performance in mathematics achievement even after controlling for various explanatory factors, such as long-term memory retrieval, phonological processing, and information-processing speed (Blair, Ursache, Greenberg, Vernon-Feagans, & the Family Life Project Investigators, 2015; Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Bull & Lee, 2014; Fuhs, Nesbit, Farran, & Dong, 2014; Geary et al., 2007). The development of mathematics skills relies on EFs, including working memory, decision making,
and attentional flexibility (Menon, 2010). Specifically, numerical tasks require simultaneous and sequential processing of information, such as maintaining and manipulating individual numbers in the mind and producing an answer that consists of all or combinations of the numbers (Best et al., 2011; Cragg & Gilmore, 2014; Geary et al., 2007; Kolkman, Kroesbergen, & Leseman, 2013). Moreover, children use EFs to set goals and sequence their behaviors in a wide range of tasks: for example, to recall and apply strategies to answer math questions successfully, to switch between operations and notations, to store and retrieve the necessary parts to solve a complex multistep problem, and to inhibit or suppress any inappropriate strategies (Assel et al., 2003; Blair et al., 2015; Bull & Lee, 2014; Menon, 2010). Functional MRI studies further confirm these links between EFs and mathematics. For instance, there is coactivation of the posterior parietal cortex (region implicated in numerical processing) and the PFC (region implicated in EFs) in most arithmetic tasks (Menon, 2010).

**EFs and subdomains of mathematics.** Specificity also emerges in the nature of associations between EFs and subdomains of mathematics. For instance, the planning aspect of EF was more closely related to applied problem solving than to calculation (Best et al., 2011), whereas working memory uniquely predicted students’ scores on a standardized math test (Monette et al., 2011), calculation accuracy (Lan, Legare, Cameron Ponitz, Li, & Morrison, 2011), and early numerical magnitude skills (Kolkman, Kroesbergen, & Leseman, 2014). In contrast, working memory and inhibition control both predicted young children’s counting skills (Lan et al., 2011). This suggests that EF may be differentially necessary for success in certain mathematics areas, further supporting the idea that the development of mathematics skills involves distinct cognitive systems. For example, mathematics problem solving requires coordinating several distinct EFs: the ability to recall and manage information in different ways while exhibiting appropriate behaviors related to learning, such as sustaining and switching attention and using working memory to follow directions (Geary, 2013). However, calculation may rely more on fact retrieval or on a single EF component, such as attentional flexibility (Fuchs et al., 2010), rather than the integration of several EF components (Best et al., 2011). In other words, consistent with automaticity theory, performing simple calculations may not require working memory or attention after they are automatized. Working memory, however, may promote early variability in strategy use, which then may assist in adopting higher-level strategies, such as retrieval (Barrouillet & Lépine, 2005; Blair et al., 2008).

Variability in the use of strategies is especially relevant in the development of mathematical competence (Blair et al., 2008). Studies have shown that children show greater activity in the frontal areas of the brain (associated with EF) when asked to verify simple sums or to compare two digits, whereas adults show greater activity in the posterior parietal areas of the brain (associated with numerical cognition; e.g., Ansari, Garcia, Lucas, Hamon, & Dhiwal, 2005). Furthermore, some children may have trouble with processing numerical information and performing numerical tasks accurately because they may have problems in more general cognitive skills (e.g., EFs) rather than problems with understanding the information (Kolkman et al., 2013).

**VS skills and overall math.** VS skills are another necessary foundation for children to learn mathematics (Ansari et al., 2003; Mix & Cheng, 2012; Uttal et al., 2013). Studies have robustly linked VS skills to mathematics ability—theoretically (e.g., Geary, 1993, 2004) and empirically (e.g., Gunderson et al., 2012; Mazzocco, Singh Bhatia, & Lesniak-Karpiak, 2006; Verdone, Golinkoff, et al., 2014). VS skills likely contribute to children’s mathematics performance through their ability to use adaptive strategies to solve arithmetic problems (Geary & Burslim-Dubree, 1989) and to spatially represent and interpret numerical information (Geary, 1993; Gunderson et al., 2012). For instance, when children are first learning to count, they typically rely on VS representations of the objects that are being counted (Assel et al., 2003). At first, children use their fingers to physically touch the objects as they count; however, this process becomes automatized as they learn to mentally represent the objects (Assel et al., 2003). VS skills thereby contribute to the development of children’s mental representation of the number line, which is closely related to their mathematical performance (Gunderson et al., 2012; Mix & Cheng, 2012), specifically in approximate calculation and estimation (e.g., Booth & Siegler, 2008). In addition, VS skills, such as replicating two-dimensional geometric puzzles and block constructs, may be related to later mathematics ability because success on these tasks may require the understanding of part/whole relationships and units, which is implicated in problem-solving tasks (Verdone, Golinkoff, et al., 2014).

