WHY AND HOW TO STUDY WORKING MEMORY DEVELOPMENT

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Why and how to study working memory development

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ABSTRACT

Working memory is the information held in mind, and it is used in all sorts of problem-solving and comprehension. There are many different purposes for studying working memory development in childhood. Here I discuss some of the purposes, and bring up considerations of which kinds of tasks should be best-suited to each purpose. The purposes include investigations of

1) the extent to which working memory is already operational in infancy,
2) working memory correlates of cognitive maturational level, and intelligence,
3) working memory as a clue to the basic principles of cognitive growth in childhood,
4) working memory deficits as diagnostic signs of learning disorders,
5) working memory indices of the presently optimal level or complexity of learning materials for a particular child,
6) possibilities for training working memory as a means to enhance cognitive development,
7) working memory and brain function.

For each of these purposes, I discuss the prospects for study as I see them, with a few examples of recent work along the way.

Keywords: working memory development; developmental methodology; recognition; recall; cognitive development.

WHY AND HOW TO STUDY WORKING MEMORY DEVELOPMENT

What is the point of selecting children of various stages of immaturity, coaxing each one to sit in a sound-attenuated booth when his or her

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appointed time arrives, and increasing the amount of information to be held in mind until a level of non-functionality is reached? It sounds like a slightly sadistic game.

Well, there are many potential points. This is how one typically tests *working memory*, the small amount of information that can be held in mind, which is needed for all sorts of complex cognitive tasks, such as reasoning and language processing. As I will suggest, there are many potential purposes to test working memory development, and somewhat different ways to do the testing to make it well-suited to the particular purpose. Before we examine how to test working memory, I had better explain a bit more about how the term has been used.

HISTORY OF THE TERM WORKING MEMORY

Working memory itself is a broad term that has been used in radically different ways, as I previously pointed out (Cowan, 2017). The term was first used, it appears, by computer scientists within a program that was capable of solving geometry proofs (Newell & Simon, 1956). Aside from all of the information programmed into the computer, the authors indicated that in order to prepare to complete one step of a proof, it was helpful to assemble the necessary information into a working memory. This use was comparable to the use of the term *short-term storage* in later, psychological work (e.g., Atkinson & Shiffrin, 1968), except that humans are limited to a small amount of information in working memory at a time.

Miller, Galanter, and Pribram (1960) used the term working memory, not to specify information from a list repeated back immediately (Miller, 1956), for which the term short-term storage would be apt, but to refer to any mechanism that individuals used to hold on to plans at any level, including superordinate plans such as getting a college degree, subordinate plans such as getting to class, and sub-subordinate plans such as getting dressed.

Baddeley and Hitch (1974) used the term working memory in a different way, to indicate that the notion of a single short-term store must be replaced by a multicomponent system to hold information while processing it, which they termed working memory. It was supposed to have separate phonological and visual information stores. The processing itself was at first considered part of the storage system, probably because the processing component, the central executive, was thought to include its own storage of plans and what not. That storage aspect was removed by Baddeley (1986) but it appears that the central executive was still grandfathered into the cover term working memory. Others (especially Daneman & Carpenter, 1980) seemed to begin to define working memory as anything measured by tests that engaged both storage and processing. There also was a movement to define working memory as the part of the process that involved attention and executive function, leaving the term short-term storage to cover the passive retention of materials (Engle, 2002).

It would be understandable if you felt bewildered by the wide range of uses of a single term. Yet, taken together, these uses of the term working memory aptly describes something that allows a conscious mind, and allows it to be used with reference to the immediate and far-reaching past. We have an ocean of ideas stored in long-term memory, but we cannot use it without dipping a net into the ocean to pull out the little bit that we want to use next, along with anything useful that comes sailing our way. It is safest to skim over controversies that accompany the various bespoke definitions and use a more general definition of working memory, as Cowan (2017) recommends, simply referring to any mechanisms that allow us to retain, temporarily, a small amount of information in an especially accessible state. The assumption that it is only a small amount of information is something that researchers generally agree upon in the case of humans, even though the strict limit does not apply to computers.

