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Working Memory Development: A 50-Year Assessment of Research and Underlying Theories

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Abstract

The author has thought about working memory, not always by that name, since 1969 and has conducted research on its infant and child development since the same year that the seminal work of Baddeley and Hitch (1974) was published. The present article assesses how the field of working memory development has been influenced since those years by major theoretical perspectives: empiricism (along with behaviorism), nativism (along with modularity), cognitivism (along with constructivism), and dynamic systems theory. The field has not fully discussed the point that these theoretical perspectives have helped to shape different kinds of proposed working memory systems, which in turn have deeply influenced what is researched and how it is researched. Here I discuss that mapping of theoretical viewpoints onto assumptions about working memory and trace the influence of this mapping on the field of working memory development. I illustrate where these influences have led in my own developmental research program over the years.

Keywords

working memory development; empiricism; nativism; cognitivism; constructivism; neo-Piagetian theory; memory decay; working memory capacity

What is now termed working memory has interested me since I read sundry things: a technical summary of research on dreams in 1969, just after high school; Hebb (1949) and a little of William James' work, in college; and other cognitive and developmental research. By working memory, I mean the small amount of information held in mind and used in cognitive tasks. Definitions of working memory vary; nine of them in the research literature were noted by Cowan (2017a). As in some of those definitions, I will sometimes refer to short-term retention to mean the same as working memory. Here I share observations of what may have shaped research on working memory development and its role in cognition for the past half century: in particular, three overarching views: *empiricism*, related to *behaviorism*; *nativism*, related to *modularity*; and *cognitivism*, related to *constructionism*. I

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contrast the three views and related concepts to discern their distinctive features (cf. Gibson, 1969) and implications for research, and also discuss the role of *dynamic systems theory*.

The term working memory can be seen as a product of the emerging cognitive revolution in the 1950s, starting with the use of this term to refer to temporarily accessible sets of critical information needed to allow computers to solve geometric proofs (Newell & Simon, 1956). The term was soon afterward used in a similar manner for the information needed for human planning and problem-solving (Miller et al., 1960) before it was widely used to imply a multicomponent system for short-term retention during the processing of the information stored (after Baddeley & Hitch, 1974).

There have been debates about whether the stark distinction between empiricism and nativism is defunct (Spencer et al., 2009) or inevitably important for research (Spelke & Kinzler, 2009). For the area of working memory development, it seems useful to consider how such basic influences have shaped research and how they can be integrated into an adequate modern view, along with cognitivist, constructivist, and dynamic systems perspectives that heavily rely on both kinds of influences.

Although most of the research on working memory has used abstract stimuli to reduce the effects of knowledge and highlight basic processes, the field of working memory development can hardly be considered to be removed from the rest of cognitive development. There are strong correlations between working memory capacity and cognitive abilities in children, including those with and those without learning challenges (e.g., Cowan et al., 2017; Geary et al., 2004; Gray et al., 2017; Slattery et al., 2021; for reviews see Cowan, 2010, 2014). We need to know more to understand why these correlations exist. There have also been some developmental studies in which memory for everyday objects was used (e.g., Forsberg et al., in press) and studies of the development of memory for spoken sentences (e.g., Gilchrist et al., 2009). These show age trends that are generally comparable with the studies using more abstract materials, though knowledge clearly also contributes to performance. Several studies have examined working memory for instructions given in schools, highlighting the importance of working memory in predicting children’s scholastic success (Holmes et al., 2014; Jaroslawska et al., 2016). In children, the ability to remember what needs to be done at the correct time, or prospective memory, also depends on working memory availability (Cheie et al., 2017). At least in the adult literature, as well, arrays of information can be compressed and simplified, taking up less space, to the extent that individuals can use knowledge and formulate rules to find patterns in the stimuli (e.g., Brady & Alvarez, 2015; Chekaf et al., 2016; Hollingworth, 2004; Jiang et al., 2000) and more developmental work of that sort is needed to understand the practical limits of working memory in everyday activities. In sum, in many ways improving our theoretical understanding of working memory development has considerable importance for practical issues of education and child neuropsychology.

Below, I describe how multiple theoretical views can influence research in one area, working memory development, and then document the main influences that appear to have have occurred, related to each view. My own research program is used to illustrate the evolution of the field over the years, and owes the most to the cognitivist view.

An Overview: Multiple Influences on Research on Working Memory Development

There are several reasons why these theoretical stances to be examined in detail can enlighten our understanding of working memory development. Throughout the long history of working memory research, there have been strong influences of different schools of thought on understanding memory over the short term, which we now call working memory. These influences include the idea of the empiricists that there is no special working memory structure, only general rules of memory; the idea of nativists that there are automatically-operating, inherited neural structures or modules that produce a simple taxonomy of verbal versus non-verbal stimuli; and the idea of cognitivists that working memory integrates some temporary information with long-term knowledge and does so strategically, in ways that depend on what the participant can manage using attention. One can find myriad examples of adult and developmental working memory studies over the years that appear to be influenced by these theoretical starting points. Understanding more about the relevant intellectual traditions should make us better able to interpret the findings and point to a good future path of research on working memory development.

Table 1 summarizes the tenets and potential implications of seven views under consideration, to be explained in turn later. Figure 1 is a snapshot illustrating what issues may be at stake, considering three major views for the sake of simplicity. From each theoretical view shown in the figure (left column), there is an expected set of mechanisms of most interest in describing how working memory operates (second column). For each view, there is also a kind of evidence that can be seen as somewhat problematic (third column). Each view leads to a different conception of how working memory is likely to improve during childhood (fourth column) and it is the developmental data regarding these expectations (fifth column) that are highlighted here. The point of this exercise is not to pit the theories against one another. Rather, the perceived urgency of certain experimental manipulations has been influenced by the overarching theories, and it is useful to see this to understand where the field of working memory has gone over the years. The influences go back to before the term working memory came into general use after the seminal article of Baddeley and Hitch (1974).

No one denies that people and most animals can experience an event and remember various aspects of that event a few seconds later. However, the way in which this memory performance is interpreted differs a great deal between theorists, according to their interests and beliefs about the mind. The research questions that are thought most worth pursuing also differ according to beliefs. Suppose researchers are presented with the finding that, as children progress through the ages 4–15 years, the length of a series of items that they can repeat, or memory span, increases steadily (which is true, e.g., Gathercole et al., 2004). An empiricist may believe that the most important changes during this age range will be the learning history, and they will want to know the learning history for the items. The emphasis on learning, often to the exclusion of the internal structure and function of the brain, is not logically required by the empiricist view but, when one focuses on behavior, it would be convenient if there were simple laws relating stimuli to responses, so the effort has been in searching for those simple laws. There may be not many individuals that adhere strictly to the empiricist view, or any one view, but one can point to an effort to find out the role of learning history in terms of the familiarity of items used to in working memory tests (e.g., Melby-Lervåg & Hulme, 2010).

A nativist, on the other hand, would focus on whether the basic working memory mechanisms in the brain are inherited, and may have questions stemming from that proposition. Working memory should be operational at birth (e.g., Reznick et al., 2004), but how does its improvement with age correspond to biological growth of the brain (e.g., Thomason et al., 2009)? Are there specific modules inherited to carry out different kinds of working memory tasks? Do individuals differ in the quality of what they inherit (e.g., Friedman et al., 2008), and does that difference explain working memory differences between children at any particular maturational level? These types of considerations illustrate that the field of working memory should not be viewed as isolated from more general theoretical initiatives, in this case nativism.