**VS skills and subdomains of mathematics.** The VS area of the brain, located in the parietal cortex, is the same area of the brain that is activated when building the foundations of numerical processing (Dehaene, 1992). This area is also activated when numbers are represented mentally (mental number line), as in visualizing numbers (Seron, Pesenti, Noel, Deloche, & Cornet, 1992) and magnitude representation, and when the numerical representation is nonverbal and approximate (Dehaene, 1992). In addition, VS skills share cognitive processes with mathematics ability beginning early in development, and this relation becomes increasingly stronger as mathematical tasks become more complex (Kaufmann, 1990). Moreover, VS skills allow children to develop abilities that are useful and necessary for learning mathematics, such as the understanding of
lines and angles, size and relative size, planning, and relationship of parts to whole, because visualizing these mathematical concepts may help with the acquisition of basic mathematics skills.

**EFs and VS skills in learning mathematics.** Taken together, studies suggest that VS skills and EFs work together over time to distinctly contribute to the development of mathematics. The close interrelations between EFs and VS skills and mathematics could be due to the role of VS working memory. This “visuospatial executive function” is involved whenever children must manipulate spatial information—for example, when visualizing the back side of a three-dimensional object, remembering and reproducing a spatial arrangement, or organizing numbers on a page to manipulate mathematically (Baddeley, 1996). A meta-analysis indicates that VS working memory, more than auditory or verbal working memory, is sensitive to intervention (Melby-Lervag & Hulme, 2012), which has implications for thinking about VS working memory in educational settings.

While EFs and VS skills are both linked to mathematics, we posit whether the strength of association depends on whether mathematics skills have been automated already and to what extent the mathematics problem draws on specific executive or spatial processes (e.g., Blair et al., 2008; Bull & Lee, 2014; Geary et al., 2007). For example, when children have number facts memorized (e.g., addition combinations and multiplication tables), this means a lower working memory demand when performing calculation problems, and attentional flexibility appears most important for keeping children on task. According to work with adults, experts posit that EF is needed to a greater extent in VS tasks than in phonological tasks, which may be more easily automated (Miyake et al., 2001). Along these lines, developmental differences in problem solving exist, where children shift between verbal and VS strategies depending on the problem type and difficulty (Meyer, Salimpoor, Wu, Geary, & Menon, 2010). This in turn suggests that different skill sets are needed for different math problems but that this changes during development (perhaps related to the degree of automaticity).

**Evidence from individuals with ASD and WS.** Individuals with WS and ASD are particularly interesting to examine due to their unique cognitive profiles and mathematics abilities. Comparing the two groups can illuminate how the differences in the cognitive processes of EFs and VS skills may be related to the development of mathematics ability (Figure 1).

**Autism spectrum disorder.** Research evidence on the specific mathematical abilities of those with ASD is scarce and provides mixed results, in part due to the different emphases of these studies, as well as the wide spectrum of phenotypes that are present in ASD. Here, we provide some general patterns of their mathematical abilities, with the caveat that these observations are based on relatively few existing, sometimes opposing, findings.

Overall, individuals with ASD have relatively intact mathematical abilities that are on par with their intellectual abilities (Chiang & Lin, 2007). In terms of more specific subdomains, those with ASD have particular strengths in fact-based materials, such as producing rote arithmetic facts; however, they have difficulties with numerical operations, such as the ability to write verbalized numerals, calculate problems, and solve equations (Griswold, Barnhill, Myles, Hagiwara, & Simpson, 2002). This finding was corroborated by a study that found persons with ASD generally had average mathematical abilities: Relative to their overall mathematics skills, these individuals showed strengths in rote memory and encoding skills and weaknesses in complex processing, including problem solving and numerical operations (Whitby & Mancil, 2009). Furthermore, and especially relevant here, the deficits in mathematics may not become apparent until one moves from rote tasks to abstract conceptual learning. For instance, preschoolers with ASD showed similar early number processing as compared with typically developing children; by first grade, however, children with ASD scored significantly lower in number fact retrieval and word problems (Titeca, Roevers, Josephy, Ceulemans, & Desoete, 2014). To summarize, children with ASD generally have average or enhanced mathematical abilities, except in the subdomains that require complex processing (i.e., problem solving, numerical operations).