PURPOSES FOR TESTING WORKING MEMORY DEVELOPMENT

The present review of working memory purposes and methods in developmental research will be illustrated with a smattering of experiments, include the author's own research whenever possible, and should not be taken as a thorough review of each area but, rather, an invitation to explore further using other sources.

EXAMINATION OF THE EXTENT TO WHICH WORKING MEMORY IS OPERATIONAL IN EARLY LIFE

Philosophers such as Rousseau (1762/2009) have long been interested in knowing the nature of humans before they can be either trained for good thinking or corrupted into bad thinking. One way to examine that kind of philosophical question is to probe what capabilities are already present in infancy. Just about everything a human thinks and does, since birth, requires integrating across time, and often responding after the fact. There is evidence of working memory from the outset, and indications of its maturation in interesting ways in infancy. A few procedures to demonstrate this will now be described.

Spontaneous head-turning

Clifton, Morrongiello, Kulig, and Dowd (1981) played a rattling sound to newborn infants from the left or right side and found that infants almost always (40/42 times) turned their head toward the sound; to get this response, the infant had to be held supine by the experimenter, who wore headphones that masked the direction of sound directed to the infant. Interestingly, though, the mean latency of the head-turn was 7.58 seconds, and it seems likely that the head-turn wasn't in response to the most recent segment of the sound, but to the percept building up from the beginning and therefore in some sort of working memory by the time the response could be mustered.

The interest of the infant precipitating a head turn can be put to use in the visual modality as well. For example, Ross-Sheehy, Oakes, and Luck (2003) presented 1, 2, or 3 colored squares on the left of the screen and the same number on the right, flashing on a half second and off a quarter second. On one side of the screen, one color changed between each presentation and the next, making the display on that side more interesting if the infant could perceive enough of the display to notice the changes. At 6 months, infants differentially looked to the changing side with a set size of 1, but not 2 or 3. By 10 months, all set sizes were equally potent in evoking preferential looking.

Non-nutritive sucking

It turns out that fairly young infants will work to hear changes in an otherwise monotonous presentation, and this fact has been used to study a kind of working memory. Cowan, Suomi, and Morse (1982) tested 8-9-week-old infants for their memory for acoustic sensation using a computer-operated, non-nutritive sucking procedure. We tested the possibility that sensory memory for one brief sound would be interrupted by a second brief sound presented too soon afterward. Infants listened to rapid pairs of very brief vowels, beginning with "*ah-ah*" or "*eh-eh*." When the baby sucked on a pacifier, it caused the sounds temporarily to switch in some way. In a forward masking condition, the second sound in each pair changed (*ah-ah* to *ah-eh* or *eh-eh* to *eh-ah*). These changes were readily heard by the babies, and resulted in increased sucking motivated by the opportunity to hear the difference. In a backward masking condition, however, the first sound in each pair changed (*ah-ah* to *eh-ah* or *eh-eh* to *ah-eh*). Infants failed to respond to this change, with no difference from a control condition in which nothing changed. Presumably, infants' sensory working memory for the first sound in each pair was cut short or masked by the second sound in the pair, before the information from the first sound could be well-encoded into working memory. Another experiment showed very little responding with only 250 milliseconds between sounds in a pair in backward masking, but considerable responding with 400 milliseconds, presumably long enough for each sound to be encoded into working memory. Adults, in contrast, are able to recognize brief sounds maximally well when they have about 250 milliseconds to work with, though it is difficult to compare results across this huge age gap and inevitable procedural difference.

