Human
Development

Article

Human Development
DOI: 10.1159/000540164

Received: March 13, 2024
Accepted: June 26, 2024
Published online: August 29, 2024

Tools to Assess Neurocognitive Development: Reciprocal Insights from Theory and Neuroscience

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Keywords
Constructivist theory · Neuroscience · Cognitive potential · Attention · Task analysis

Abstract
Neurocognitive assessments are fundamental for modeling human development. The proposition of this article is that insights from both theory and neuroscience can mutually advance each other, and both can serve as reciprocal tools for constructing improved assessments. Children begin with an abundance of neurons at birth and evolve into sophisticated problem solvers. Grounded in historical perspectives shaped by classic figures such as Ramon y Cajal, Binet, and Piaget, this article delves into the developmental theory of constructive operators. It integrates ideas from psychological theory and neuroscience findings. Four guiding principles emerge that can help steer the course of developmental cognitive neuroscience (i.e., age groupings, child-friendly and culture-appropriate assessments, and meta-subjective task analysis). These principles underscore the benefits of employing theoretically based measures that highlight cognitive potential in complement to learning outcomes and have applications both behaviorally and in neuroimaging. This strategic approach holds considerable promise for driving progress in science, education, clinical practice, and policymaking.

Children are born with an abundance of neurons. Neurons are the cells responsible for receiving input from the environment and sending information to execute actions or thoughts. In the late 19th century, Santiago Ramon y Cajal dedicated a considerable portion of his time to drawing elaborate images of brain cells and persuading his contemporaries that the brain is composed of neurons that are distinct cells. Have you ever wondered how these brain cells help contribute to solving complex problems? This question has fueled my research curiosity since my early ventures in science, particularly in the context of human development. Human development is a complex and fascinating process that encompasses the physical, cognitive, and socio-emotional growth of individuals. One of the most prominent figures in cognitive development is Jean Piaget. Piaget proposed one of the first theories of cognitive development widely embraced among educators. His epistemology may have been influenced in part by experiences he had while working on assessments developed by Alfred Binet and Theodore Simon (the inventors of the Intelligence test; Piaget, 1952; Smith, 1994). Observing and recording that children made different mistakes at different ages might have contributed to Piaget's theory. In turn, Piaget's ideas inspired many developmental psychologists, some of whom proposed new constructivist theories of cognitive development called neo-Piagetian theories (Morra et al., 2012 for review). Having had the privilege of studying with the first neo-Piagetian, Juan Pascual-Leone

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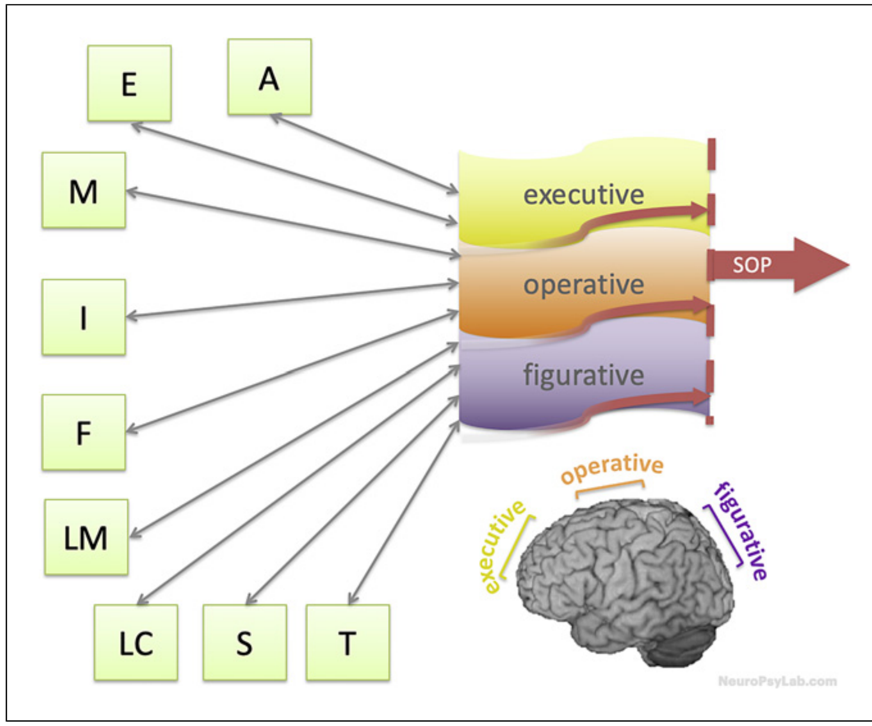

Fig. 1. An illustration of the theory of constructive operators. Operators' initials are in green boxes, and definitions are listed in Table 1. Schemes corresponding to executive, operative, and figurative are in yellow, orange, and purple, respectively. Gray bidirectional arrows illustrate that operators regulate schemes, and in turn, operators can be modified by schemes. The schematic principle of the overdetermination of performance is illustrated in red.

(1970), I have been inspired to apply theoretical ideas in the construction of child- and culturally appropriate developmental assessments of neurocognitive potential.

Neuroanatomical principles have shaped how we view the brain and psychological theories have shaped how we view cognition and behavior. Although these fields of study have evolved separately in the past, the technology and resources that exist today can help converge knowledge for an improved understanding of neurocognitive development that will lead us into the future. In this article, I discuss how I use constructivist theory and meta-subjective task analysis to construct developmental assessments and map neurocognitive processes and follow with examples of how neuroscience findings have helped shape theoretical ideas about brain-behavior dynamics. This discussion will distill into a series of fundamental guiding principles that can help mold the future of cognitive developmental neuroscience research.

Neo-Piagetian Theory of Constructive Operators

Juan Pascual-Leone, one of Piaget's former doctoral students, introduced the theory of constructive operators during Piaget's lifetime, making him the pioneering neo-Piagetian to do so. The theory of constructive operators was conceived in the 1960s, with its first publication being a mathematical model aimed at predicting Piaget's developmental stages (Pascual-Leone, 1970). The theory of constructive operators is a general theory of cognitive development (Pascual-Leone, 1970; Pascual-Leone & Johnson, 2021). A general theory is one that applies across domains (e.g., visual, verbal, numeric, etc.). It was shaped by the ideas of Piaget's developmental constructivism, the theories of Vygotsky and Luria (Pascual-Leone, 1987, 1995, 1996, 2011, 2014; Miller, 2011), along with insights from neuropsychology and neuroscience.

Operators, Schemes, and a Key Principle in the Theory of Constructive Operators

The theory of constructive operators is framed in terms of operators, schemes, and a basic principle of schematic overdetermination of performance. In short, operators regulate schemes, and the winning scheme emerges to signify a motor or mental action by utilizing the schematic overdetermination principle (Fig. 1). In more detail below, I outline operators, schemes, and the key principle.

Table 1. Description of operators and their corresponding brain regions in a likely evolutionary order (after Arsalidou, 2003, and Arsalidou et al., 2019)

Operator	Description	Brain region
A	Specific **affective** boosting or inhibition processes that intervene in motivation and attentive arousal	Limbic system
C	Both the process of **content** learning and the schemes derived from associative content	Primary and secondary association areas
F	The internal **field** operator together with the Schemes' Overdetermination Principle (*SOP*, see below), which act as brain's *binding mechanism* to bring closure to mental representations in a neo-Gestaltist manner	All areas
LC	The process of automatized logical-structural learning reflectively abstracted from **content learning** (and other) through over-practice	Right hemisphere
T	Effortlessly collates time-flow *sequences* of schemes, thus facilitating coordination of **temporally** structured invariants that constitute *distal* objects (which emerge in agency and praxis)	Occipito-temporal
S	Facilitates emergence of **spatial** schemes by effortlessly coordinating *relations of coexistence* among activated schemes within the situation	Occipito-parietal
B	*Self and psychosocial schemas* associated with the **being** of one's self	Default mode network
I	The attentional **interrupt**: it produces the central *active inhibition* of unwanted schemes activated by the situation or the mind	Prefrontal
M	Effortful **mental attentional** *activation* of simple or complex (functional-system) schemes	Prefrontal
LM	**Logical-structural** learning caused by effortful use of **mental attentional** capacity	Left hemisphere tertiary areas
E	**Executive**, i.e., dominant *set of activated executive schemes* in the person's repertoire that is useful for the task at hand	Prefrontal

Operators

Operators are content-free general resources that can apply across any scheme (Pascual-Leone, 1970; Pascual-Leone & Johnson, 1991, 2005, 2011). Table 1 lists operators in an ontogenetic and phylogenetic order of emergence. Operators that emerged later are comparable to domain-general processes, such as executive skills and effortful attention, whereas operators that emerge earlier favor the coordination of schemes with specific characteristics such as time and space. Because operators have specific propensities to regulate schemes, and they work together, they allow for novel synthesis and manifestation of performance. Novel synthesis can be a result of an "aha" moment, which reflects a sudden breakthrough in understanding. For example, a child reading may encounter new words, which can be frustrating. A novel synthesis of schemes by operators can manifest when the child figures out how to consider story illustrations and surrounding text to infer new word meanings. Specifically, the A (affective)-operator represents an affective regulator and appears first, followed by learning (e.g., L-learning and C-content) and perceiving (i.e., T-temporal and S-spatial) operators, followed by self-internalizations (B-being operator) and finally by higher order goal-directed abilities (I-inhibition, M-mental attention, and E-executive operators).