The relative strengths and weaknesses in certain mathematics skills, in conjunction with their unique cognitive profile, suggests specific connections between the cognitive processes of EF and VS skills and mathematics. Deficits in certain cognitive areas may account for the discrepancy among children diagnosed with ASD who have average to above-average IQ but relative weaknesses in certain subdomains of mathematics (Whitby & Mancil, 2009). For example, individuals with ASD do typically show deficits in EFs, including planning and cognitive flexibility, which are critical for numerical operations and problem solving. These EF components are necessary for attending to the problem, formulating and implementing strategies, and self-correcting when necessary (Best et al., 2011; May, Rinehart, Wilding, & Cornish, 2013). As compared with typically developing children, children with ASD especially struggle with attentional flexibility, which is associated with mathematics learning (May et al., 2013). In contrast, difficulties with inhibitory control have been linked with lower mathematical ability (Bull & Scerif, 2001), and those with ASD generally exhibit relatively typical inhibitory control abilities. Hence, this may account for their generally unimpaired mathematical abilities.

Surprisingly, although VS skills have been extensively linked to mathematics achievement, having average to
relatively strong VS skills does not seem to provide an advantage for individuals with ASD in their mathematics skills, especially arithmetic and numerical processing. A limited number of studies have examined specific mathematics skills of persons with ASD, however, so we do not know whether other mathematics skills may be enhanced due to their relatively strong VS skills. Future work should examine other mathematics skills that are related to VS skills, such as approximate and magnitude representations.

Williams syndrome. Examining persons with WS provides further evidence of the interrelations among EFs, VS skills, and mathematics. Individuals with WS largely show poor performance on general mathematical skills; however, research shows that they have an uneven profile of mathematics skills, which appears unique in WS (O’Hearn & Luna, 2009). Specifically, they show impairments in magnitude representation and approximate number but strengths in rote memory for math facts (O’Hearn & Luna, 2009). For instance, children with WS (15–53 months old) were unable to discriminate 8 dots from 16, which typically developing infants at 6 months of age are able to do (Xu & Spelke, 2000). However, on addition and multiplication problems, which presumably rely heavily on rote memorization, children with WS performed as fast as typically developing children (Krajcsi, Lukfiffes, Iggiffes, Racsmffiny, & Ploh, 2009).

Additionally, children with WS could recite the count sequence for small numbers with very few errors, although the ability to count accurately and quickly did not predict their actual understanding of counting (Ansari et al., 2003). Together, these findings suggest that individuals with WS struggle with mathematics tasks that require the mental number line; however, they also show relative strengths in certain verbal aspects of mathematics skills.

This unique mathematics skills profile of people with WS, as well as their distinct cognitive profile, provides further insight into the associations among EF, VS, and mathematics. Individuals typically exhibit relatively poor inhibitory control, as well as deficits in other EF components, which we posit explains their generally poor mathematics skills. However, those with WS show strengths in mathematics facts and reciting numbers, which relies more heavily on rote memorization and tap into the area of verbal abilities. The second theme has to do with protective processes. For example, inhibitory control, which is relatively intact among learners with ASD, appears protective in helping them acquire quantitative skills that can be automated, such as rote math facts. Similarly, despite their low inhibitory control, learners with WS appear able to acquire rote math facts because of their strong language abilities. The second theme has to do with affected or impaired processes. Those with ASD and those with WS have difficulty with most EFs (except inhibitory control and working memory processes for individuals with ASD), and this prevents them from carrying out those mathematics problems that require combining or manipulating information and planning. Importantly, the strong VS skills of ASD do not appear to be all that helpful beyond the early levels of mathematics learning, which may arise because when more complex mathematics problems require VS skills, they also require a host of other skills that require EF (e.g., attentional shifting, planning) to successfully master.

Summary. The evidence from studies of individuals with ASD and WS suggests two primary themes with regard to mathematics learning. The first has to do with protective processes. For example, inhibitory control, which is relatively intact among learners with ASD, appears protective in helping them acquire quantitative skills that can be automated, such as rote math facts. Similarly, despite their low inhibitory control, learners with WS appear able to acquire rote math facts because of their strong language abilities. The second theme has to do with affected or impaired processes. Those with ASD and those with WS have difficulty with most EFs (except inhibitory control and working memory processes for individuals with ASD), and this prevents them from carrying out those mathematics problems that require combining or manipulating information and planning. Importantly, the strong VS skills of ASD do not appear to be all that helpful beyond the early levels of mathematics learning, which may arise because when more complex mathematics problems require VS skills, they also require a host of other skills that require EF (e.g., attentional shifting, planning) to successfully master.