Conditioned head-turning

Older infants may be tough customers when it comes to repeated changes, but they respond to something more interesting. One method is to reinforce a head turn toward a sound when it changes in the critical way with illumination and activation of a box containing a motorized toy. Goodsitt, Morse, Ver Hoeve, and Cowan (1984) used this method to determine whether 6-month-old infants' ability to detect a changing sound (for example, from "*bah*" to "*doo*" was impaired when that change was accompanied by multiple syllables (as in *tee-bah-koh*) as opposed to a redundant syllable (as in *tee-bah-tee*). This was the case, even though the serial positions of the syllables kept changing in the presentation. This study, along with that of Ross-Sheehy et al. (2003) using spontaneous head-turning, illustrates an effect of increasing the memory load in infants.

Retrieval of hidden objects

Piaget (1936, 1963) described how infants develop the ability to retrieve an object that has been hidden, as infancy progresses. Presumably what developed was the ability to keep the object in mind while it is hidden from view and an action must be planned to get the object back, i.e., object permanence. Baillargeon and DeVos (1991) showed that this ability occurs much earlier than Piaget thought, using a measure of gaze rather than reaching with the hand.

Nevertheless, Feigenson and colleagues have found interesting results with a version of reaching in which there are multiple objects to be retrieved. A particularly intriguing example is the study by Zosh and Feigenson (2012). They hid 1, 2, or 3 toys in a box and sometimes, unknown to the infants, changed the toys within the box. Infants of 18 months were not satisfied with the substitutes when 1 or 2 toys had been hidden, and kept searching, presumably for the original toys. In contrast, when 3 toys were hidden, infants retrieved the 3 toys and then stopped, or at least searched no longer than in a control situation in which the toys were not switched. In sum, with a large enough memory load, it appeared that details of the toy identities may have been lost from working memory.

WORKING MEMORY CORRELATES OF COGNITIVE MATURATIONAL LEVEL AND INTELLIGENCE

Maturational increases in performance

Since the beginning of psychometric testing, psychologists have been looking for tasks that assess what has been termed fluid intelligence, the ability to solve a new problem or task without having been trained on it. Since that effort began, a popular task has been digit span, in which lists of digits of various lengths are spoken in a monotone, steady voice, and the child or adult is to repeat the list verbatim. This task is used because performance increases steadily as a function of age in childhood. In fact, viewed in terms of standardized scores, performance on many different types of immediate recall tasks increases with age in childhood (Gathercole, Pickering, Ambridge, & Wearing, 2004). Therefore, one can measure a child's ability on one or more of these tasks and assign a maturational age based on the score, which may be above or below the average for the child's chronological age. Together with other intelligence test scores, this kind of result has been used to help determine the optimal educational level for a particular child.

Possible attention- and rehearsal-based measures

Cowan et al. (2005) proposed that the ability to predict performance on a wider range of cognitive tasks depended on a distinction between attention-dependent processes and verbal-rehearsal-dependent processes. The general idea is that covertly reciting series of words to oneself helps keep them active in working memory (Baddeley, Thomson, & Buchanan, 1975) while requiring relatively little attention. When rehearsal is not possible, attention is presumably needed to retain items (Cowan, 1988, 1999, 2001, 2019). For children studied by Cowan et al. who were considered too young to engage in effective rehearsal, digit span correlated well with other cognitive tasks, but that was not the case for sixth-grade children and adults. Presumably, attention-dependent processes were needed for digit span when effective rehearsal was not possible, and related attention-dependent processes were needed for various other cognitive aptitude tests. In support of this interpretation, Cowan et al. also used running digit span, in which rehearsal cannot be carried out because the presentation is fast with an unpredictable endpoint. The running digit span score correlated well with other cognitive tasks at all ages in the study. Running digit span has been found to correlate not only with standard digit span and other phonologically-based tasks, but just as strongly with visual working memory tasks (Gray et al., 2017), which also are presumed to require more attention than most phonological tasks do (Morey & Bieler, 2013).