A cognitivist believes that one can talk about working memory in terms of the inferred internal components, a conception of working memory consistent with Baddeley and Hitch (1974). The cognitivist perspective can be compared to the more functionalist use of the term working memory (focusing on what the outcome is, in a somewhat more behaviorist manner) by Miller et al. (1960); their use of the term only referred more vaguely to whatever processes hold or retrieve the information necessary for the task of planning behavior, without inferences about what those mechanisms are. To understand those internal components, the cognitivist emphasis is on what processes change with age, based on a combination of both learning and biological maturation, and to try to disentangle those processes (Cowan, 2016).

One belief, especially with the constructivist wing of cognitivism, is that the processes taking place within the individual, both obligatory and voluntary, are important in forming and retaining ideas. Whereas it may be nativist to propose that a working-memory component of the brain simply increases its holding capacity with age in childhood, it is more cognitivist and constructivist to consider that, with age, there are increasing strategies such as grouping items together, chunking them to form larger units, mentally refreshing representations with attention, and verbally rehearsing the items. These strategies open the conversation to possibilities of the improved use of attention and executive function with age to achieve the most working memory storage and to use it most effectively for other tasks.

A researcher of dynamic systems theory (Table 1) might, however, check whether there are simpler means to use knowledge together with neural processes with which results can be emergent without having to propose higher-level cognitive processes. There can be an interplay of cognitive behavioral and neural modeling results, creating a tension in which increasingly complex behaviors are documented and in which the dynamic systems approach can be used to see if the proposed cognitive constructions can be pared back while still predicting the observed behaviors. For a summary of one such research program, see Spencer (2020).

Theoretical Views and Implications for Working Memory Developments

The views summarized in Table 1 are mostly grouped into pairs of related views: empiricism and behaviorism, nativism and modularity, and cognitivism and constructivism. The last view, dynamic systems theory, also is related to neuroconstructivism (Westermann et al., 2011) that is not based on abstract symbols like other types of constructivism. The majority of the author's work that will be discussed comes from a cognitivist and constructivist viewpoint. However, the other views provide an important context for the progression of ideas over the years. This is not to say that the influence of these views on the field was always intentional, but the influence seems clear.

Working Memory Development and Empiricism: In Search of General Learning Principles

Empiricism is the philosophical notion that our sensory experience is the basis of all knowledge. Empiricism as a scientific philosophy in psychology refers to the special importance of observed behavioral evidence. Proponents of behaviorism accepted these ideas and took them to mean that we should study the relation between stimuli and responses, looking for orderly relationships in behavior without trying to divine the nature of processes hidden in the mind and brain. Under the influence of this type of theoretical view, considerable research was carried out involving remembering information recently presented (e.g., in the field of verbal learning), as well as developmental norms such as those embedded within tests of intelligence. This research strives to determine the most general principles that can account for behavior. Thus, behaviorism led to a verbal learning theory, which was based on the hope that one set of laws can explain learning regardless of the species or the time between encoding and retrieval. This theory is at odds with the notion that working memory depends on some specialized mechanisms, as opposed to one general set of learning mechanisms.

Even though behaviorism is essentially a methodology, it has carried with it an implicit theory of the mind. For example, regarding various psychological research endeavors, Watson (1913, p. 170) stated that "There is no reason why appeal should ever be made to consciousness…Or why introspective data should ever be sought during the experimentation, or published in the results. In experimental pedagogy especially one can see the desirability of keeping all of the results on a purely objective plane. If this is done, work there on the human being will be comparable directly with the work upon animals." The hope was that one could find a set of laws of behavior that would be generally applicable across species. One can see that implicit theory as being appealing if learning is empiricist, based on simple associations built from sensations to eventually yield more complex behaviors. If the learning mechanism is supposed to be one in which sensory neurons become associated with effector neurons to produce behavior then, with that assumption, the resolution to study just the laws relating stimuli to responses would reasonably follow.

Influence of Empiricism and Behaviorism in Adult Research on Working Memory: Against Decay and Capacity Limits—The notion that one set of principles for all learning is opposed to the idea that there are certain qualities of working memory that set it apart from long-term memory. In working memory, the information could be lost because information decays rapidly over time, or because there is a mechanism with a limited capacity. In the empiricist initiatives within verbal learning theory, there were efforts to show that decay and capacity limits are not needed at all.

The issue of decay.: An outgrowth of empiricism and behaviorism in adult research was the field of verbal learning, summarized, for example, by Kausler (1974) and Postman (1975) and, in child development, by Keppel (1964) and Goulet (1968). The issue is that when rapid loss of information over time is observed, it could be the result of retroactive interference from subsequent stimuli or thoughts, not rapid decay. In order to prevent rehearsal, researchers often use distracting tasks during the retention interval after a set of stimuli and before recall; but the distracting stimuli might not only tie up attention, but also replace the items to be recalled in currently accessible memory – an example of retroactive interference.

Many rules of learning in animals were found to apply to verbal learning in humans. A fundamental rule of special importance here is that, if one learns an association A-B and later learns an association A-C, the second learning episode will encounter interference from the first, termed proactive interference, that is, interference of the earlier stimuli on memory for the similar, later stimuli. Moreover, the interference is time-dependent, such that A-C is at first predominant but, as time elapses, A-B re-emerges and competes with A-C (the definition of proactive interference). As proactive interference emerges, retroactive interference caused by the A-B association on the retrieval of A-C subsides. That is, if one receives A-B and then A-C, one will at first remember A-C best but, after a delay, there will be a recovery of A-B at the expense of A-C. Thus, contrary to decay, some learning was seen to re-emerge over time (McGeoch, 1932).

Decay across seconds?: A challenge to the verbal learning tradition came from research on the rapid decay of information, both in humans (Brown, 1958; Peterson & Peterson, 1959) and in animals (Mishkin et al., 1975; Olton et al., 1977). The idea was that information from stimuli does not inevitably remain accessible until there is interference with it. Instead, there is said to be a process in which temporarily-available representations of stimuli, or short-term memory traces, undergo a decay process. After a certain amount of decay, the information may still be in a long-term memory store but is no longer readily accessible without a retrieval process that could fail. This distinction between short- and long-term memory was also proposed by Broadbent (1958) in a seminal book published the same year that he became Director of the Applied Psychology Unit in Cambridge, UK. Behaviorism was still in fashion, and that shows in the vocabulary Broadbent used, but the diagram of an information flow that included separate short- and long-term stores that appeared in a footnote in his book show him actually as an early cognitivist.

Proponents of the verbal learning tradition fought back against the notion of so much structure in the mind. As a key example, consider the method of Peterson and Peterson (1959) and a response by Keppel and Underwood (1962). On every trial of the Peterson and Peterson procedure, a trigram of letters, such as CHJ, was to be remembered while the participant counted backward from a given number by threes until receiving a signal to stop counting backward and recall the trigram. It was assumed in the behaviorist approach that letters and numbers are different enough not to interfere with each other much. Yet, there was a severe loss of information about the trigram over 18 s of counting backward. However, Keppel and Underwood (1962) argued against the need for a distinction between short- and long-term memory faculties in this work by Peterson and Peterson, on the basis of an alternative interpretation of what was going on. Rather than the trigram being lost due to short-term memory decay, they proposed that the information suffered more proactive interference from the trigrams in previous trials as the retention interval filled with counting backward increased. They found that, in the first several trials, before there was much proactive interference, there was little forgetting even if the retention interval was long. Only in subsequent trials did the loss of memory as a function of the retention interval emerge.