Operators, like organismic propensities, are proposed to represent brain structural and functional dynamics (e.g., Arsalidou, 2003; Pascual-Leone & Johnson, 2005, 2021; Arsalidou & Pascual-Leone, 2016; Arsalidou et al., 2019). For instance, sub-cortical areas mature biologically earlier as they are responsible for initiating affective processes. For instance, the A-operator can reflect the primary urge for food that triggers a baby's crying when hungry. The C-operator reflects associated content learning by acting in the environment. For instance, a response to an action: a parent appearing (i.e., response) after the baby cries (i.e., action) represents this operation. Acting in the environment creates opportunities for learning that lead to the emergence of L- and LC-operators and basic effortless perception of space (parietal lobe) and time (temporal lobe; Kastner & Ungerleider, 2000) that are represented by the S-space and

T-time operators. Consider how effortlessly you raise your hand at the correct height to switch on the light in a familiar room; this is driven by the S-operator. The T-operator regulates effortless sequences. For instance, if a pen rolls off your desk, you have a sense of when to hear the click it makes when it hits the floor. The field F-operator reflects a binding mechanism that organizes schemes. In essence, the F-operator forms the field of relevant information needed for processing. For example, when thinking of the scent of bread, the F-operator creates a field for scents (e.g., freshly baked, buttery, moldy) to optimize identification and processing for scents by other operators.

The B-operator regulates self-internalization processes that relate to affect and cognition. It is expressed in the set of medial fronto-parietal brain regions often referred to as the default mode network. For instance, one's ideas of how caring, patient, anxious she or he is compared to others would be regulated by this operator.

Higher order operators are represented in the prefrontal cortex as they coordinate effortful processes of I-inhibition, M-mental attention, and E-executive processes. The I-operator effortfully suppresses unwanted schemes that interfere in a situation. For example, when driving in a country where vehicles go on the opposite side of the road than you are used to, the car setup is typically reserved, and you might automatically reach for the handbrake or gearstick on the same side as the car you drive at home. This is a prepotent response and to drive properly in the new country, you need to actively inhibit such prepotent motor actions. The E-operator represents executive know-how and encompasses all sorts of mental action plans such as updating, switching, sequencing, and strategizing. It is responsible for devising and implementing a plan for reaching the goal of the task at hand. For example, an executive plan to implement a visual search for a "contact us" button on a new website would be searching from left to right on the top of the page or left to right at the bottom of the page. An executive plan could also be the steps taken to solving math equations using parentheses, exponents, multiplication, and division, and addition and subtraction in this order. The M-operator represents the energy to execute effortful mental activities. This operator represents mental attentional capacity that changes with age as well as circumstances (e.g., fatigue). Below I give examples of how children of different ages can solve tasks based on their developmental level. Notably, I consider that constructive operators work together to optimize the organism's potential for survival, and malfunction or elimination of any of them should elicit an observable deficit. For example, damage to the prefrontal cortex should be measurable in deficits to later emergent operators such as E-executive, I-inhibition, and M-mental attention.

Schemes

Schemes are self-propelling entities that carry information (Pascual-Leone & Johnson, 2021). I consider the "self-propelling" mechanisms of schemes to be founded on the need for neurons to be active. Neurons that activate receive nourishment and energy and ultimately become stronger and better connected. This is related to the famous statements about properties of neurons that fire together wire together by Donald Hebb (1949) and to the notion of "use it or lose it" championed by Mariam Diamond (1993). Schemes are represented by bundles of neurons or circuits and are distributed across the brain based on their type. There are three main types of schemes: figurative, operative, and executive. Figurative schemes lead to perceptions and representations of objects and concepts. For example, simple figurative schemes can be objects such as a pencil or an avocado, whereas complex figurative schemes can be concepts such as prosperity or equality. Operative schemes correspond to actions and procedures that can be applied to objects. For instance, effortless motor actions such as writing the word "avocado" with a pencil, or eye movements needed to read this text by a trained reader. Executive schemes are a subset of operative schemes that embody mental procedures and plans. Executive schemes apply across content domains and serve an individual by orchestrating actions for other operators or schemes. For example, an executive plan for identifying grammar errors when proofreading text is to check for the part of speech, punctuation, singularity and plurality, and pronouns. An executive scheme for discovering the sorting rule in the Wisconsin Card Sorting Task is to consider the sorting rules that are not currently in use and select the one that has not been used as frequently in the past.

Most schemes are learned by interacting with the environment and they can dynamically change based on experience. Consequently, children's performance often hinges on the range of schemes at their disposal. For example, consider two children Child A and Child B both pointing at the sky toward a flying object. Parent A responds with a simple "that is a bird," whereas Parent B provides a more elaborate response "That is a bird. It is a seagull. Look how white it is. It must be searching for fish to eat." In the absence of prior knowledge, Child A is likely to form a scheme that defines a bird as something in

Table 2. Model of right-left-right hemispheric dominance

Mc/Md trade-off	Familiarity/ novelty	Hemisphere – strategy	Factors of transformation – hemisphere
Md < < Mc	High familiarity	Right – associative heuristic to cope fast with easy task	With experience remains familiar – processing at right
Md ≤ Mc	Novel	Left – mental attentional heuristics for problem solving	With experience becomes familiar, overlearned – transfer to right
Md > > Mc	High novelty	Right – associative heuristic to cope with a too difficult task	With maturation Mc increases, and with experience task becomes less novel – transfer to left

Mc, mental attentional capacity of the individual; Md, mental attentional demand of the task (adapted from Arsalidou et al., 2018).

the sky. On the other hand, Child B is likely to construct a more comprehensive scheme in its repertoire, envisioning a bird as something in the sky that can be a seagull, is white, and feeds on fish.

The central sulcus in the brain separates figurative and operative schemes (Fig. 1). Figurative schemes are organized in areas of the occipital, parietal, and temporal cortices, whereas operative schemes are organized in the frontal cortex. Operative schemes are supported by supplementary motor and primary motor regions whereas executive schemes are supported by prefrontal cortices in a hierarchical fashion. Basic well-known executive schemes are supported by the ventrolateral prefrontal cortex, complex but known executive schemes are supported by the dorsolateral prefrontal cortex, whereas novel executive schemes creation is supported by the frontopolar prefrontal cortex (Christoff et al., 2009). Which hemisphere is going to engage depends on a trade-off between the mental attentional capacity of the individual and the mental attentional demand of the task, as well as on the novelty versus familiarity of the situation as explained by the right-left-right hemispheric dominance model (Table 2).

Distinguishing Left Hemisphere from Right Hemisphere Functions

Historically, the differentiation between left and right hemisphere processing was based on the contrast between verbal-analytical functions attributed to the left hemisphere and visuospatial-global processing associated with the right hemisphere (Gazzaniga et al., 1962). Critically, this traditional viewpoint no longer adequately captures the semantic distinction between the two hemispheres as research reveals that both hemispheres can activate in response to various content types, including both verbal (Turker et al., 2023; Enge et al., 2020, Emch et al., 2019, for meta-analyses) and visual-spatial ((Li et al., 2019; Li et al., 2021; Cona & Scarpazza, 2019, for meta-analyses).

Within the theory of constructive operators, the left and the right hemispheres take a process-based rather than a material-based role (Table 2; Fig. 2; Arsalidou et al., 2013, 2018; (Pascual-Leone, 1995; Pascual-Leone and Johnson, 2011, 2021). Specifically, the left hemisphere favors analytical mental attentional processing, particularly in demanding problem-solving scenarios that require novel and effortful working memory within the individual's mental attentional capacity. In contrast, the right hemisphere fosters propensities for overlearned or automatized processing, coming into play in very easy or very challenging tasks.

Table 2 outlines the conditions that lead to left or right hemisphere dominance, taking into account task novelty, the mental demand of the task, and the mental attentional capacity of the individual (Pascual-Leone and Baillargeon, 1994; Pascual-Leone and Johnson, 2011). Hemispheric dominance can be predicted by weighing the trade-off between mental attentional demand of the task and mental attentional capacity of the individual (Fig. 2). Specifically, when task demand is very low and mental attentional capacity is high, processing tends to favor the right hemisphere. When mental attentional demand of the task is close or equal to the mental attentional capacity of the individual, processing leans toward the left hemisphere. In cases when mental attentional demand of the task is greater than the mental attentional capacity, the right hemisphere is more likely to take the lead.

This distinction offers novel insights into the function of the right hemisphere, which comes into play in two different scenarios: (1) during more or less automatized (easy) processes and (2) when the mental attentional requirements exceed an individual's available capacity. In the latter case, when a task's mental attentional demand

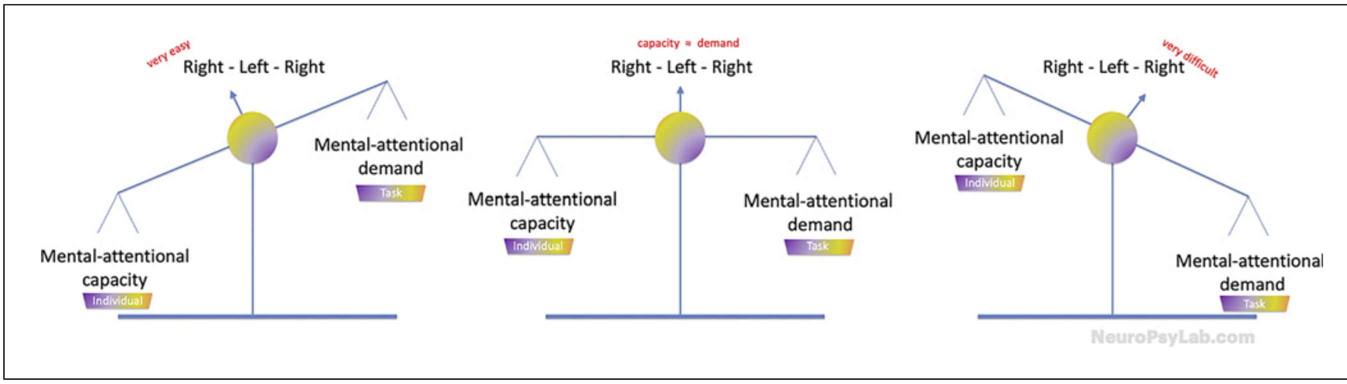

Fig. 2. An illustration of the right-left-right hemispheric dominance hypothesis. Colors yellow, orange, and purple represent executive, operative, and figurative schemes.

surpasses what the left hemisphere can handle alone, the right hemisphere is activated in search of potentially useful overlearned or automatized schemes. This right-left-right hemispheric dominance model is not limited by the domain of the scheme or the type of scheme. Ultimately, schemes engage, and performance is characterized by a motor or mental output. The output corresponds to the scheme that is applied. The scheme that will eventually apply is defined by the principle of schematic overdetermination of performance.