Consistent with this suggestion of the importance of attention in development of memory even for verbal materials, Elliott (2002) examined effects of irrelevant speech on memory for printed digits, with each participant tested at span, and found that performance was disrupted more in children in the early elementary school years than in older children or adults.

Working memory and assessment of intelligence

In these measures of maturational level there is often a tacit assumption that children who perform relatively well at a particular age are not only maturing faster than other children, but also will reach a higher endpoint in adulthood. This assumption seems to be well-justified except in cases in which a child or adult may face difficult circumstances that preoccupy his or her attention when taking the test at one age, if this circumstance changes later in life. It probably can be assumed that the better one's fluid intelligence is, the more opportunity one finds to increase knowledge, or crystallized intelligence. Therefore, difficult circumstances that exist for a period of time may not permanently depress fluid intelligence, but they may leave a residue of deprived learning that depresses the crystallized intelligence score, and both crystallized and fluid intelligence contribute to the usual intelligence quotient (IQ) that is calculated in intelligence tests.

IQ remains relatively stable across ages in middle-class communities but drops across childhood in disadvantaged communities (Breslau et al., 2001). As another example of conditions that can fluctuate over an individual's lifetime, Sackeim et al. (1992) found that depressed patients score more poorly on IQ tests, but that the scores are improved after electroconvulsive therapy. In theory, environmental deprivation (as in poverty) should affect crystallized intelligence, whereas preoccupation (as in depression) should affect fluid intelligence, but in practice the tests may not be pure enough to capture that distinction. The same uncertainty may be true of working memory tests, as one kind of knowledge involves familiarity with the kinds of tests that are constructed and materials that are used to try to measure fluid intelligence.

WORKING MEMORY AS A CLUE TO BASIC PRINCIPLES OF COGNITIVE GROWTH

Everyone knows that children become better able to carry out more complex tasks as they develop with age. It is a tough problem, though, to find out why this age-related development happens because so many aspects of development co-occur. Fundamentally, the difficulty is that brain structures grow and mature at the same time that learning and experience increase, making it a complex problem to isolate the effects of any single cause of developmental change.

There have been some very creative attempts to isolate factors in working memory development. As detailed by Cowan (2016), where Jean Piaget delineated some developmental increases in cognitive abilities throughout childhood, neo-Piagetians proposed that these cognitive changes indirectly resulted from improvements in the foundations of cognitive processing, including processing speed (e.g., Case, Kurland, & Goldberg, 1982), processing resources including energy and working memory capacity (e.g., Pascual-Leone, 1970), and the ability to bind items together to form more complex dependencies (e.g., Andrews, Halford, Murphy, & Knox, 2009; Halford, Phillips, & Wilson, 2001). These processes will be explored in turn.

Measures of speed

Case et al. (1982, Experiments 1 & 2) examined memory for lists of words and also the speed of repeating these materials when presented one at a time. It was found that children 3-6 years of age had word spans that were linearly related to the speed of repetition. To change this correlation into an inference of causation, in Experiment 2, adults were taught nonsense words and then received span and speed tests using those words. With those materials, both the speed and the span of adults were similar to 6-year-old children, which was taken as an indication that controlling for operational efficiency equates span performance. Similarly, Hulme and Tordoff (1989) examined memory span as a function of rehearsal speed in children 4-10 years of age, estimating speed by how quickly pairs or triads of words could be repeated 10 times. Plotting age group means, a near-linear relation was obtained between speech rate and memory span.

Cowan et al. (1998) distinguished between two speeds in a developmental study involving children from elementary school: a speed of verbal rehearsal, similar to Hulme and Tordoff (1989), and the speed of retrieving items from working memory during verbal recall in the span task, estimated by the rate of speech in recall of 3- and 4-digit lists. The rate of recall had previously been found to increase linearly with list length, suggesting that participants have to consider all list items before deciding on the one to be pronounced next, a kind of memory search. The rehearsal and retrieval speeds were found to be uncorrelated with one another and, together, they accounted for most of the effect of age on memory span. This study makes the point that speed is not a primary factor, but rather a consequence of the efficiency of certain processes involved in recall.