Baddeley and Scott (1971) countered the verbal learning type of explanation by running many participants for only one trial each, varying the retention interval across participants. They found a loss of information across at least a few seconds, briefer than what Peterson and Peterson (1959) observed, when the list length was longer to avoid ceiling effects.

Even if one accepts the Keppel and Underwood (1962) result, there are two interpretations possible, essentially empiricist versus nativist interpretations. The Keppel and Underwood (empiricist) interpretation is that the longer counting-backward intervals allowed time for proactive interference from previous trials to take place in a unitary memory. In an alternative account, though, there are separate stores for short- and long-term retention, both used at the same time but with proactive interference being a more important factor in the longer store (cf. Cowan et al., 2005b). This account combines the empiricist-inspired mechanism of proactive interference, along with the nativist-inspired mechanism of a separate short-term store. When the counting-backward interval is short, then short-term storage (working memory) can be used. When the interval is long, short-term storage has decayed and only long-term memorization can be used. In that situation, proactive interference on later trials will tend to be strong as Keppel and Underwood thought.

The idea from verbal learning that the passage of time allowed proactive interference was later formalized in the notion of temporal distinctiveness (e.g., Bjork & Whitten, 1974; Crowder, 1976; Glenberg & Swanson, 1986). The idea is that items are represented in memory in a temporally-organized stream, metaphorically like a row of telephone poles (e.g., with poles clustered into groups of three to represent the items in a trigram in Peterson & Peterson, 1959). As the retention interval elapses, it becomes more difficult to tell which item occurred in which location, like walking away from the series of poles so that they begin to merge perceptually. That merging would be the basis of proactive interference. Cowan et al. (1997) tried to assess temporal distinctiveness in a two-tone comparison task by manipulating not only the time between the tones to be compared, but also the times between trials that affect distinctiveness. With the ratio of times held constant, there was still forgetting over 12 s as a function of the time between tones to be compared. Ricker et al. (2014) did something similar for memory of arrays of unfamiliar characters or English letters and found very little effect of distinctiveness, with a much larger effect of loss over 6 s from decay. Subsequent works suggests that decay occurs primarily when items are presented with insufficient time for thorough working memory consolidation, which depends on the materials (Ricker et al., 2018; Ricker & Cowan, 2014; Ricker & Hardman, 2017) and not much when encoding is good (e.g., Oberauer & Lewandowsky, 2008).

Decay across milliseconds?: The issue of decay can be examined on at least two different time scales. Cowan (1984, 1988) reviewed evidence suggesting that in every modality (but validated especially for vision and hearing), there are two phases of sensory storage: a vivid mental afterimage lasting only a fraction of a second, as perceptual processing of the stimulus is ongoing, and a longer, more processed memory that lasts on the order of seconds. A good example of both types of stores appears in the study by Phillips (1974). On each trial, an irregular checkerboard-like pattern was presented, varying in the number of cells (complexity). It was to be compared to a second pattern, after a variable interval, that differed from the first in having one more or one fewer black square. If the interval was very short (~100 ms) and there was no change in the location of the patterns and no masking pattern, performance was excellent regardless of the complexity. At longer inter-pattern time intervals, performance dropped as a function of time to an extent that depended on the pattern complexity and persisted despite a change in location or the presence of a mask. It appears that the short-lived representation is more literal, and the longer representation is more abstract and immune to sensory interference. With a different procedure, Kallman and Massaro (1979) demonstrated two phases of auditory sensory memory in a tone-comparison task. A masking sound following the first tone could interfere with both phases of sensory memory, whereas a masking sound following the second tone could only interfere with the first phase of sensory memory of that tone, allowing an intact longer sensory store of the first tone to facilitate the comparison process after the second tone was perceived. Unlike a unitary memory view, sensory memory seems tiered.

Summary of decay issues.: From an empiricist / behaviorist base, the verbal learning outlook survived in the adult research for many years (e.g., McGeoch, 1932; Melton, 1963, both formerly at the University of Missouri) and is still ongoing, with proponents who do not believe that there are separate short- and long-term storage processes (e.g., Crowder, 1982; Nairne, 2002). In situations in which stimuli can be encoded well, there is evidence against decay from studies in which the duration of the recall period is manipulated (e.g., Oberauer & Lewandowsky, 2008). When encoding time or capability is quite limited, though, as in the case of simultaneous arrays or non-categorized tones to be compared, there appears to be loss over time that requires something more than a single process for all of learning and memory (e.g., Ricker et al., 2018). This finding does not exclude the reality of principles put forward by verbal learning researchers, such as proactive and retroactive interference, but it suggests that we need further divisions of the memory system to understand all the evidence. There must be something in the mind and brain other than a single, all-encompassing neural network for memory that operates according to just one set of rules for memory at any time scale, as the unitary memory theorists from an empiricist approach seem to believe (e.g., Chater & Brown, 1999; Nairne, 2002).

The issue of capacity limits.: Working memory, by definition, can hold a limited amount. The limit logically can occur because the representations of items in working memory decay or because the number items that can be represented in working memory at once is limited, a capacity limit. A capacity or a decay mechanism must be found if one wishes to claim that there is such a thing as a working memory separate in its process from long-term memory, i.e., to disprove the learning theory view. Miller (1956) famously suggested a capacity limit, specifically that working memory is limited to about seven chunks, or integrated items. A chunk has strong associations between elements within it and weaker associations with items outside of it. For example, a known acronym like USA can be a chunk, as can a known word (as opposed to its phonemes).

In a seminal chapter initiating the field of working memory and a related article, Baddeley and Hitch (1974) and Baddeley et al. (1975) changed the emphasis away from capacity limits to concentrate on decay limits. Baddeley et al. showed that people could retain about as many verbal items in a list as they could recite in about 2 s, and the notion was that covert rehearsal allows each speech element to be renewed before it decays in about 2 s, like a juggler repeatedly throwing balls into the air. I, however, thought that both mechanisms were viable (Cowan, 1988).

The issue of knowledge.: There are aspects of working memory that still suggest it can be reasonably interpreted without a dual process or dual storage mechanism. Craik and Lockhart (1972) found that when stimuli are processed more deeply, they are remembered longer; that is the levels-of-processing argument. For example, a printed word's font is considered most shallow, the phonological representation is deeper, and the semantic representation is still deeper. (For a recent summary see Craik, 2020.) An argument can be made that the phenomena we call short-term memory involve series of stimuli that do not include good sets of cues for retrieval, which (although Craik does not claim this) may be compatible with an empiricist, learning-theory-based, unified-memory approach.

There is no question that knowledge effects are important. For example, series of nonsense syllables are more difficult to retain than series of known words (e.g., Saint-Aubin & Poirier, 2000). The question is just whether the apparent duration and capacity of storage can be predicted from knowledge available, and that theory has not been worked out. Evidence against a unified-memory approach comes from neuropsychological syndromes in which an individual has damage to the hippocampus, resulting in loss of long-term learning without a noticeable change in short-term memory or interactions. The best-known case of this is H.M., whose hippocampi were removed to treat epilepsy.

Recently, MacKay (2019) suggested that there were important deficits in H.M.'s sentence comprehension that were not due to memory for the sentence, which remained in front of him during the test. If processing is impaired, then the absence of new long-term learning by H.M. could be attributed to him not forming deep representations. In this light, the support for separate short- and long-term memory storage from neuropsychology may be uncertain, even after all these years.