Principle of Schematic Overdetermination of Performance

The principle of schematic overdetermination of performance defines the process for scheme application (Pascual-Leone & Johnson, 1991, 1999, 2005, 2011). In each situation, affective schemes provide the vital energy for relevant schemes to apply. Affective schemes provide the impetus or motivation for performing a cognitive or motor action. For example, one looks for food when one is hungry. The sensation of hunger motivates the need for using cognitive and motor resources to search for food because it is needed for survival, often called a primary reward. Secondary rewards, such as monetary rewards, share sub-cortical brain correlates with primary rewards (Arsalidou et al., 2020), and can also motivate cognitive actions. This is vital because, in essence, every cognitive goal is motivated by an affective goal (e.g., relieving hunger, quenching thirst, finding a mate, acquiring resources, rising up the social ladder) that contributes to survival.

After the affective goal is set and when needed, executive schemes can regulate which schemes can be inhibited and activated. The scheme with the highest energy will eventually apply. In other words, it is a winner-takes-all principle in line with Sherrington's neural principle of a final common path (Sherrington, 1906; McFarland & Sibly, 1975). Sherrington explained elegantly: "Where it is a question of 'mind' the nervous system does not integrate itself by centralization upon one pontifical cell. Rather it elaborates a million-fold democracy whose each unit is a cell." (Sherrington, 1940, p. 277). In the case of the theory of constructive operators, the principle of schematic overdetermination posits that all compatible schemes are activated, and the one with the strongest activation will apply to determine performance.

The F-operator works with this principle to integrate and provide closure so that the winning scheme can apply. For example, when answering the question: "What is the tallest land mammal?" A set of schemes associated with large animals are cued and activated. Considering the cues for "mammal," "land," and "tallest," for most of us, the strongest scheme would be "giraffe." Problem solving with higher complexity also mobilizes this principle. The theory of constructive operators operationalizes problem solving within the model of endogenous mental attention.

Model of Endogenous Mental Attention

The model of endogenous mental attention outlines the mechanisms that give rise to effortful thoughts and actions (Fig. 3; Pascual-Leone & Johnson, 1991, 2005, 2011). Consider the tallest land mammal example. Everyone has a repertoire of schemes of different types, figurative, operative, and executive, as illustrated by the large rectangle in Figure 3. If you are sufficiently motivated to answer the question when you think of a mammal, the field of activated schemes that is nested

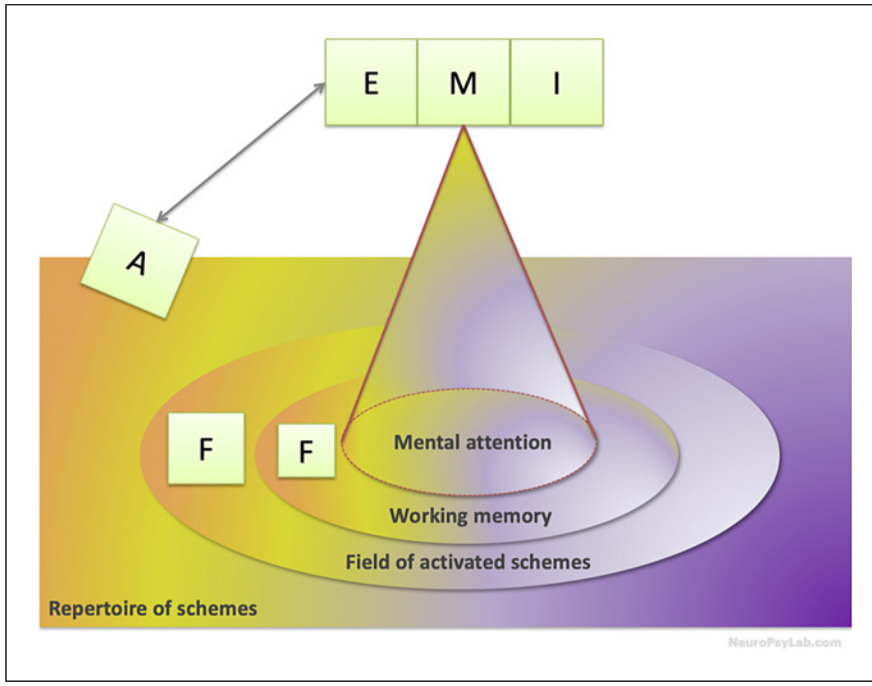

Fig. 3. Flashlight illustration of the model of endogenous mental attention. *E-*, *M-*, *I-*, *F-*, and *A*-operators are shown in green boxes, and the principle of schematic overdetermination of performance is depicted in red. Operator information is listed in Table 1. Colors yellow, orange, and purple represent executive, operative, and figurative schemes.

within the repertoire of schemes activates mammals rather than insects, reptiles, or other things. Then the question gives a clue that we are searching for a land mammal, so dolphins and whales are excluded. As the number of clues increases, working memory, which is nested within the field of activated schemes, regulates the next level of abstraction. Now the question clues for the tallest land mammal and mental attention that is nested within working memory evaluates possible options; although other candidate land mammals such as elephants are tall and could be the heaviest, the giraffe wins this race as the tallest land mammal. Thus, we can visualize a metaphorical flashlight shining on the giraffe scheme.

More technically, operators E, M, I, F, and A regulate schemes to produce effortful outcomes. The A-operator offers affective value to the need for partaking in an effortful mental task; in other words, it motivates thoughts and actions. The E-operator designs and implements the executive plan to coordinate resources and schemes. The F-operator acts at every nested level to regulate relevant schemes and with the schematic principle of overdetermination of performance eventually helps determine which scheme will apply. The I-operator suitably interrupts distractors and inhibits salient irrelevant schemes. Mental attention, the M-operator, illustrated by the central circle in Figure 3 represents the amount of energy available for activating schemes and problem solving.

The M-operator corresponds to the individual's mental attentional capacity. Mental attentional capacity is limited and corresponds to the amount of energy an individual can allocate to problem solving. In terms of schemes, it corresponds to the energy needed to activate or inhibit available schemes in an effort to problem solve. As a general-purpose resource, it can apply to all types of schemes. According to the theory of constructive operators, mental attentional capacity grows in infancy, childhood, and adolescence. The sensory-motor scale accounts for the typical growth in mental attention during the first 2 years of life. In the third year, the symbolic scale takes over, charting the typical expansion of mental attention up to the age of 16 years (Pascual-Leone, 1970; Pascual-Leone & Johnson, 2005, 2011, 2021).

Theoretically, the symbolic scale predicts that mental attention increases by one unit every 2 years (Table 3). Empirical research has supported this growth function (e.g., Pascual-Leone, 1970; Bereiter & Scardamalia, 1979; Lawson, 1983; Johnstone & El-Banna, 1986; Pascual-Leone & Baillargeon, 1994; Pennings & Hessels, 1996; Morra, 2001; Johnson et al., 2003; Pascual-Leone & Johnson, 2005; Im-Bolter et al., 2006; Agostino et al., 2010; Arsalidou et al., 2010; Morra et al., 2011, 2013; Powell et al., 2014; Arsalidou & Im-Bolter, 2017; Milani et al., 2022). Age-appropriate performance can be assessed using tasks adjusted for the mental attentional

Table 3. Symbolic scale showing theoretically predicted values of mental attentional capacity as a function of age

Age, years	Mental attentional capacity
3–4	1
5–6	2
7–8	3
9–10	4
11–12	5
13–14	6
15–16	7

demand of the task, which can be determined using meta-subjective task analysis. Meta-subjective task analysis can be used to model performance based on individual characteristics, content, and context (Arsalidou, 2013; Pascual-Leone & Johnson, 2005). Whereas content refers mainly to material presented, context refers mainly to the processes needed for tackling a problem. These situational factors can be sorted in terms of the degree of facilitation or misleadingness.

Distinguishing between Facilitating and Misleading Situations

In the theory of constructive operators, a critical distinction is made between facilitating and misleading situations. This differentiation is essential for understanding which cognitive operators come into play. Imagine a continuum: on one end, you have straightforward situations with clear-cut solutions, and on the other, you encounter complex situations with obscured solutions that demand concentrated effort. These are, respectively, known as facilitating and misleading situations (Pascual-Leone, 1970, 1980, 1989).

In the context of the theory of constructive operators, a situation is considered misleading when it augments cognitive demands due to prominent, irrelevant features (e.g., Stroop task) or different processes that activate schemes (e.g., dual tasks), leading individuals to errors in contrast to the intended task performance (Pascual-Leone, 1989; Pascual-Leone & Johnson, 2005). Misleading situations often involve integral features that interfere with or elicit conflicting executive plans, necessitating a division of attention and a more effortful approach to achieve the intended outcome (Pascual-Leone & Baillargeon, 1994).