A speed-related investigation of development was also carried out by Gaillard, Barrouillet, Jarrold, and Camos (2011). Their approach was based on the finding of cognitive load effects, in which it has been found, in adults, that the time between items to be remembered that is occupied by a distracting task rather than free for the participant to engage in mnemonic activity (presumably, refreshing the items in memory using attention), i.e., the cognitive load, is negatively related to span (Barrouillet, Portrat, & Camos, 2011). Controlling various mnemonic processing opportunities to adjust for age differences in speed, including the speed of refreshing, they were able to equate performance in Grades 3 and 6. Camos and Barrouillet (2011) showed that cognitive load was only a factor in children old enough to use refreshing. In 6-year-olds, what mattered was the time since the presentation of an item, not the cognitive load during that time; the key variable changed from retention time per se to cognitive load in 7-year-olds, suggesting a rapid period of transition at roughly the point at which Piaget had suggested a developmental transformation from a preoperational stage to a concrete operational stage.

One limitation with the speed-based account of development is that it is unclear whether speed is primary or is an index of some other, more fundamental process (cf. Cowan et al., 1998). For example, children with a larger working memory capacity in terms of items could reproduce list items faster because they are able to consider more items at a time (Portrat & Lemaire, 2015; Lemaire, Pageot, Plancher, & Portrat, 2018), similar to how a computer with more memory is sometimes found to be faster on a particular task. Similarly, another approach popular among neo-Piagetians focuses on memory capacity or resources.

Measures of capacity

Early measures of capacity from a neo-Piagetian view seem designed in a manner that would prevent simple rehearsal and require attention to multiple features at once. Pascual-Leone and Smith (1969) used a very theoretically-driven task to examine children's ability to notice and keep in mind the multiple characteristics of objects. For example, a napkin and a Kleenex were considered the same in material and size but were different in color and use. The task, after some training, was for the child to select one of the items by mentioning a single word that would identify it (e.g., "blue"). Pairs of objects varied in how many matched or mismatched features they had. Pronounced differences in performance between 5 and 9 years of age occurred. Pascual-Leone (1970) introduced a *compound-stimuli visual information task* in which children were first taught stimulus-response connections (e.g., raise your hand if you see a square; clap your hands if you see something red) and then were presented with stimuli requiring multiple responses. The results were analyzed with a mathematical model suggesting that performance increased with working memory capacity or "M-space", which increased by 1 unit every Piagetian substage. Case (1972) obtained similar results in a task in which a series of numbers was presented (e.g., 12, 15, 22) and then, with the numbers concealed, another number (e.g., 19) was to be placed where it belonged in the series.

A persisting problem in this field is that what is taken as a capacity difference could stem from other processes. I have been engaged in a series of experiments on children from the early elementary school years to adulthood to disentangle capacity from these other processes.

Cowan, Morey, AuBuchon, Zwilling, and Gilchrist (2010) showed that working memory development cannot be attributed entirely to an inability of older children and adults to prioritize items so as to keep the most relevant ones and filter out less-relevant ones. On each trial of the most critical type, children received an array containing two colored triangles and two colored circles, followed by a single probe item (a colored triangle or colored circle) to be placed in the correct location within the array or judged absent from the array. In different trial blocks using these stimuli, the mixture of test trial types varied (in the different trial blocks: memory of an item of one of the shapes consistently tested, e.g., always memory of a triangle; an item of one shape tested on 80% of the trials and the other on the remaining 20% of the trials; or each shape tested on 50% of the trials). Consequently, the relative relevance of each shape differed by trial block. Performance on a shape increased as a function of the frequency of testing of that shape in the trial block, in the same way across age groups, indicating an ability to prioritize the more-often-tested shape that did not change with development. However, this function was at an overall lower level in 7-year-olds compared to older children and adults, indicating that an age difference in capacity remained. Cowan, AuBuchon, Gilchrist, Ricker, and Saults (2011) found the same thing when items were presented on a much slower, 1-at-a-time schedule, ruling out encoding speed as the critical factor, and the pattern was not changed when participants were required to say “wait” after every item, inhibiting verbal rehearsal.