Influence of Empiricism and Behaviorism in Developmental Research on Working Memory

Development and the issue of decay.: Decay has been espoused in some leading theories of working memory throughout the years (e.g., Baddeley, 1986; Barrouillet et al., 2011).

Accordingly, I had hoped to examine whether short-term memory decay can be shown to change in its rate during development, as a potential basis of cognitive maturation that would affect thinking. There have been studies suggesting that what changes with development is the rate of carrying out activities that could counteract decay: covert verbal rehearsal of words (Hulme & Tordoff, 1989; Kail & Park, 1994) or attention-based refreshment of information (Camos & Barrouillet, 2018). These theories relied on the existence of decay but typically assumed that the decay rate itself stayed constant throughout development.

Decay across seconds.: Cowan et al. (2000) examined working memory decay by presenting spoken digit lists to children in Grade 2 (7–9 years), Grade 5 (10–12 years), and college students, in a condition in which participants could not use attention during the presentation, only afterward during retrieval. Spoken lists of the participant's span length were presented at irregular intervals while they engaged in a silent game in which pictures with rhyming names were to be selected. The game was occasionally interrupted 1, 5, or 10 s after the most recent spoken list, the task then being to recall the list. Overall, there was no age difference in the rates of forgetting of list items across 10 s, with an impressive closeness in the results across ages. There was, however, a pronounced, selective deficit of the youngest group compared to the older children and adults in the performance on the most recently presented word. This finding suggested to Cowan et al. that the uninterrupted auditory memory of the last item was more persistent in the older children. An alternative possibility is that attention is directed to a fading auditory memory of the last item more efficiently in older participants. Against this interpretation, though, another method showed that the memory for the precise pitch of a single tone was lost more quickly in younger children (Keller & Cowan, 1994). Regardless, a difference across age groups of this sort would not be expected according to a simple learning theory in the empiricist tradition.

Decay across milliseconds.: James (1890, p. 462) wrote that newborns experience a “blooming, buzzing confusion” but that view was later criticized by infant researchers who documented the capabilities of infants. Nevertheless, there is evidence suggesting that there is some truth to the notion of confusion. If each sensation has a brief afterimage, then it is possible for sensations to blur together if the afterimage of one sensation persists while a second sensation is occurring. Something like sensations running together has been found in vision in the form of flicker fusion (e.g., Regal, 1981) and in audition in the form of perceptual fusion between brief noises (Plomp, 1964). The duration of an auditory afterimage can be assessed by masking a brief sound with a subsequent sound, which can result in the inability to identify the first sound because the second one interrupts the extraction of information from the afterimage of the first. In adults, this backward recognition masking reaches an asymptotic level when the time between the onset of the brief target to be identified and the brief mask reaches about 250 ms (Massaro, 1975). Given converging information from other procedures (Efron, 1970a, 1970b, 1970c; Plomp, 1964), Cowan (1984) assumed that the end of masking is related to the point at which there has been too much decay of the afterimage for image extraction to continue.

Cowan et al. (1982) tested the duration of backward recognition masking in 8- to 9-week-old infants using a modified non-nutritive sucking procedure. Infants heard a steady stream of masked vowel sounds coming from one tape-recorded channel but, when they sucked on the pacifier, the soundtrack switched to a second recorded channel with a change in the masked vowel. Sucking allowed infants access to a change in the sound (except in a no-change control condition). This access elicited an increased rate of sucking on the pacifier when the onset-to-onset interval between the target and mask was 400 ms, but much less so when the interval was only 250. These results suggest that infants may have acoustic persistence for longer than adults, which may be useful for the extraction of information at a slower pace. It also might result in the experience of a smearing of sounds in a stream such as speech, compared to what adults experience, i.e., something of a blooming, buzzing confusion after all. There is supporting evidence from another infant procedure in audition (Morrongiello & Trehub, 1987; Trehub et al., 1995) and, in vision, developing temporal acuity of flicker fusion (Regal, 1981). These findings seem in keeping with the importance of maturation of physiology and against the notion of all organisms being roughly comparable; it points to some age differences other than simple learning.

Longer periods of time beyond minutes.: There has been some beautiful work on the temporal qualities of memory in infants using behaviorist principles and procedures, such as using reminders and demonstrating developmental increases in the stability of memory over time (Rovee-Collier & Cuevas, 2008). Perhaps because this work was carried out from a tradition quite different from other researchers of working memory, and more like the animal research from a learning theory tradition, there has not been very much integration of this body of research with the working memory literature. Developmental researchers seem to have emphasized long-term learning principles or short-term memory principles, but rarely the integration of the two (although see recent work on dynamic systems theory, e.g., Spencer, 2020).

Development and the issue of capacity.: Aside from the possibility of decay, capacity limits are the other way that there could be a separate working memory system. Cowan et al. (1999) showed that capacity for spoken lists of digits increased during the elementary school years, using the aforementioned, silent rhyming task to prevent the use of mnemonic strategies during presentation of lists. Each participant heard lists of digits intermittently, with list lengths adjusted to equal the participant’s attended span or to be 1, 2, or 3 items shorter than that. The silent rhyming game was interrupted intermittently, at which point the participant was to recall the most recent list, which had ended 1 s previously. The number of items recalled from unattended lists in these circumstances was approximately constant across list lengths but differed by age, at about 3.5 items in college students, about 3 items in fourth-grade children, and about 2.5 items in first-grade children. The constancy across list lengths was taken to indicate that, with mnemonic strategies removed, only a core working memory capacity was indexed. Similar capacity estimates later emerged from studies of visual array memory development (e.g., Cowan et al., 2005a, 2006b; Riggs et al., 2006, 2011). These seemingly small differences are proportionally large (e.g., from 2.5 to 3.5 is a 40% increase), with major implications for cognitive processing.

Capacity versus filtering.: It remained possible that children may develop a better ability to carry out mnemonic processing that creates these apparent capacity limits. One type of mnemonic processing is attention to the most relevant items, excluding irrelevant information. Cowan et al. (2010) addressed this possibility with arrays of colored objects of two different shapes to be remembered for subsequent probe item recognition mixed together on each trial. In some trial blocks, there was a much higher frequency of testing one shape compared to the other (e.g., the colored circles tested on 80% of the trials, with the colored triangles tested on the other 20%). When the array size was small (with only 2 items of each shape), participants in all age groups filled working memory primarily with the more-often-tested shape, according to the recognition data. However, the youngest, 7-year-old children remembered far fewer colors of either shape. Cowan et al. (2011) replicated this finding with a much slower, one-at-a-time presentation of the objects, so the age difference was not an encoding speed limitation. Younger children's working memory was not more cluttered with less-relevant items, except when memory was overloaded (Cowan et al., 2010) by presenting 3 items of each shape.

Capacity versus speed as the causal factor.: Children's speed of mnemonic processing increases with age (Camos & Barrouillet, 2011; Cowan et al., 1998; Gaillard et al., 2011; Hulme & Tordoff, 1989; Kail et al., 2016). Mnemonic processing speeds of some sorts theoretically could govern the increase in capacity across ages if faster rehearsal or attention-based refreshing allows more items to avoid decay. Possibly, increasing processing speed as a basis of development could fit a unitary memory theory like the verbal learning theories, by applying to all processes equally. However, it is also possible that speeds are the result, rather than the cause, of capacity differences across age groups. If more items can be retained in the focus of attention at once, for example, then it may be possible to refresh more items in parallel, increasing the observed speed of refreshment (Lemaire et al., 2018). Cowan et al. (2006a) showed that second-grade children could be instructed to speed up their repetition of lists to equal the speed adults naturally used; yet, working memory did not increase at all as a result. This finding suggests that a basic capacity difference may underlie working memory development, not a speed difference.