Misleading situations often have context with integral features. Integral features refer to aspects of the situation that, due to perceptual and learning processes, appear to be interlinked into a single salient object or pattern. For example, when searching for a specific figure within a complex pattern or context (Witkin 1949; Witkin & Goodenough, 1981). Consider Witkin's Embedded Figures Task as an instance (Witkin, 1950), where a figure, like a triangle, is concealed within the intricate composition of the entire figural compound. Each part of the triangle belongs to distinct components within the compound, making it challenging to discern.

Another type of misleading situation is encountered in the Stroop task (Stroop, 1935), where individuals must resist the automatic response of reading color words and instead focus on naming the ink colors. Children and adults who can read experience the Stroop effect (e.g., Arsalidou et al., 2013). The Stroop task is renowned for measuring inhibition, requiring individuals to suppress the automatic reading response to attend to the incongruent ink color. Successfully navigating misleading situations involves actively inhibiting perceptually salient or automated distractions, be they irrelevant features or actions.

Competing executive plans can also introduce misleading situations, particularly when attempting to multitask. Dual-task paradigms, such as those outlined by Daneman and Carpenter (1980) and Engle (2001), aim to explore this topic. Engaging in dual tasks requires simultaneously managing two tasks, like reading sentences and keeping track of numbers, leading to interference between the goals of both tasks and creating a misleading executive context (Cowan & Morey, 2007).

In contrast to misleading situations, facilitating situations predominantly feature task-relevant schemes that align with the requirements of the task (Pascual-Leone & Johnson, 1991, 2005, 2011). A typical example of a facilitating situation is found in pro-saccade tasks, where participants are instructed to make an eye movement toward a conspicuous visual target. Conversely, anti-saccade tasks involve suppressing the automatic orienting reflex to a visual cue and intentionally making eye movements in the opposite direction. Anti-saccade tasks contain a strong misleading component, necessitating the suppression of the automatic urge to look at the cue. Consequently, anti-saccades engage prefrontal cortices (Jamadar et al., 2013), a region associated with executive schemes for controlling attentional activation and inhibition, requiring intentional and effortful cognitive control.

Facilitation and misleadingness exist on a dynamically graded continuum, meaning a situation can vary in its degree of facilitation or misleadingness, significantly impacting the cognitive operators needed for task resolution. The determination of a task's degree of

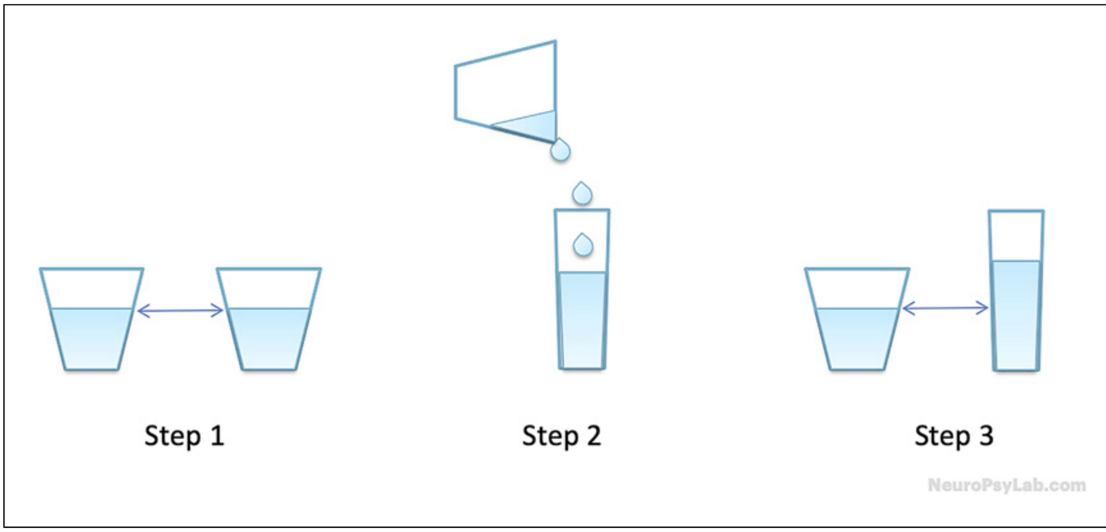

Fig. 4. Meta-subjective task analysis of Piaget's conservation task. Underline in the formula indicates the schemes in each step that count toward the mental attentional demand of the step. Step 1 = M [EVALUATE^{L1} (#SCANEXTRACTLiquidlevel <sglassA, sglassB>)]. Step 2 = M [WATCH (#TRANSFORM <sglassB, tglassB>)]. Step 3 = M [EVALUATE^{L1} (#SCANEXTRACTLiquidlevel <sglassA, tglassB>)].

misleadingness or facilitation calls for a thorough meta-subjective task analysis. A main purpose of meta-subjective task analysis is to utilize content and context to model the mental attentional demand of a task given an exemplar problem solver.

Meta-Subjective Task Analysis

Meta-subjective task analysis is a theory-informed, rational approach used to estimate the quality (i.e., operative, executive, and figurative) and quantity of operators and schemes needed to complete a task by an exemplar participant (Pascual-Leone & Johnson, 2021). It earns its "meta-subjective" title because it is a method that seeks to model task-solving steps from the vantage of an individual's perspective. The step with the highest scheme count indexes the mental demand of the task. The theory of constructive operators equips us with the fundamental constructs and essential elements to model basic process components.

The trade-off between the mental attentional demand of the task and mental attentional capacity of the individual is used to assess performance levels. Specifically, if a child has a mental attentional capacity of 3, then this child should be able to successfully complete tasks with mental attentional demand of 3 or less (Table 3). Mental attentional demand is the minimal number of schemes that an individual can activate simultaneously to complete a task.

Consider Piaget's water conservation task (Fig. 4), a measure of conservation of continuous quantity. A child is presented with two identical tumbler (i.e., short) glasses filled with the same amount of liquid. The child is asked to evaluate whether short glass A (sglassA) and short glass B (sglassB) have the same amount of juice (or liquid). After the child verifies the amount of juice is the same, the experimenter takes one glass (say glass B) and transfers the liquid into a tall glass B (tglassB). Then the experimenter asks the child to look at the glasses (now short glass A and tall glass B) and evaluate whether the amount of juice is more in one glass or the other glass or whether it is the same. In notation of a meta-analysis scenario, there are three steps. Step 1 shows that there are two operative schemes, first the child scans and extracts liquid level (#SCANEXTRACTLiquidlevel) for short glass A and short glass B and second evaluates (EVALUATE) to provide a response. Figurative schemes that correspond to the glasses are facilitating and salient in this case; therefore, they do not load mental attention. Step 2 has two operative schemes for the transformation (TRANSFORM) of the liquid from short glass B to tall glass B and the child must watch (WATCH) the process. The third step has two operations and one figurative scheme that counts toward the mental attentional demand of the step as the child now must extract liquid level and evaluate; however, the one figurative scheme, liquid level of tall glass B (tglassB), is misleading as the liquid level has transformed in the previous step. Figure 4 illustrates the steps and in the caption, I have used underlining in the formula to indicate the schemes in each step that must be held active using mental attentional capacity. Specifically, step 1 and step 2 have a mental attentional demand of 2,

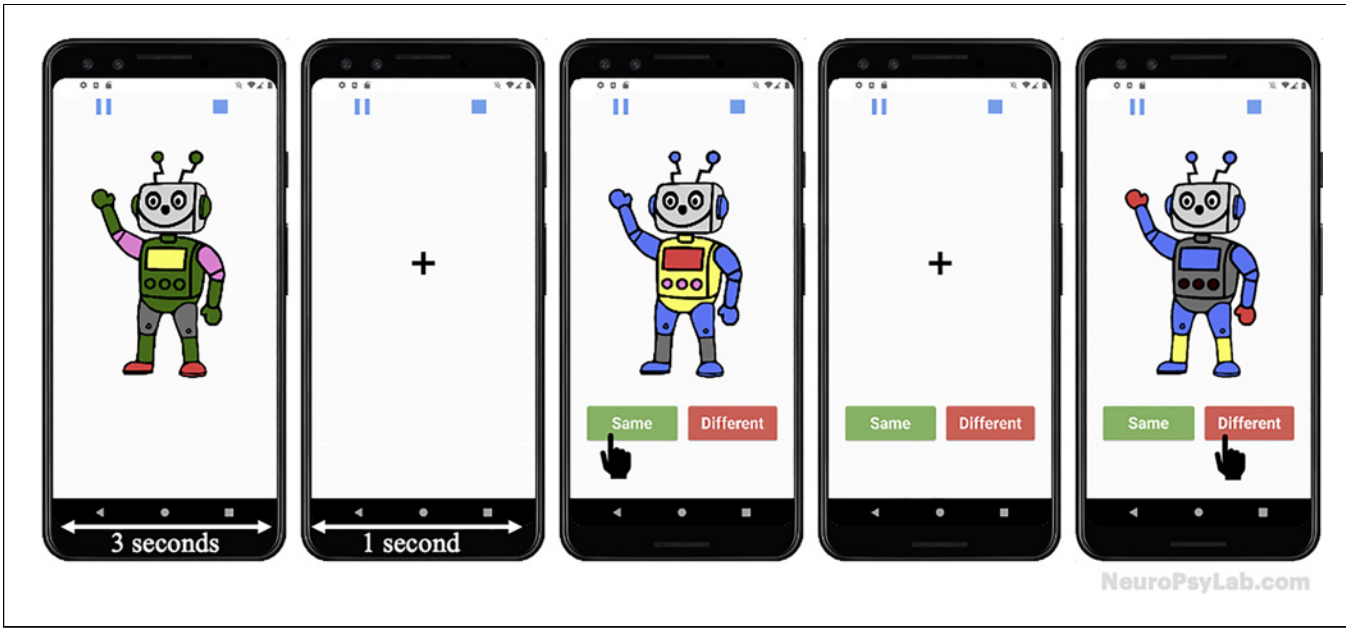

Fig. 5. An illustration of the color matching task with four relevant colors. All colors are relevant except blue and green. Players are asked to remember the relevant colors and indicate if the next creature has the same or different relevant colors. Colors can change location and the face does change. Images are presented for 3 s with a 1 s interstimulus interval.

whereas step 3 has a mental attentional demand of 3. Thus, a child with a mental attentional capacity of 3 or more should be able to successfully solve Piaget's conservation task. According to theoretical predictions by the theory of constructive operators, children of 7 years and older should be able to solve the task.