Two other studies rule out a role of knowledge as the sole reason for the developmental increase in observed capacity. Cowan, Ricker, Clark, Hinrichs, and Glass (2015) presented on each trial an array of 5 English letters or of 3 unfamiliar characters. Although everyone did better on letters than on unfamiliar characters (except for a few young children who were excluded for not knowing their letters), when results were presented in the form of standardized scores for each type of material, the developmental change from 7 years to adulthood was almost identical for unfamiliar characters and English letters, and consistent with the developmental trend observed on many other types of working memory tasks (Gathercole et al., 2004). In another approach to this same issue of the role of knowledge, Gilchrist, Cowan, and Naveh-Benjamin (2009) examined immediate memory for lists of unrelated, simple sentences to be repeated verbatim on a trial. This arrangement provided both an index of capacity (the number of sentences that were at least partly recalled) and an index of knowledge (given that a sentence was at least partly recalled, the proportion of words from that sentence that were recalled). Although the index of knowledge for these simple materials was about 0.8 in every age group, there was a large increase in capacity from first grade to fourth grade, and a small additional increase between fourth grade and adulthood.

Additional research has focused on whether the capacity that develops in childhood is a type of capacity that allows working memory to share attention between different materials, or whether it is a type of capacity that allows the detailed storage of items in any one set in a dedicated manner, i.e., in a way that insulates those items from interference by another set. Cowan, Li, Glass, and Saults (2018) examined this issue by presenting, on each trial, a visual set (an array of colored squares) and an acoustic set (a list of spoken digits in one experiment and a list of tones in another experiment), in either order. In some trial blocks the participant knew which set to remember, whereas in other trial blocks, both sets were to be remembered. It was found that the decrement caused by having to remember two sets was rather stable over age groups from the early elementary school years through adulthood. However, with age, there was a pronounced increase in the number of items that could be saved in a dedicated manner for both vision and hearing, the part of recall that was stable no matter whether one or two sets had to be recalled. Cowan et al. suggested that, with age, children learn to detect and memorize patterns so that the memory becomes mostly independent of the focus of attention and the two sets do not have to trade off with one another very much to be remembered.

Recent research in adults has employed a popular method (Zhang & Luck, 2008) in which a stimulus from an array must be reproduced (e.g., reproduction of color or angle using a response wheel), which, according to the model applied, allows separation of the number and precision of representations. Clark et al. (2018) applied this technique to development after adapting it to memory of tones in a sequence, and learned that both the number and the precision of representations improves with development in the elementary school years. It is remarkable that capacity develops in all these studies, given that the adult value is little higher than 3 items.

The number of items that can be retained potentially may be fixed at about 3 or 4 across development (when mnemonic strategies cannot be used). However, some of these object representations may not include the critical features needed to respond in the task correctly. In a 2018 dissertation in the Cowan laboratory, Christopher L. Blume found that the younger children in the elementary school years, queried in the middle of a trial, thought that they had in mind about 3 items in working memory for visual arrays, when the actual results of the memory tests suggested that sufficiently complete representations were not, in fact, present for that many items at once in those younger children.

A notion of objects in mind without all of the necessary details of each item, i.e., incomplete object files, comports with other recent research in the adult literature (Cowan, Blume, & Saults, 2013; Hardman & Cowan, 2015; Oberauer & Eichenberger, 2013) and seems consistent with the finding that infants, too, may hold about 3 objects in the abstract but without all of the necessary detail to detect dramatic changes in the objects (Zosh & Feigenson, 2012). Moreover, knowing that one needs to do some mnemonic process to retain the necessary details of the items in working memory could be part of what develops, consistent with the theory of Spanoudis, Demetriou, Kazi, Giorgala, and Zenonos (2015).