Development and the issue of knowledge.: The empiricist approach might suggest that developmental changes in working memory could be attributed to learning. As children learn, they know more items that are used in working memory tasks and can form better patterns from them, resulting in fewer, larger chunks and more extensive inter-item associations. But can this learning account for all of the development of working memory? Cowan et al. (2015) addressed this issue by presenting arrays of English letters or unfamiliar characters to elementary school children at various ages, and to college students (method, Figure 2; results, Figure 3A). A few first-grade children did not know their letters well enough to be successful at even the smallest array set sizes. With those few excluded, English letters were remembered much better than unfamiliar characters at all ages. Using separate cross-age-standardized scores for the two types of materials, however, a steep developmental growth curve looked almost identical for letters and unfamiliar characters, indicating that the developmental increase in knowledge alone cannot explain working memory development in this situation.

In a convergent, very different method, Gilchrist et al. (2009) examined verbatim recall of lists of unrelated, simple spoken sentences. Working memory capacity could be examined by the number of sentences that were at least partly recalled. Knowledge could be examined by the degree of completion of sentences that were at least partly recalled. Across age groups, the rate of completion of the at-least-partly-recalled, short sentences was about 80%, so knowledge was equated by the simplicity of the sentences; yet children in second grade recalled fewer sentences than older participants, indicating a lower capacity.

Empiricism and working memory development: A summary.: In sum, I have looked for developmental effects that are either consistent or inconsistent with an empiricist view and find that the view has merit but is not in itself complete. Age differences in working memory capacity and sensory decay cannot be totally explained by increasing knowledge or learning principles. Thus, the complete model of development appears to require learning principles supplemented by a working memory system with additional limits. In favor of that description, as I will explain further under the constructivist view, the embedded processes model of Cowan (1988, 1995, 2019) considers working memory to comprise activated long-term memory elements, including rapid new learning, and a capacity-limited focus of attention embedded within the activated portion of long-term memory.

Working Memory Development and Nativism: In Favor of Specialized Modules

Nativism differs dramatically from empiricism in emphasizing the importance of the genes in creating the neural organization that produces responses. Nativism (with modularity) is consistent with the idea that more specialized structures exist, and with the idea that fundamental properties of cognition are inborn, albeit with the possibility of change with maturation. Although there is relatively little work directly linking genes to the neural understanding of working memory and its development (though there is some, e.g., Friedman et al., 2008), there are many studies focusing on what appear to be special constructions of the brain, or modularity, for the purpose of carrying out working memory processes. There have been investigations from this viewpoint focusing on possible development changes in these modules.

Influence of Nativism and Modularity in Adult Memory Research—This approach is characterized in the second row of Figure 1. Online OxfordLanguages (2021b) defines nativism in psychology as “the theory that concepts, mental capacities, and mental structures are innate rather than acquired by learning.” The idea is usually associated with Kant’s philosophy and, in psychology, Fodor’s view of modularity (Wikipedia, 2021). Nativists are among those who have looked for individual differences in intelligence and the extent to which they are heritable, and certainly have included working memory among the abilities that are candidates for largely inherited cognitive ability (e.g., Deary, 2012; Friedman, et al., 2008).

Implications for working memory.: In the psychology of memory, the idea of nativism would imply that there are modules specific to memory that are inherited and that determine the quality of thinking in an organism. The question here would be, what kinds of modules, and how many, and with what developmental course? The nativists would be quite comfortable with the notion of separate short- and long-term memory modules but these might not appear to be enough. There are neurological dissociations in which an individual with a brain lesion is found to have good verbal working memory but very poor visual working memory, or vice versa (for reviews see Hanley & Young, 2019; Shallice & Papagno, 2019), and these helped support the notion that visual and verbal working memory are separate modules (e.g., Baddeley, 1986). To this day, there are scientific arguments about whether the neurological support for working memory modules supports the existence of separate visual and verbal modules, or whether the data can be explained by mnemonic processes without separate modules for different types of storage (Buchsbaum & D'Esposito, 2019; Cowan, 2019; Logie, 2019; Majerus, 2019; Morey, 2018, 2019; Morey et al., 2019, 2020).

All theories acknowledge that the individual inherits some neural apparatus that used to carry out the kinds of tasks that we term working memory tasks. However, there is a difference between the kind of theory in which specialized modules are inherited (e.g., Logie, 2016) versus a theory in which the kinds of processes that are inherited are general-purpose, problem-solving mechanisms that can be adapted across different types of tasks and materials (e.g., Cowan, 2019; Kane et al., 2004). It is the former type of theory that can be more closely identified with nativism and modularity, whereas the latter type of theory is more cognitivist and must go on to explain more about strategies used to adapt to each kind of task.

Influence of Nativism and Modularity in Developmental Research on Working Memory—From the broad field of cognitive science, the spirit of nativism was brought to developmental psychology by Chomsky (1965) with the claim that language is learned so fast, resulting in such a complex structure, that it can only be the result of an innate language acquisition device. This kind of sentiment was suitable to infant researchers, who found that if a sensitive measure like eye movements is used, there is evidence of infant capabilities far beyond what psychologists had supposed, such as the maintenance of an object in working memory when it has been hidden (object permanence), as early as 5 months of age (Baillargeon et al., 1985), much earlier than Piaget and colleagues had suggested based on manual responses.

As Cowan (2016) noted, there have been many infant studies of working memory and other skills, suggesting that even working memory capacity gets a very early start in life. At first glance, it appears that infants have a capacity of about 3 items (e.g., Ross-Sheehy et al., 2003; Zosh & Feigenson, 2012, 2015). This estimate seems similar to what is found in adults with procedures in which mnemonic strategies cannot be used (e.g., Cowan, 2001; Luck & Vogel, 1997; Zhang & Luck, 2008). If there were no developmental increase in basic working memory capacity, and it were about 3 items at all ages, then certainly it would have to be considered a fundamental mental capacity that is innate rather than influenced by learning. This apparent equivalence, however, is paradoxical because studies that examine working memory using the same procedure across age groups in childhood do find substantial changes with age (e.g., with change detect and related procedures, Cowan et al., 2005a; Simmering, 2016; with a variety of span tasks, Gathercole et al., 2004).

Something about the infant procedures allows infants to demonstrate a seemingly higher capacity than young children.

To help resolve this paradox, a study by Zosh and Feigenson (2012) with 18-month-olds may be relevant. The study suggests that there may still be a monotonic developmental change in working memory. In particular, it may be a change not in the number of working memory slots but in the completeness of the feature representation of objects in working memory. Zosh and Feigenson asked whether the infants' memory of how many items were in a container included memory of all the features of those items. Toys were hidden and, in one condition, the toys were secretly swapped out for others without the infants knowing this. Infants were then allowed to search for the toys, extracting them from the container. What was measured was the duration with which infants kept searching in the container. When there were one or two toys, infants were not satisfied after extracting them and often kept on searching in the container, apparently for the not-yet-retrieved, original toys. However, when three toys were hidden and then secretly exchanged for new toys, children typically stopped searching after extracting the three new toys. The explanation was that they knew there were three toys but no longer remembered the other features of the original toys, and so they had no motivation to keep on searching. That is, there was supposedly a tradeoff between memory for details of the original toys, up to two toys, and loss of the memory for detail after a third original toy was encoded into memory. Together with the literature, one possible implication is that the developmental change from infancy to adulthood might be not in the number of items in working memory, but rather in the featural detail possible within each of about three representations in working memory. A change in featural detail sounds much less like a nativist concept than does a change in capacity per se.