In my research, I have used meta-subjective task analyses to construct parametric measures of mental attentional capacity (see Arsalidou et al., 2010 for meta-subjective task analysis formula). In the color matching task (CMT; Fig. 5) participants are asked to play a game with colors. They are presented with a charming creature that has several body parts such as face, arms, and legs with different colors. The players are asked to determine whether the relevant features (i.e., colors) of the current creature match (i.e., indicate the same or different) those of the immediately preceding creature. This means players respond to whether the relevant set of colors is the same or different in consecutive items. Notably, the colors blue and green are irrelevant, and the players are asked to ignore blue and green when making a decision. The difficulty of a trial is determined in part by the number of relevant colors that can range from one to six or more.

Using meta-subjective task analysis, we can map one primary operation: which is the executive scheme used to scan and identify that applies to relevant colors (figurative schemes) that range typically from one to six across items. Besides ignoring irrelevant colors, participants must also disregard factors such as color location, the creature's face, and the integrated compound figure of the creature, including its body parts like gloves, buttons, and shoes. These distracting and misleading elements are crucial in estimating the task's mental attentional demand because they lead players to adopt error-avoiding strategies by effortfully extracting relevant schemes – thus requiring an additional executive scheme. Thus, one can estimate the mental attentional demand of an item to be two executive schemes plus the number of relevant colors. In other words, to quantify the mental attentional demand for an item with n relevant colors, the estimate should be $n + 2$ executive schemes. For instance, a task with four relevant colors will have a mental attentional demand of six (Fig. 5). Knowing that children of 13–14 years of age have a symbol-processing mental attentional capacity of six (Table 3), they should be able to successfully complete this level of task difficulty, whereas younger children would not. Children are assigned a mental attentional capacity score corresponding to the mental attentional demand of the highest item level they can reliably pass.

Empirical findings (Arsalidou et al., 2010; Powell et al., 2014; Milani et al., 2022) provide robust evidence for the construct validity of this constructivist-developmental modeling, first proposed over five decades ago (Pascual-Leone, 1970; Pascual-Leone & Baillargeon, 1994; Pascual-Leone & Johnson, 2005, 2011). The consistency of quantitative scores obtained across different task types and age group samples underscores the developmental reliability and construct validity of this measurement method, which is notably culturally inclusive (Arsalidou & Im-Bolter, 2017; Miller, Pascual-Leone, & Andrew, 1992; Miller, Pascual-Leone, Campbell, & Juckes, 1989; Pascual-Leone, 2000).

In addition to the powerful technique of meta-subjective task analysis, another notable strength of the theory of constructive operators is that it offers a neuroscientific representation of fundamental constructs and processes. Critically, a comprehensive neuroscience model of human development is an ongoing endeavor and a reciprocal knowledge exchange between theory and neuroscience is needed for continued progress.

Reciprocal Knowledge Construction between Neuroscience and Theory: Examples from Higher Order Cognition

Higher order cognition refers to processes that go beyond sensory perception and simple or automatic processes. It refers to complex problem-solving that requires coordination of schemes and strategies. Behavioral data obtained during problem-solving typically reflect a measurable output of response, often recorded as some metric of reaction time and accuracy. Generally, problem solving is set in motion by a stimulus and unfolds over a period before a response is generated. To glean insights into the mechanisms of the interval between the stimulus and the response, it is crucial to deduce the nature of these underlying processes. In the past, before the advent of neuroimaging techniques, inferring these post-stimulus, pre-response mechanisms relied mainly on philosophical and theoretical ideas. However, with the introduction of neuroimaging methods, we now have a means of gathering evidence that sheds light on the processes leading up to a response. In the past 3 decades, functional magnetic resonance imaging (fMRI) has transformed the way we view the brain, reshaping the field by either providing support for certain theoretical concepts, challenging others, or uncovering novel mechanisms that contribute valuable insights to theoretical frameworks.

When planning the first functional neuroimaging study using the CMT, I predicted that fronto-parietal areas would increase in activity as a function of multiple levels of the color matching task (Arsalidou et al., 2013). According to the theory of constructive operators and the meta-subjective task analysis we prepared (Arsalidou et al., 2010), I expected that two executive schemes should engage the prefrontal cortex and figurative schemes should engage the parietal cortex. Indeed, analyses of fMRI data revealed large clusters increased in activation as a function of difficulty in bilateral inferior and middle frontal gyri (Brodmann areas, BA, 9, 46, 10) and bilateral parietal activation in the precuneus (BA 7), and right inferior parietal lobule (BA 40). However, results also revealed an extensive set of regions that included the dorsal cingulate (BA 32), the anterior insula (BA 13), and the fusiform gyri (BA 37). We attributed activity in the dorsal cingulate and anterior insula to initiating motivated behaviors that theoretically correspond to the A-operator that controls affect. The fusiform gyri showed a marked increase in higher levels of difficulty attributed to navigating the image more intensely to extract relevant colors, which theoretically corresponds to the T-operator that coordinates sequences of action. Thus, these neuroimaging data converge with understanding of theoretical constructs and provide a more detailed signature of the processes that underlie problem solving in the visual-spatial domain with multiple colors.

In the same CMT study, the observation of a specific set of brain regions exhibiting a linear decrease in activity as task difficulty increased was even more intriguing (Arsalidou et al., 2013). These regions included the medial frontal gyri (BA 10), anterior cingulate (BA 32), posterior cingulate (BA 31) and superior temporal gyri. Notably, these areas were consistent with the default mode network, a set of areas primarily along the brain's midline that become active in the absence of a task, typically during self-referential thinking (Raichle et al., 2001; Spreng et al., 2009). Considering only behavioral knowledge and theoretical ideas of cognition, there was no foundation for predicting a linear decrease in default mode-associated areas with increasing task difficulty. When Raichle and colleagues (2001) first introduced the concept of the default mode network, it seemed counterintuitive to consider that apparent rest elicited consistent and substantial brain activity. However, this phenomenon of brain activation in the absence of a task has since become an established concept, linked to various self-referential functions such as autobiographical memory and theory of mind (Spreng et al., 2009 for meta-analysis). In the context of my study, with multiple levels of task difficulty, the findings underscored the linear and anti-correlated properties of the fronto-parietal and default mode networks. This is a compelling example of how neuroscience can inform theories by providing novel insights on brain dynamics.

Theoretically, mental attention is nested within working memory. Working memory is a core cognitive resource and a popular topic of investigation for functional neuroimaging studies. I am interested in understanding the brain foundations of such core cognitive resources and recognize that individual studies may not provide definite answers. Consequently, quantitative meta-analyses of fMRI studies provide great value in understanding brain patterns. Several meta-analyses have been published examining overarching brain patterns associated with working memory in adults (Rottschy et al., 2012; Yaple et al., 2019), reporting concordance mainly in fronto-parietal brain regions. From a neuroscience empirical perspective, one would expect that children should also show concordance in fronto-parietal brain regions.

Collaborating with a graduate student at the time, we conducted quantitative meta-analyses of brain responses to the n-back task in children and adults (Yaple & Arsalidou, 2018). The n-back task asks participants to indicate whether the current stimulus matches the stimulus n times back. This was the first study to examine concordance of brain activity in children, with an average age of 10.61 ± 1.75 years. Our findings revealed significant concordance in bilateral parietal regions (BA 7, 40), along with activity adjacent to the dorsal cingulate and the anterior insula. Thus, children's results were partially aligned with our expectation that children would engage the parietal areas of the front-parietal network. However, the lack of significant concordance in lateral prefrontal areas was most intriguing. In the course of our investigation, we meticulously compiled data on prefrontal activations reported by original articles revealing that children did engage prefrontal cortices during problem solving. Critically, activation patterns in the prefrontal cortex were notably inconsistent across studies. The prefrontal cortex constitutes about 12.5% of the total brain volume in humans (McBride et al., 1999). Relatively, this is a large proportion. Some of the original studies we included in our meta-analysis showed activity in the inferior frontal cortex, whereas others showed activity in the middle frontal cortex, and yet others showed activity in both hemispheres while others favored one hemisphere. This variability aligns with the theoretical perspective proposed by the right-left-right hemispheric dominance hypothesis, which posits a hemispheric contribution influenced by the trade-off between the mental attentional capacity of the individual and the mental demand of the task. Based on the theory of constructive operators, and the right-left-right hemispheric dominance model, the age-related trajectory in mental attentional capacity suggests that children at different ages should be able to solve different problems by favoring different hemispheres. Thus, this is an example where neuroscience and theory can work together to offer a novel perspective of developmental brain-behavioral mechanisms.