Measures of binding complexity

Halford and colleagues (e.g., Andrews, Halford, Murphy, & Knox, 2009; Halford, Cowan, & Andrews, 2007; Halford, Phillips, & Wilson, 2001) have proposed that what is important for cognitive development is not the number of items that can be held in working memory per se, but the number of concepts that can be bound together into a complex. The more items can be bound together, the more complex are the concepts that can be comprehended. For example, in order to distinguish between a set of animals that include a zebra, a horse, a tiger, a lion, and a house cat, one must concurrently consider whether the animal is large (not the house cat), striped (not the horse or lion), and cat-like (not the zebra or horse). Yet, one theoretical possibility is that, as Cowan (1988, 2019) has proposed, items present in the focus of attention at the same time may be inter-related, so that capacity for binding is dictated by the individual's capacity of attention more generally. This seems like a fertile ground for research.

WORKING MEMORY DEFICITS AS DIAGNOSTIC SIGNS OF LEARNING DISORDERS

Because working memory requires such an ensemble of skills, it is not surprising that learning disorders are often accompanied by working memory deficits, which can contribute to the difficulty of learning. For example, several studies suggest that the memory for serial order is especially affected in children with language impairment (Gillam, Cowan, & Day, 1995) or dyslexia (Cowan et al., 2017; Majerus & Cowan, 2016). Children with language impairment may have difficulty using verbal encoding and rehearsal, and therefore are paradoxically at their worst when a memory task allows them to receive verbal lists in a visual form and respond manually, without making the useful recoding to a phonological form as most children would do, in the age range of the children tested, 8-12 years (Gillam, Cowan, & Marler, 1998). Useful applications of this kind of result include trying to use working memory to diagnose problems and trying to ease the use of working memory to improve learning in these children.

According to a baseline, not-very-interesting model of learning disabilities, children with these disabilities respond like younger, normal children. In one counter-example showing that working memory evidence can lend more insight, Jarrold, Cowan, Hewes, and Riby (2004) found contrasting types of deficits in two disorders. A slow speech rate explained working memory deficits in Williams syndrome, but not in Downs syndrome. In sum, working memory can contribute to an understanding of learning disorders in multiple ways.

WORKING MEMORY INDICES OF THE PRESENTLY OPTIMAL LEVEL OR COMPLEXITY OF LEARNING MATERIALS FOR A PARTICULAR CHILD

In contemplating the use of working memory scores to assist education, elsewhere (Cowan, 2014) I suggested that the level of material that a child is suited to learn could be assessed in part by examining working memory. This use would be similar to the original intent of constructing aptitude tests for children (e.g., Binet & Simon, 1916/1980). It is also similar to the thrust of arguments about learning the complexity that a child can handle by testing memory for the binding between features (e.g., Halford et al., 2001; Pascual-Leone, 1970).

One could make the case that to know how well a particular child can learn a particular type of material, the most straightforward way to examine it is simply to try to teach that type of material and find out how well it is learned. However, some misunderstandings between teachers and students can occur if working memory capabilities are not realized. For example, Gathercole, Lamont, and Alloway (2006) found that some children were perceived as disobedient when, in fact, they were having trouble remembering teachers' instructions (see also Jaroslawska, Gathercole, Logie, & Holmes, 2016).

WORKING MEMORY AS A MEANS TO ENHANCE COGNITIVE DEVELOPMENT

One hope of many parents has been that working memory training can succeed in enhancing a child's "brain power" by increasing the strength and flexibility of executive function and retention. It has been found that working memory training, or training of attention-related tasks, can succeed at improving performance on a narrow range of tasks that rely on similar processes. However, there is not a finding that such training generally increases brain power or general improvement across a wide range of tasks (Diamond & Lee, 2011; Melby-Lervåg & Hulme, 2013).