Based on these infant results and adult findings of Cowan et al. (2013), Cowan (2017b) suggested that in subsequent child development, too, there may be a tradeoff between the number of items in working memory and the specificity of the feature representation of each item. Perhaps feature specification of items continues to increase during childhood. Given the potentially large role of learning in feature specification, the developmental story no longer sounds as uniquely nativist as it might if a working memory module (or several) simply grew in capacity with age.

Working Memory Development, Cognitivism, and Constructivism: Innate Readiness for the Assimilation and Construction of Knowledge

At a certain point in the history of science, investigators realized that they had enough information to make inferences about the chemical and atomic makeup of objects (such as, for example, the sun) even though the inferred units were not directly observable. Similarly, in psychology, in the mid-1950s there was a realization that one could make inferences about the organization or makeup of the mind using a variety of techniques, ranging from the behavioral study of immediate memory (Miller, 1956) and attention (Broadbent, 1958) to the analysis of grammar (Chomsky, 1957) and the use of computers to simulate human thinking (Newell & Simon, 1956). That was the beginning of the cognitive revolution that helped establish a cognitivist view in the field. In this view, the internal manipulation of symbols is said to describe mental functioning.

Beyond cognitivism, Bruner et al. (1956) presented research suggesting that ideas and mental categories do not simply come from the stimuli; they depend on participants' decisions as to what cues and factors to consider or ignore in forming their conclusions. This appears to be one beginning of the concept of constructivism, the idea that concepts are constructed by the individual. Thus, this view as important even in adult research, though constructivism occurs over time and therefore is well-suited to developmental study. Researchers in the field of education (Jonassen, 1991, for example) distinguished between an objectivist and a constructionist view. In objectivism, individual learners process symbols and discern reality, whereas in constructivism, individuals build symbols and determine their own reality. According to this analysis, cognitivism has an objectivist component and a constructivist component. Most likely, the reality falls in between the extremes.

The cognitivist viewpoint was not devised with development particularly in mind and its influence on developmental research has waxed and waned in the field of developmental psychology (Spencer et al., 2011; Thelen & Bates, 2003). Spencer et al. (p. 261) stated, "we conducted a survey of the fourth through sixth editions of the Handbook of Child Psychology: Theoretical Models of Human Development. These editions span more than 20 years in developmental psychology (from 1983 to 2006). Although this book is just one indication of how the field is changing, our survey revealed that four theoretical viewpoints have disappeared from the Handbook over time: nativism, cognitive and information processing, symbolic approaches, and Piaget's theory. Of course, scholars still actively pursue all of these perspectives." Given that the field may have shifted away from these perspectives, it may be especially helpful to understand how they shaped some of the past and ongoing research. This is very true in my own program of work because I have conducted both adult and developmental research on working memory heavily over the years, which has allowed a great deal of cross-fertilization between the two lines of research. In general, in fact, many investigators of working memory development have had close ties to the adult research from a cognitivist perspective (e.g., the work of Bayliss et al., 2003; Camos & Barrouillet, 2018; Gathercole et al., 2004; Hitch et al., 2001; and Towse et al., 2010), and all of these investigators have also published steadily in the adult literature. The finding that developmental handbooks do not much focus on these areas, along with my own experiences, suggest to me that this faction of the developmental field may have turned toward the working memory theorists more than it has interacted with other developmentalists, increasing the need for the present review and reconciliation of approaches.

The relevance of cognitivism and constructivism to working memory research differ. Cognitivism is related to inferences about mental activities, and opens up consideration of new storage and processing mechanisms that were not discussed in empiricism because they are not directly observable. Constructivism is relevant in two ways. First, although a nativist view also includes the possibility of internal structures, constructivism increases the amount of attention paid to the possibility that storage is flexible and regulated strategically by the individual, as opposed to an inflexible and rote storage mechanism. (Note that a separate type is neuroconstructivism, to be considered later with dynamic systems theory.) Second, if individuals do construct their own concepts, they presumably do it by holding symbols in working memory to allow these symbols to be recombined in that cauldron. Cognitivism and constructivism should add to what is contributed by empiricists and nativists. To understand behavior, their previous insights must be combined and must explain how knowledge and strategies are constructed.

Influence of Cognitivism and Constructivism in Adult Research on Working Memory

Early cognitive revolution.: The work of Miller et al. (1960), *Plans and the structure of behavior*, involved an early mention of the term working memory. It did not get into internal mechanisms of the mind but can be considered a bridge between empiricism and constructivism. The notion was that people must hold on to information temporarily and use it to plan activities to meet a hierarchy of goals ranging from the immediate, such as popping a piece of toast into the toaster, to long-term, such as planning to purchase a home or furthering a career.

A slew of models in the 1960s were attempts to use what had been learned about behavior and computers together to formulate models of human information processing. These models had some similarities, as pointed out for example by Murdock (1967), who described a "modal model" of commonalities between the models. It included a sensory store susceptible to decay, an attention process that can select among sensory items, a more limited-capacity primary memory susceptible to displacement, a rehearsal process, and a secondary memory susceptible to interference at the time of retrieval. Work serving as an important precursor to this model is Sperling (1960), and the best-known model of this cohort described by Murdock is that of Atkinson and Shiffrin (1968), with an earlier version of their work available to Murdock as a 1965 technical report. The term working memory was not used but the sensory and short-term stores are its relevant precursors. It is the prominence of the control processes, represented in these early models by attention and rehearsal, that might most strongly indicate that we are not just talking about some autonomous, mechanistic stores that are inherited; what is presumably inherited includes mechanisms that allow different processing strategies to be used in a manner up to the discretion of the individual.

Baddeley and Hitch (1974) conception of working memory.: The general message of the seminal Baddeley and Hitch (1974) work is that something was amiss in the elegant modal model. It seemed that multiple storage and processing mechanisms were needed, and the term working memory was applied to the multicomponent system. Materials that were very different, such as digits to be remembered and sentences to be comprehended, still interfered with each other, but not as much as if they had totally displaced each other in primary or short-term memory. In free recall of 16-word lists, the advantage of recall for the most recent several items was unaffected by a concurrent digit load, which was odd if those last several items in the word list were held in a short-term store needed for digit storage. Concurrently speaking to prevent verbal rehearsal had a large effect on recall of printed words, but little if any effect on recall of spoken words. The results suggested that what was needed was a theory in which there are separate dedicated modules for different purposes, as in a nativist view. These developed to be the phonological and visuo-spatial stores of Baddeley's (1986) model. However, it was also suggested that general attention was needed to store and process complex items. The processing component was the central executive in Baddeley's model, whereas the central storage component of attention was excluded by Baddeley (1986). A general storage was restored to the model as the episodic buffer (Baddeley, 2000, 2001). Attention was a central part of Cowan's (1988, 1995) alternative conception that included storage in the focus of attention. Although the early work by Baddeley was concentrated on understanding what might be considered the more nativist, modular storage buffers, much of his more recent work has focused largely on the more cognitivist concept, the attentional aspect of immediate memory, more in keeping with the emphasis of Cowan and colleagues (for a summary, see Baddeley et al., 2021).

Embedded-processes model.: Cowan's (1988, 1995, 2019) model of information processing includes the activated portion of long-term memory embedded within the memory system and, embedded within activated memory, the focus of attention. It also includes a perceptual process giving rise to a brief, initial sensory storage process that deposits information into the memory system, whereas a longer kind of sensory storage is considered to be one kind of activated memory (along with semantic activation). There is a central executive that helps to control the focus of attention, much like its function in previous models.