Because in science findings need to be replicated, I offer another example that shows lack of concordance in prefrontal areas; however, the topic now is mathematical cognition. Similar to the findings from the working memory meta-analysis, children solving problems with numbers did not show significant concordance in prefrontal regions, rather concordant activity was observed in cingulo-opercular regions, which I attribute to the maintenance of motivated behaviors (Arsalidou et al., 2013, 2018). This meta-analysis covering mathematical problem solving in children reveals that they predominantly activate the right parietal cortex when solving number tasks (i.e., symbolic and non-symbolic number judgments; Arsalidou et al., 2018). Comparatively, number tasks are processed by simpler figurative schemes. Whereas calculation tasks (i.e., arithmetic operations such as addition and multiplication) primarily engage the left parietal cortex as math operations involve more challenging and relational figurative schemes that require coordination within the child's mental attentional capacity. In accordance with the right-left-right hemispheric dominance model, simple number tasks activate the right hemisphere, whereas calculation tasks more extensively implicate the left hemisphere. Overall, these are compelling examples in my work that show how theoretical ideas can help explain neuroscience data and neuroscience research can inform theory, so we can drive knowledge on age-related modeling of brain activity.

NeuroPsyLab's Guiding Principles for Research on Developmental Science

Developmental science is a broad interdisciplinary field that encompasses all dimensions of human development, including biological, psychological, social, and cultural. Developmental neuroscience, a subfield of developmental science, utilizes neuroscience techniques to study biological underpinnings and mechanisms related to the nervous system. Neuroimaging is a set of neuroscience techniques used for studying brain correlates. It is important to recognize that neuroimaging methods are typically first established with young adults. However, methods and practices validated with young adults are not always suitable for research involving other age groups. For example, young adults are more likely to participate in longer MRI sessions (e.g., >1 h); however, MRI sessions for children or older adults should be shorter (e.g., <1 h). Further, most MRI studies involving young adults typically include participants aged between

20 and 30 years, a period in adulthood when behavioral performance is relatively stable. In contrast, children in MRI studies, usually aged between 7 and 17 years old, experience significant changes in brain and behavioral factors during this developmental period. Thus, MRI tasks validated for young adults are not always suitable for use with children because of cognitive performance differences (Arsalidou & Pascual-Leone, 2016). Technical challenges and practical advice for pediatric neuroimaging such as using mock scanners to familiarize participants with the environment, using pediatric MR head coils, and language choices for informing parents have been discussed (e.g., Jones et al., 2020; Leroux et al., 2013; Raschle et al., 2012). Here I focus on guidelines founded on ideas from constructivist-developmental theory for advancing developmental science in general and cognitive developmental neuroscience in particular.

I find great satisfaction in studying complex cognitive processes from an age-related perspective and have founded the NeuroPsyLab in an effort to advance knowledge in measurement and evaluation of higher order neurocognitive abilities across the lifespan. I have investigated behavioral and brain correlates of core executive processes and decision making such as mental attention (Arsalidou et al., 2010; 2013; Bachurina & Arsalidou, 2022; Bachurina et al. 2022; Milani et al., 2022), working memory (Yaple & Arsalidou, 2018; Yaple et al., 2019), reward processing (Yaple et al., 2020), inhibition (Arsalidou et al., 2013; Hung et al., 2018), and mathematical cognition (Arsalidou et al., 2018; Arsalidou & Taylor, 2011). Recognizing the dynamic nature of neurocognitive processes across development, I adopt and teach a multilevel approach in my investigations. This approach allows me to more comprehensively examine and model how these complex processes evolve with age. In pursuit of these scientific inquiries, I follow four guiding principles that remain at the forefront of my scientific endeavors.

Age Groupings

I use age both as a continuous and categorical variable depending on the hypothesis. Although considering age as a continuous variable has its merits, it is limited in the type of questions this method can address. When nonlinear or age-related effects are being evaluated, categorizing age simplifies data analysis and interpretation. For instance, in developmental neuroscience, this can be particularly meaningful when studying brain microstructural differences using diffusion tensor imaging (Buyanova & Arsalidou, 2021). Developmentally appropriate age grouping can minimize confounds and advance hypothesis development. Constructivist theories and the theory of constructive operators, in particular, posit that children's cognitive trajectories follow multiple measurable steps. Therefore, I am very careful in selecting age groups. When working with school-age children, for instance, I typically aim for grouping children, using Table 3. Notably, there are also stages of adulthood, albeit these trajectories vary by 10–15 years; you can read more about adulthood cognitive milestones (Pascual-Leone, 1983). As empirical research documents cognitive variations with age (e.g., Hartshorne & Germine, 2015), when specifying the age range for young adults I aim for 20–30-year-olds. In essence, because cognitive and brain development are dynamic processes, it is fundamental to have targeted and clear justification for age group selection.

Child-Friendly Assessments

Developmentally appropriate assessments can advance predictive power and minimize motivational issues in investigations with different age groups. Ideally, measures for assessing individuals of variable capabilities should be tailored from a developmental standpoint, taking into consideration unique characteristics of different age groups. Frequently, tasks utilized in cognitive developmental neuroscience are adaptations of tasks designed for adults (see discussion in Arsalidou & Pascual-Leone, 2016). This is rooted in part in the fact that neural correlates of most constructs are typically explored in adults first. However, it is imperative to recognize, in line with constructivist-developmental theorizing, that children are not merely miniature versions of adults. For instance, in fMRI research, child-friendly paradigms should favor a block-design to improve power, shorter acquisition runs (i.e., two 5-min runs rather than a 10-min one) with more breaks (i.e., scanning sequences) to ensure that children are still engaged and shorter overall scanning time to ensure that children are not tired. Consequently, tasks employed to investigate cognitive and brain processes in child samples should be inherently suitable for the developmental trajectories of the individuals involved. Considering both the quantity and quality of operations and schemes needed for problem solving enables the estimation of the mental demand of a task. This estimation can then be aligned with age-related expectations (see meta-subjective task analysis for method).

Culture-Appropriate Assessments

Culture relies on content and experience and is critical when choosing assessments. Because performance relies at least on motivational (e.g., affective

Table 4. Distinguishing characteristics of parametric mental attentional capacity measures

1	Controlled assessment of variable performance: parametric measures of mental attentional capacity introduce multiple difficulty levels with constant executive demand (i.e., rules) and a controlled number of figurative schemes (e.g., features or objects) to be processed. This design enables younger children to succeed at easier levels, whereas older children can progressively attain items with higher levels of difficulty
2	Unified scaling and metric: employing the same scaling (e.g., difficulty levels, trial numbers, trial length) and metric (comparable scores) across domains ensures methodological consistency (Milani et al., 2022). This is particularly crucial when evaluating cognitive abilities in cross-cultural and atypical samples, thus preventing confounding factors arising from disparate task characteristics
3	Flexibility in constructing difficulty levels: parametric task difficulty, coupled with constant executive requirements, allows for the construction of graded difficulty levels through simple manipulations. For example, the color matching task's executive requirement remains constant, with difficulty manipulated by altering the number of colors to be compared
4	Simultaneous behavioral and neuroimaging data collection: for samples with restricted capabilities, the concurrent collection of behavioral and functional neuroimaging data proves efficient. Tasks like the color, letter, or number matching task (Milani et al., 2021) offer interpretable indices from a single assessment, thereby saving valuable time for children and their families
5	Statistical analysis options: multiple difficulty levels in a task facilitate various statistical analysis options for brain responses as a function of age. This includes examining brain activity within an age group across difficulty levels, assessing brain responses, based on individual performance, and analyzing brain responses according to theoretical expectations for each age group
6	Contrasts of difficulty levels across domains: the methodology permits direct contrasts of difficulty levels across different cognitive domains. This enables the examination of whether brain responses to a specific difficulty level in one domain significantly differ from the responses in another domain
7	Within-child performance comparison: quantifying mental attentional capacity allows for comparisons within a child's performance history and against theoretical developmental expectations. This individualized approach, distinct from normative comparisons, provides a developmental baseline for intervention protocols

processes), core cognitive (e.g., mental attention), and available repertoire (e.g., schemes), one needs to be very clear on what they are measuring. Many assessments evaluate content knowledge (i.e., available repertoire), rather than core cognition (e.g., mental attention) that I consider the foundation of learning potential. Intelligence tests are an example of content-based tests, where children with homogeneous experiential opportunities can be evaluated on (Liashenko et al., 2017). The Program of International Student Assessment (PISA) also evaluates students on content learning (math, science, reading). Critically, staggering performance differences among youth show that resources and opportunities are not homogeneous across cultures, countries, and communities. Therefore, I spend a lot of my time exploring and explaining that tasks that assess learning potential (not based on past content knowledge) need to complement assessments of content learning (based on content knowledge). In essence, tasks of content learning evaluate what children have learned, whereas tasks of learning potential evaluate what children are capable of learning. Tasks of mental attentional capacity are suitable for culture-appropriate assessment of learning potential as performance on such tasks does not primarily rely on complex content and experience. Specifically, measures of mental attentional capacity use simple concepts that have minimal background requirements. For example, most school-aged children have experience with colors, letters, and numbers. During the training phase, it is confirmed that children can distinguish the colors, letters and numbers before the main test begins. As all the task rules are taught during training and the content is simple and familiar, these measures place minimal cultural requirements and thus are more appropriate for evaluating performance across cultures. For this reason, in my research I use parametric measures of mental attentional capacity. Parametric measures of mental attentional capacity are valuable tools for behavioral and neuroimaging assessments (Table 4: Arsalidou & Im-Bolter, 2017).