Although this kind of pessimistic finding may have caused many people to lose interest in working memory, I hope it is clear that working memory is important in order to understand the mechanisms of cognition and potentially to adjust teaching and training materials to match the capabilities of each child, making teaching and learning more efficient and enjoyable. It also still remains possible that working memory training will prove to be important for children who have certain learning disabilities or states of deprivation and, as a result, may not experience the range of stimulation that a typically developing child experiences (e.g., Holmes et al., 2010; Klingberg et al., 2005).

WORKING MEMORY AND BRAIN FUNCTION

It is clear that brain development has a long course and that some of the last structures to mature include the frontal-parietal structures (for a review see Casey, Tottenham, Liston, & Durston, 2005), which are central to attention, executive function, and working memory storage. Cowan (2019) reviewed evidence from adult studies that working memory operates with parietal areas serving as a focus of attention that is controlled by frontal areas and is functionally connected to posterior regions that differ depending on what kinds of information are being represented; in particular, the intraparietal sulcus may index up to several items held in the focus of attention concurrently. There is evidence that structural maturation of the brain and its activity can predict working memory capacity during development (Ullman, Almeida, & Klingberg, 2014).

Exciting findings in brain research on working memory are happening so quickly that it hardly seems possible to hold up progress to carry out developmental research on these processes. Yet, soon, there will be an enhanced arsenal ready for a new era of developmental research. Although magnetic resonance imaging research may be plagued by the difficulty of comparing brain responses that depend on hemodynamic properties that could change with age (Casey et al., 1995), this concern may be less when the measures are richer, including for example multivoxel pattern analysis that can identify the types of representations currently active (e.g., Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012).

The sophistication of brain activity measurement is progressing to the point that it may be possible to focus on qualitative, and not only quantitative, changes with development in childhood. For example, in recent adult work, Rademaker, Chunharas, and Serences (2019) found that seen items and remembered items show a different pattern of activation, with seen items represented more in occipital cortex and remembered items represented more in parietal cortex. Using this kind of procedure, it would be possible for a developmental study to examine when in development one first finds contributions of top-down influences on retaining remembered items in the absence of sensory stimulation, and/or in the presence of distraction.

There also are improved opportunities to use measures of physiology outside of the brain that yield evidence about brain function. For example, Morey, Mareva, Lelonkiewicz, and Chevalier (2018) used eye movements to examine the extent to which children looked at items that they were supposed to remember, perhaps a visual sign of refreshing the items. They concluded that 7-year-old children do carry out strategies to remember items, but those strategies are reactive and cue-driven as opposed to the more covert and proactive methods that older children use.

CONCLUDING OBSERVATIONS

I have tried to present a panorama of research findings that show what a truly immense and rich endeavor it has been so far to study the childhood development of working memory. Going forward, I would recommend that investigators in this area should keep in mind the broad scope of research on working memory development and try to link their findings theoretically to that broad scope, even while carefully honing the narrower, specialized tools that are needed to make progress in a particular area (that is, a particular corner of the panorama). Scientific terminology and methods change over time and there is the danger that, after a few major shifts in the zeitgeist, all of our work could be forgotten by most researchers. It can be argued similarly that we tend to forget the research from the rich era of verbal learning that mostly preceded the cognitive revolution (e.g., Kausler, 1974). It is important to incorporate older research (e.g., see Cowan & Rachev, 2018) in order to avoid reinventing the wheel and to keep an historical perspective regarding what one has accomplished. A recent historical summary of working memory phenomena, the existence of which the field seems to agree upon (Oberauer et al., 2018), could help focus developmental work. If we explore and integrate in equal parts, I am confident that, 10 years from now, we will know much more about how children remember and think, and may even be in a position to make strong recommendations for schools and educational programs.

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