The embedded processes model did not arise specifically in response to the Baddeley and Hitch (1974) or Baddeley (1986) models per se, but rather to a number of puzzling aspects of information processing stemming from the modal model. Unattended aspects of stimulation were supposedly dropped from further processing after sensory memory; yet, somehow, when these filtered-out channels of information changed in their physical properties, as when there is a sudden flicker in the lighting or a sudden change in the background noise that was being ignored, people noticed these changes (Cherry, 1953; Broadbent, 1958). Moreover, it appeared that the unattended information somehow made contact with information in long-term memory. For example, people sometimes noticed when their name was presented in an unattended channel (Moray, 1959). Treisman (1960) explained this by proposing that attention did not totally filter out unselected information; that information was merely attenuated, so it could still reach the long-term memory system and changes could, presumably, still be noticed. It seemed to Cowan (1988), however, that a more detailed concept of what might occur could be constructed, based on the notion from Sokolov (1963) that an intelligent organism builds up a neural model of the environment and then notices changes to that environment. This could be represented by doing away with the sequential arrangement of stores and allowing incoming stimuli, once perceived, to make direct contact with long-term memory, activating the relevant features to the extent that it could be processed (Cowan, 1988, 1995, 2019). Moreover, attention could be represented as focused on a limited amount of newly-perceived changes, task-relevant information from the environment, and recently-encountered or thought-of information. In each case, the information in the focus of attention would result in the best-analyzed, most coherent and meaningful view of the world. It could include some, but not all, of the many features of long-term memory currently activated by the environmental input and the recent work of the focus of attention in eking out the meaning of stimuli and thoughts. Within this theoretical framework, working memory would be represented by the activated long-term memory information (a concept related to the activated cell assemblies proposed by Hebb, 1949) serving as a collection of currently highly-accessible thoughts, and the focus of attention (a concept related to the primary memory of James, 1890) as the central core of this working memory system.

Like Baddeley's (1986) model, the model of Cowan (1988, 1995, 1999) was influenced by brain research. However, these models were influenced by different aspects of brain research. Baddeley had experience with neurology patients who had diminished verbal immediate memory along with preserved visual immediate memory or vice versa. Instead, I was interested in consciousness and focused on individuals with parietal and frontal damage, important for the functioning of a focus of attention and for executive operations on the material being stored. In Baddeley's model, the reason why verbal and visual sets of information do not interfere with each other very much is that they are handled by different dedicated stores. Cowan (1988) reasoned, however, that an adequate taxonomy would also have to consider other kinds of information: acoustic (duration, pitch, etc.), orthographic, visual (color, shape, spatial location, etc.), and semantic features, as well as information from other senses. Some features crossed modalities (e.g., duration and location). It seemed likely that a given stimulus would give rise to feature activation that is not limited to one type, and the taxonomy of stores seemed possibly too inflexible and complex to propose in a modular sense. Rather than doing so, Cowan (1988) simply proposed that stimuli having similar processed features would interfere with one another within activated long-term memory. Thus, the model seems more heavily cognitivist and constructionist than the Baddeley model, which appears to have a larger nativist influence.

Even in the embedded-processes model, though, there does appear to be some nativist influence. For example, the use of features probably depends on the inherent suitability of the modality to the task so that, for example, phonological features may be well-suited for retaining a sequence, more so than unrelated meanings (Saint-Aubin & Poirier, 2000). As another example, the visual modality is better-tuned to fine spatial information, whereas the auditory modality is better-tuned to fine temporal information (e.g., Penney, 1989). These inherited aspects of cognition are acknowledged in the embedded processes model. Innate aspects of perception could cause separations by modality and code that apply to working memory. For example, acoustic advantages in serial order retention of speech (Penney, 1989) are partly retained as phonological advantages even for written items (Conrad, 1964). Auditory and phonological materials may be especially suited to sequential presentation, which may allow them to be learned and retained in working memory with relatively little investment of attention, compared to visual materials, which require more attention to be retained in working memory (Gray et al, 2017; Li & Cowan, 2021; Morey et al., 2013; Penney, 1989; Vergauwe et al., 2010).

As a different kind of example of the possibility of an innate module contributing to perception rather than working memory per se, suppose there is a specialized face perception module. It would contribute information to working memory that is privileged by any innate face category information. In contrast, a category like house perception could not be innate and would presumably be less privileged in perception (for a discussion see Farah et al., 1998). If working memory looked superior for faces compared to houses, it could be because of the contribution of the face perception module, but that would not be a demonstration of modularity in working memory per se, just modularity in perception used by working memory.

Where do capacity limits come from according to an embedded processes approach? It is a complex problem but here is an example that may help. To hold a set of separate items successfully, one must (1) retain the items, (2) keep them from being confused with one another, and (3) know which object goes where (that is, remember their serial, temporal, and spatial positions). For Requirements 2 and 3, similarity between items can be harmful. Several studies of object array item recognition fit a model in which working memory is limited to about three objects, but with limited numbers of features (location, shape, color, texture, size, and so on) that can be retained for each object (Cowan et al., 2013; Hardman & Cowan, 2015; Oberauer & Eichenberger, 2013).

Brain imaging evidence supports this description of capacity limits. The focus of attention in working memory especially relates to one area, the intraparietal sulcus (Cowan et al., 2011), which may not represent the information retained in working memory but rather the number of items being retained (Majerus et al., 2016), perhaps serving as indices pointing to other brain areas to coordinate their input. There is functional connectivity between the intraparietal sulcus and the posterior cortical regions that clearly do represent the information currently being retained (Li et al., 2014). The intraparietal sulcus is more active not simply as a function of the number of items in working memory, but as a function of the similarity between those items; Gossaries et al. (2018) found that it was more active when retrieving one direction of movement from a memory set that also included two other directions, as compared to a memory set that included just the one direction along with two colors.

In sum, I do not subscribe to visual and phonological working memory stores per se like Baddeley (1986) and Baddeley et al. (2021), given the need for many additional feature distinctions such as loudness and pitch dimensions in an acoustic store, shape and color dimensions in a visual store, direction or location separate from the modality conveying it, other senses, semantics, and so on. Baddeley (2000, 2001) dealt with these cases by appealing to a new storage unit, the episodic buffer, but this wide net cast by the new buffer does not seem able to handle them all in a principled manner. A more microscopic or network-like level of analysis may be needed, following on the activated long-term memory approach.

Cowan (1988, 1995, 1999; updated view described 2019) suggested a model of processing that was meant to coordinate results suggesting decay and those suggesting capacity limits. In this approach, working memory consists of embedded processes. A portion of long-term memory is temporarily activated, with activation limited by decay as well as interference from subsequent input. It includes features of recently seen or thought-of items, though the features are not well-integrated. Rapid, new learning takes place via the focus of attention, and this new learning can produce activated long-term memory elements used even in the current trial of a task (a point noted by Cowan, 1988 but amplified by Cowan, 2019). Embedded within activated memory, there is a focus of attention that can maintain only at most several chunks at once; unlike activated memory, it is capacity-limited. Working memory performance is based on information in the focus of attention and information that can be rapidly retrieved into the focus because it is in still activated long-term memory. Recent research suggests that information can be off-loaded through rapid memorization to free the focus of attention for other work (e.g., Cowan et al., 2018; Rhodes & Cowan, 2018).