Meta-Subjective Task Analysis

When (1) designing tasks, (2) developing hypotheses, or (3) when trying to understand complex findings, I use meta-subjective task analysis. Performing meta-subjective task analysis offers at least three notable advantages. First, it is particularly valuable in the design of new tasks aimed at assessing various forms of performance. Second, it facilitates hypothesis development by enabling the qualification and quantification of schemes required for problem-solving, thus predicting whether children within a specific age group possess the content (pretraining to scheme quality and type) and capacity (i.e., pertaining to quantity of schemes) to tackle a task. Third, the classification of schemes and operators in steps can inform brain mechanisms in support of a priori hypothesis development or a posteriori data interpretation. For example, a sequential step approach used in Meta-subjective task analysis can model the cognitive and brain resources needed for a problem-solving strategy from the vantage of a child (i.e., considering various task and individual factors such as complexity and experience, Tables 1 and 2). Assessing the mental demand of a task has demonstrated its value in an investigation of artificial intelligence (machine learning) algorithms utilized for predicting performance (Bachurina et al., 2022). Specifically, the mental demand of the task ranked as one of the top most influential features in predicting individual trial performance using machine learning models. Overall, these advantages have implications in research, industry, education, and clinical practice. For instance, meta-subjective task analysis can be a valuable tool for assessing effectiveness of educational interventions. Through the assessment of the mental attentional demands of tasks and the requisite quality and quantity of schemes, educators and researchers can determine the suitability of these tasks for distinct age groups or individuals with differing cognitive capacities. This evaluation ensures that educational materials and interventions are precisely tailored to the mental attentional capacity of the target audience, thereby enhancing their learning and problem-solving experiences.

Conclusion

Through the lens of the theory of constructive operators (Pascual-Leone, 1970; Pascual-Leone & Johnson, 2021), the first neo-Piagetian theory, I conceptualize development in terms of operators, schemes, and a key principle (Fig. 1). These theoretical constructs are explained with relatable examples, and their brain representations are proposed (Table 1). The roles of the left and right hemispheres are discussed in terms of a trade-off between familiarity and novelty and a trade-off between demand of the task and the mental attentional capacity of the individual (Table 2; Fig. 2). Mental attention, a maturational limited resource (Table 3), applies across content domains (Fig. 3), and in part drives developmental change. This article also presents examples of how facilitating and misleading factors can influence task difficulty and affect performance. The theory section concludes with a systematic method for evaluating task demand called meta-subjective task analysis.

Importantly, this article elaborates on concrete examples from my research on mental attention and mathematical cognition to illustrate that developmental constructivist theory is crucial in developmental cognitive neuroscience and evidence from neuroscience can inform and advance developmental constructivist theory. Constructivist theory combined with my background in neuroscience has led me to design tasks that adhere both to developmental principles and neuroimaging considerations to advance assessments in developmental science (Table 4).

Developmental science is vast in terms of dimensions, including psychology, neuroscience, etc. It faces the challenge of explaining what changes with development. Therefore, I present four guiding principles inspired by constructivist cognitive theory that have informed my research: age groupings, child-friendly assessments, culture-appropriate assessments, and meta-subjective task analysis.

Many questions about human development remain open. Theories, methods, practices, and data are tools in the service of science and must withstand the test of time. Therefore, I advocate an "in" inclusive, international, and innovative approach to research in human development. Recognizing that insights from both neuroscience and theory can inform each other and create a dynamic interplay enhances our understanding of complex cognitive processes and helps in the construction of tools that can advance the way we develop assessments and make decisions. The reciprocal knowledge gained from data-driven and theory-guided exploration of brain regions allows for a more robust and nuanced understanding of brain-behavior dynamics that will lead us to improved science, education, clinical practice, and policymaking.

Statement of Ethics

Ethical approval is not required since this is a review article.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Funding Sources

This study was not supported by any sponsor or funder.

Author Contributions

Marie Arsalidou: conceptualization, writing – original draft, and writing – reviewing and editing.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

References

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. https://doi.org/10.1016/j.jecp.2009.09.006

Arsalidou, M. (2003). *Neural processes of visual problem solving and complexity*. York University. Master's Thesis.

Arsalidou, M. (2013). Working memory capacity: The need for process task-analysis. *Frontiers in Psychology*, *4*(257), 1–2. https://doi.org/10.3389/fpsyg.2013.00257

Arsalidou, M., & Im-Bolter, N. (2017). Why quantitative measures are critical for understanding typical and atypical cognitive development. *Brain Imaging and Behavior*, 1–11.

Arsalidou, M., & Pascual-Leone, J. (2016). Constructivist developmental theory is needed in developmental neuroscience. *npj Science of Learning*, *1*(1), 16016. https://doi.org/10.1038/npjscilearn.2016.16

Arsalidou, M., & Taylor, M. J. (2011). Is 2+2= 4? Meta-analyses of brain areas needed for numbers and calculations. *NeuroImage*, *54*(3), 2382–2393. https://doi.org/10.1016/j.neuroimage.2010.10.009

Arsalidou, M., Agostino, A., Maxwell, S., & Taylor, M. J. (2013). I can read these colors. Orthographic manipulations and the development of the color-word Stroop. *Frontiers in Psychology*, *3*, 37142. https://doi.org/10.3389/fpsyg.2012.00594

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. https://doi.org/10.1016/j.cogdev.2010.07.001

Arsalidou, M., Pascual-Leone, J., Johnson, J., & Kotova, T. (2019). The constructive operators of the working mind: a developmental account of mental-attentional capacity. *Russian Journal of Cognitive Science*, *6*, 44–55.

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. https://doi.org/10.1002/brb3.128

Arsalidou, M., Pawliw-Levac, M., Sadeghi, M., & Pascual-Leone, J. (2018). Brain areas associated with numbers and calculations in children: Meta-analyses of fMRI studies. *Developmental Cognitive Neuroscience*, *30*, 239–250. https://doi.org/10.1016/j.dcn.2017.08.002

Arsalidou, M., Vijayarajah, S., & Sharaev, M. (2020). Basal ganglia lateralization in different types of reward. *Brain Imaging and Behavior*, *14*(6), 2618–2646. https://doi.org/10.1007/s11682-019-00215-3

Bachurina, V., & Arsalidou, M. (2022). Multiple levels of mental attentional demand modulate peak saccade velocity and blink rate. *Heliyon*, *8*(1), e08826. https://doi.org/10.1016/j.heliyon.2022.e08826

Bachurina, V., Sushchinskaya, S., Sharaev, M., Burnaev, E., & Arsalidou, M. (2022). A machine learning investigation of factors that contribute to predicting cognitive performance: Difficulty level, reaction time and eye-movements. *Decision Support Systems*, *155*, 113713. https://doi.org/10.1016/j.dss.2021.113713

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. https://doi.org/10.1016/0160-2896(79)80005-7

Christoff, K., Keramatian, K., Gordon, A. M., Smith, R., & Mädler, B. (2009). Prefrontal organization of cognitive control according to levels of abstraction. *Brain Research*, *1286*, 94–105. https://doi.org/10.1016/j.brainres.2009.05.096

Cona, G., & Scarpazza, C. (2019). Where is the "where" in the brain? A meta-analysis of neuroimaging studies on spatial cognition. *Human Brain Mapping*, *40*(6), 1867–1886. https://doi.org/10.1002/hbm.24496

Cowan, N., & Morey, C. C. (2007). How can dual-task working memory retention limits be investigated?. *Psychological Science*, *18*(8), 686–688. https://doi.org/10.1111/j.1467-9280.2007.01960.x

Daneman, M., & Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*(4), 450–466. https://doi.org/10.1016/s0022-5371(80)90312-6

Diamond, M. C. (1993). An optimistic view of the aging brain. Generations. *Journal of the American Society on Aging*, *17*(1), 31–33.

Emch, M., Von Bastian, C. C., & Koch, K. (2019). Neural correlates of verbal working memory: An fMRI meta-analysis. *Frontiers in Human Neuroscience*, *13*, 180. https://doi.org/10.3389/fnhum.2019.00180

Enge, A., Friederici, A. D., & Skeide, M. A. (2020). A meta-analysis of fMRI studies of language comprehension in children. *NeuroImage*, *215*, 116858. https://doi.org/10.1016/j.neuroimage.2020.116858

Engle, R. W. (2001). What is working-memory capacity?. In H. L. RoedigerIII, & J. S. Nairne (Eds), *The nature of remembering: Essays in honor of Robert G. Crowder* (pp. 297–314). American Psychological Association.

Gazzaniga, M. S., Bogen, J. E., & Sperry, R. W. (1962). Some functional effects of sectioning the cerebral commissures in man. *Proceedings of the National Academy of Sciences*, *48*(10), 1765–1769. https://doi.org/10.1073/pnas.48.10.1765

Hartshorne, J. K., & Germine, L. T. (2015). When does cognitive functioning peak? The asynchronous rise and fall of different cognitive abilities across the life span. *Psychological Science*, *26*(4), 433–443. https://doi.org/10.1177/0956797614567339

Hebb, D. O. (1949) *The organization of behavior; a neuropsychological theory*. Wiley.