Educational Implications

Research from learners with and without disabilities suggests that the domain of mathematics is more complex than
stages (Meyer et al., 2010). Given the importance of these skills for school readiness and later achievement (Verdine, Irwin, et al., 2014), as well as the malleability of EF and VS skills (e.g., Diamond & Lee, 2011; Uttal et al., 2013), educators may want to focus their instruction on developing these skills.

Intervention work suggests that VS working memory, more than inhibitory control, is trainable in young children using computerized programs (Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). This is convenient given that inhibitory control may already be a protective process for some children with disabilities, whereas EF generally and VS working memory specifically appear to be affected processes. At the same time, a meta-analysis suggests limited long-term effects for working memory interventions (with more promise for VS working memory; Melby-Lervag & Hulme, 2012). In any case, thoughtful attention should be paid to developing programs that (a) target the right cognitive process and (b) succeed over the long term in improving children’s EF and VS skills.

A more viable route may be to embed activities in children’s school curricula or after-school programming so that they receive regular distributed practice in engaging real-world tasks that increase in difficulty over time (Diamond & Lee, 2011). Thus, another potential way is for teachers to provide frequent opportunities for children to engage with spatial toys and activities, such as using a diagram to create a block structure in which they can practice their one-to-one correspondence as well as their spatial skills (e.g., mental rotation). Research shows that repeatedly engaging in spatial play materials can increase VS abilities, which in turn is associated with children’s mathematics performance (e.g., Casey et al., 2008; Grissmer et al., 2013; Nath & Szucs, 2014; Verdine, Golinkoff, et al., 2014). A focus on building children’s VS skills early on is especially important given that they play a unique role in the development of mathematics and, importantly, may facilitate development in the later stages (Meyer et al., 2010).

Conclusion

A developmental neuroscience perspective can complement and build on existing theories and behavioral research to meaningfully connect cognitive neuroscience to education. In this article, we use this perspective to provide an additional level of specificity to enhance our understanding of children’s learning of mathematical concepts; to help characterize variability in children’s acquisition of mathematical knowledge; and to identify potential difficulties or developmental limitations that may prevent children from gaining mathematics proficiency in certain areas. The interdependence of domain-general cognitive processes (EFs and VS skills) and mathematics skills among individuals with ASD and WS points to specific areas for further research and intervention. This approach indicates that, for example, while it is well established that EFs are important for learning in general, some components of EF or combinations of components are necessary for success in certain mathematical subdomains. Auditory working memory matters for calculations and is preserved among children with WS; however, a combination of several EF components, including planning, working memory, and cognitive flexibility, is necessary to solve complex mathematics problems (Best et al., 2011), thus posing more of a challenge to children with both types of disabilities.

A focus on building and enhancing general cognitive processes and understanding how each component is associated with learning in mathematics subdomains can help create and refine interventions to be better targeted to individual needs. For instance, an individual’s relative strengths in VS skills may not contribute much to increased mathematics skills; however, weak VS skills may be detrimental for mathematics development because VS skills that are not automated may require additional attention, increasing the cognitive load. Therefore, strengthening weaker VS skills may be one way of supporting children’s mathematics learning. Alternatively, this information can provide educators and clinicians with knowledge on which EFs support student learning for different mathematical skills and which intervention or “workaround” routes may be most fruitful for working with students, for example, whose inhibitory control is relatively intact but cognitive flexibility is impaired.

The research that we reviewed makes clear that EFs and VS skills are important processes for mathematics, but much work remains to be done. Although we used research on individuals diagnosed with ASD and WS to identify these pathways, we appreciate the heterogeneity present within groups that share a common diagnosis, and we urge further research that better incorporates individual differences. We identified areas that require more research, especially in the specificity of relations between components of EF and VS with specific mathematics subdomains. At the same time, continued specificity in describing the role of cognitive processes in math development is necessary if we want to better understand the processes that are actually relevant for learning mathematics, the developmental trajectory of these processes and their influence on math, and how to best help children with specific mathematical learning difficulties.
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