Hung, Y., Gaillard, S. L., Yarmak, P., & Arsalidou, M. (2018). Dissociations of cognitive inhibition, response inhibition, and emotional interference: Voxelwise ALE meta-analyses of fMRI studies. *Human Brain Mapping*, *39*(10), 4065–4082. https://doi.org/10.1002/hbm.24232

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. https://doi.org/10.1111/j.1467-8624.2006.00976.x

Jamadar, S., Fielding, J., & Egan, G. (2013). Quantitative meta-analysis of fMRI and PET studies reveals consistent activation in fronto-striatal-parietal regions and cerebellum during antisaccades and prosaccades. *Frontiers in Psychology*, *4*, 749. https://doi.org/10.3389/fpsyg.2013.00749

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. https://doi.org/10.1046/j.1467-8624.2003.00626.x

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

Jones, J. Y., Selvaraj, B., & Ho, M. L. (2020). Pediatric functional neuroimaging: practical tips and pearls. *American Journal of Roentgenology*, *214*(5), 995–1007. https://doi.org/10.2214/AJR.19.22178

Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience*, *23*(1), 315–341. https://doi.org/10.1146/annurev.neuro.23.1.315

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. https://doi.org/10.1002/tea.3660200204

Leroux, G., Lubin, A., Houdé, O., & Lanoë, C. (2013). How to best train children and adolescents for fMRI? Meta-analysis of the training methods in developmental neuroimaging. *Neuroeducation*, *2*(1), 44–70. https://doi.org/10.24046/neuroed.20130201.44

Li, J., Zhang, R., Liu, S., Liang, Q., Zheng, S., He, X., & Huang, R. (2021). Human spatial navigation: neural representations of spatial scales and reference frames obtained from an ALE meta-analysis. *NeuroImage*, *238*, 118264. https://doi.org/10.1016/j.neuroimage.2021.118264

Li, Y., Kong, F., Ji, M., Luo, Y., Lan, J., & You, X. (2019). Shared and distinct neural bases of large-and small-scale spatial ability: a coordinate-based activation likelihood estimation meta-analysis. *Frontiers in Neuroscience*, *12*, 1021. https://doi.org/10.3389/fnins.2018.01021

Liashenko, A., Khalezov, E., & Arsalidou, M. (2017). Methods for Identifying Cognitively Gifted Children. *Psychology. Journal of Higher School of Economics*, *14*(2), 207–218.

McBride, T., Arnold, S.E., & Gur, R.C. (1999). A comparative volumetric analysis of the prefrontal cortex in human and baboon MRI. *Brain, Behavior and Evolution*, *54*(3), 159–166. https://doi.org/10.1159/000006620

McFarland, D.J., & Sibly, R.M. (1975). The behavioural final common path. *Philosophical Transactions of the Royal Society B*, *270*(907), 265–293. https://doi.org/10.1098/rstb.1975.0009

Milani, A., Pascual-Leone, J., & Arsalidou, M. (2022). Converging evidence for domain-general developmental trends of mental attentional capacity: validity and reliability of full and abbreviated measures. *Journal of Experimental Child Psychology*, *222*, 105462. https://doi.org/10.1016/j.jecp.2022.105462

Miller, R. (2011) *Vygotsky in perspective*. Cambridge University Press.

Miller, R., Pascual-Leone, J., & Andrew, D.J. (1992). Cognitive executive processes and mental capacity on the compound stimulus visual information task in a group of Zulu-speaking children. *South African Journal of Psychology*, *22*(1), 1–9. https://doi.org/10.1177/008124639202200101

Miller, R., Pascual-Leone, J., Campbell, C., & Juckes, T. (1989). Cross cultural similarities and differences on two neo-Piagetian cognitive tasks. *International Journal of Psychology*, *24*(1-5), 293–313. https://doi.org/10.1080/00207594.1989.10600049

Morra, S. (2001). On the information-processing demands of spatial reasoning. *Thinking & Reasoning*, *7*(4), 347–365. https://doi.org/10.1080/13546780143000116

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.

Morra, S., Gobbo, C., Marini, Z., & Sheese, R. (2012) *Cognitive development: neo-Piagetian perspectives*. Psychology Press.

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. https://doi.org/10.1348/2044-835X.002006

Pascual-Leone, J. (1970). A mathematical model for the transition rule in Piaget's developmental stages. *Acta Psychologica*, *63*, 301–345. https://doi.org/10.1016/0001-6918(70)90108-3

Pascual-Leone, J. (1980). Constructive problems for constructive theories: The current relevance of Piaget's work and a critique of information-processing simulation psychology. In R.H. Kuwe, & H. Spada (Eds), *Developmental models of thinking* (pp. 263–296). Academic Press.

Pascual-Leone, J. (1983). Growing into human maturity: toward a meta- subjective theory of adulthood stages. In: Baltes, P.B., Brim, O.G. (Eds.), *Life-span Development and Behavior*, vol. *5*. Academic Press, pp. 1 18–56.

Pascual-Leone, J. (1995). Learning and development as dialectical factors in cognitive growth. *Human Development*, *38*, 338–348.

Pascual-Leone, J. (1987). Organismic processes for neo-Piagetian theories: A dialectical causal account of cognitive development. *International Journal of Psychology*, *22*(5-6), 531–570. https://doi.org/10.1080/00207598708246795

Pascual-Leone, J. (1996). Vygotsky, Piaget, and the problems of Plato. *Swiss Journal of Psychology*, *55*, 84–92.

Pascual-Leone, J. (2000). Reflections on working memory: Are the two models complementary?. *Journal of Experimental Child Psychology*, *77*(2), 138–154. https://doi.org/10.1006/jecp.2000.2593

Pascual-Leone, J. (2014). Dialectics. In T. Teo (Ed), *Encyclopedia of critical psychology* (pp. 421–428). Springer.

Pascual-Leone, J. (2011). Piaget as a pioneer of dialectical constructivism: Seeking dynamic processes for human science. In E. Marti, & C. Rodriguez (Eds), *After Piaget*. Transaction Publishers.

Pascual-Leone, J., & Baillargeon, R. (1994). Developmental measure of mental attention. *International Journal of Behavioral Development*, *17*(1), 161–200. https://doi.org/10.1177/016502549401700110

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). Erlbaum.

Pascual-Leone, J., & Johnson, J. (1991). The psychological unit and its role in task analysis: A reinterpretation of object permanence. In M. Chandler, & M. Chapman (Eds), *Criteria for competence: Controversies in the conceptualization and assessment of children's abilities* (pp. 153–187). Erlbaum.

Pascual-Leone, J., & Johnson, J. (2005). A dialectical constructivist view of developmental intelligence. In O. Wilhelm, & R. Engle (Eds), *Handbook of understanding and measuring intelligence* (pp. 177–201). 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). Psychology Press.

Pascual-Leone, J., & Johnson, J. M. (2021). *The working mind: Meaning and mental attention in human development*. MIT Press.

Pascual-Leone, J. (1989). An organismic process model of Witkin's field dependence-independence. In T. Globerson, & T. Zelniker (Eds), *Cognitive Style and Cognitive Development* (pp. 31–70). Ablex.

Pennings, A. H., & Hessels, M. G. (1996). The measurement of mental attentional capacity: A neo-Piagetian developmental study. *Intelligence*, *23*(1), 59–78. https://doi.org/10.1016/s0160-2896(96)80006-7

Piaget, J. (1952). Jean Piaget. In E. G. Boring, H. Werner, H. S. Langfeld, & R. M. Yerkes (Eds), *A History of Psychology in Autobiography* (*4*, pp. 237–256). Clark University Press. https://doi.org/10.1037/11154-011

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*(961781), 1–9. https://doi.org/10.1155/2014/961781

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences*, *98*(2), 676–682. https://doi.org/10.1073/pnas.98.2.676

Raschle, N., Zuk, J., Ortiz-Mantilla, S., Sliva, D. D., Franceschi, A., Grant, P. E., Benasich, A. A., & Gaab, N. (2012). Pediatric neuroimaging in early childhood and infancy: challenges and practical guidelines. *Annals of the New York Academy of Sciences*, *1252*(1), 43–50. https://doi.org/10.1111/j.1749-6632.2012.06457.x

Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A.R., Schulz, J.B., Eickhoff, S. B.. 2012. Modelling neural correlates of working memory: a coordinate-based meta-analysis. *NeuroImage 60* (1), 830–846. https://doi.org/10.1016/j.neuroimage.2011.11.050

Sherrington, C. S. (1906). *The integrative action of the nervous system*. Yale University Press.

Sherrington, C. S. (1940). *Man on his nature*. Cambridge University Press.

Smith, L. (1994). The Binet-Piaget Connection: Have developmentalists missed the epistemological point? Archives de psychologie; Mayer, S. J. The early evolution of Jean Piaget's clinical method. *History of Psychology*, *8*(4), 362.

Spreng, R. N., Mar, R. A., & Kim, A. S. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: a quantitative meta-analysis. *Journal of Cognitive Neuroscience*, *21*(3), 489–510. https://doi.org/10.1162/jocn.2008.21029

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Turker, S., Kuhnke, P., Eickhoff, S. B., Caspers, S., & Hartwigsen, G. (2023). Cortical, subcortical, and cerebellar contributions to language processing: A meta-analytic review of 403 neuroimaging experiments. *Psychological Bulletin*, *149*(11-12), 699–723. https://doi.org/10.1037/bul0000403

Witkin, H. A. (1949). The nature and importance of individual differences in perception. *Journal of Personality*, *18*(2), 145–170. https://doi.org/10.1111/j.1467-6494.1949.tb01237.x

Witkin, H. A. (1950). Individual differences in ease of perception of embedded figures. *Journal of Personality*, *19*(1), 1–15. https://doi.org/10.1111/j.1467-6494.1950.tb01084.x

Witkin, H. A., & Goodenough, D. R. (1981). Cognitive styles: Essence and origins. Field dependence and field independence. In: *Psychological Issues, Monograph 51*. International Universities Press.

Yaple, Z. A., Stevens, W. D., & Arsalidou, M. (2019). Meta-analyses of the n-back working memory task: fMRI evidence of age-related changes in prefrontal cortex involvement across the adult lifespan. *NeuroImage*, *196*, 16–31. https://doi.org/10.1016/j.neuroimage.2019.03.074

Yaple, Z., & Arsalidou, M. (2018). N-back working memory task: Meta-analysis of normative fMRI studies with children. *Child Development*, *89*(6), 2010–2022. https://doi.org/10.1111/cdev.13080

Yaple, Z., Yu, R., & Arsalidou, M. (2020). Spatial migration of human reward processing with functional development: Evidence from quantitative meta-analyses. *Human Brain Mapping*, *41*(14), 3993–4009. https://doi.org/10.1002/hbm.25103