Miller (1956) left some doubt about whether capacity limits are fundamental, suggesting that the limits observed in different procedures are the result of coincidence, and using the magical number seven plus or minus two as a rhetorical device to allow him to discuss several apparently unrelated phenomena that he was describing in the same talk (Miller, 1989; Cowan, 2015). Cowan (2001) helped to renew the emphasis on capacity by reviewing many phenomena indicating that there is a core working memory capacity in adults of 3 to 5 items, often augmented by mnemonic strategies including grouping, chunking, and rehearsal (see also, Broadbent, 1975; Luck & Vogel, 1997). Some modern theories have renewed the emphasis on decay, to explain why there are effects of the amount of free time on the ability to refresh item representations with attention (e.g., Barrouillet et al., 2011; Camos & Barrouillet, 2018), though decay's existence in these specific situations is contested (Oberauer & Lewandowsky, 2008).

In sum, an explosion of adult research has been taking place for some time and is ongoing, using behavioral and neuroscientific methods to understand the structure and mechanisms of working memory. As yet, little theoretical agreement has been reached, although the models are becoming more similar in some ways to accommodate new evidence. Much is still unknown regarding when decay occurs, how interference operates, and what limits working memory capacity.

Influence of Cognitivism and Constructivism in Research on Working Memory Development—Logically, the broadest response to both the empiricist and nativist positions is that both are important, an intermediate position. Even the staunchest empiricists acknowledge that an inherited nervous system is needed for behavior, and even the staunchest nativists realize that environmental input to the individual is needed for normal cognition to develop. Further, although it is logically possible for environmental and inherited properties to contribute independently to behavior, they often interact. Statistically, that means that the amount and direction of influence of the environment for a particular behavioral scale depends on the genetic makeup. A key example is that some children seem genetically sensitive, such that the exact environment makes a big difference in their psychological outcomes, whereas other children seem genetically robust, such that they are much less sensitive to the same details of the environment. The situation has been likened to the distinction between what it takes for orchids versus dandelions to thrive (for a review see Belsky et al., 2007).

The manners of relevance of cognitivism versus constructivism to working memory development differ. The cognitivist influence suggests that limits on the capacity of working memory increase with age, at each age limiting the types of concepts that can be understood. The constructivist influence, though, suggests that working memory is a cauldron for putting together concepts and symbols to construct new representations, and that a working memory limit prevents some concepts from being created pending further development. For example, a tiger is essentially a big, striped cat and those three features have to be associated in working memory for the concept to be adequately grasped as distinct from other categories. Forget to include the large size, and one can confuse a tiger with a striped house cat; forget the stripes, and one can confuse the tiger with a lion; or forget the feline category, and can confuse the tiger with a zebra. The child must compare input to decide the limits and extensions of each category. Thus, working memory constraints could contribute to young children's under- and overgeneralizations of concepts (e.g., calling a horse a dog). Once certain concepts are understood, as well, it is possible for the child to imagine (construct) imaginary new combinations, such as a dog with stripes. Cognitivist and constructivist approaches can be seen in Piagetian theory, neo-Piagetian theories, and in the present author's long-standing program of research that will be reviewed.

Piagetian theory.: Piaget's (1952, 1977) theory is a basis of constructivism. Children's concepts are said to be self-constructed. His view was influenced by his early exposure to the endeavor of intelligence testing, when there was a strong emphasis on innate individual differences (e.g., Galton, 1865; Deary, 2012). Development would come basically from the unfolding of plans built into the individual. Piaget early in his career did intelligence testing under Alfred Binet, for the purpose of placing children correctly in the French schools (Biography Newsletter, 2021; Whitman, 1980). Part of the method of intelligence testing involved finding somewhat arbitrary questions about knowledge of daily life and scoring children's ability to answer them. However, Piaget found the testing method too rigid and asked children to explain their answers. He noticed that children's wrong answers were not random, but involved some age-related misconceptions, such as egocentrism, anthropomorphization, and magical use of associations. Their wrong answers made sense based on what they knew and the level of complexity at which they could figure things out. He developed the idea that there are stages of knowledge, which he also traced back to infancy with observations of his own baby, formulating the idea that children develop in stages of cognitive development including sensorimotor (~0–2 years), preoperational (~2–7 years), concrete operational (~7–12 years), and formal operational (>~12 years) stages, with a biological foundation but very important environmental input, and the increasing ability to make use and make sense of that input as processing matures; that is, to construct schemes and ideas to understand the world and act upon it. The developmental stages of thought are said to be limited by certain key concepts that cannot be grasped without sufficient maturation, such as the concept that an object remains when it is not in sight (object permanence), the concept of the constancy of mass (e.g., changing the shape of a ball of clay does not alter the amount of clay), and the concept that certain operations are reversible (e.g., the clay can be returned to its original shape).

Great examples of constructivist thinking can be observed in the online video, Piaget on Piaget (2021; see also Piattelli-Palmarini, 1980). For example, a young child trying to draw a triangle in plain sight draws a roundish shape and then adds lines where the corners should be; the drawing is taken to indicate that the child constructs a closed shape as a first pass and then tries to add the corners in a second pass. In child language, an example is a young child's use of a self-invented form that follows a general rule, like the past tense verb *goed*, even though the child used the correct exceptional form, *went*, at an earlier developmental stage (an overregularization, e.g., Marcus et al., 1992). A nativist system like that suggested by Chomsky (1965) has inborn rules of syntax among which the final rules are to be selected on the basis of language input. In a cognitivist and constructivist system, in contrast, the individual hears language and uses general problem-solving abilities to figure out what the rules are. The latter can explain why young children make word combinations that do not fit the adult grammar (e.g., *more up*) given that young children's conclusions regarding the rules of the system may not be sophisticated or informed enough to be completely adult-like (e.g., Braine, 1976; Braine et al., 1993). So far, this constructivist interpretation did not heavily include information processing components in a modern cognitivist way that explicitly referred to working memory, but that changed with the neo-Piagetians.

Neo-Piagetian approach.: The cognitivist, constructivist view is also interactionist, in that it fully considers both biology and knowledge. A particular kind of knowledge cannot be used well until the mental schemes are in place to absorb that knowledge (in an assimilation process). Moreover, if the child is in the necessary state of readiness, which depends largely upon maturation, then new information can trigger an advancement to the next stage (in an accommodation process). Given all this, one can slightly, but not greatly, hasten the advancement from stage to stage by enriching the stimulus environment.

The relevance to working memory of both cognitivism and constructivism can be seen in the work of neo-Piagetians. Their work tries to account for cognitive performance in each stage by considering the basic, largely innate and maturing information processing abilities of the individual. Pascual-Leone and colleagues (Pascual-Leone & Smith, 1969; Pascual-Leone, 1970; Pascual-Leone & Johnson, 2021) adopted this view, suggesting that a developmental increase in mental energy results in more items in working memory, which allows more complex cognitive concepts or schemes to be thought and executed. Although mental energy is a fluid construct, at certain points it has grown large enough to allow an additional scheme to be held in mind, resulting in a stage advance. Case et al. (1982) suggested that what accounts for the increased working memory ability is something called operational efficiency, which can be measured by word identification speeds; these speeds and working memory were linearly related across age groups. Moreover, making the stimuli nonwords for adults reduced identification speeds and memory spans for these materials, so they approximate what is found with more meaningful stimuli in younger children. That is, processing efficiency is said to determine working memory capacity, which in turn governs the complexity of concepts that an individual can understand or construct. In another neo-Piagetian approach, Halford and colleagues (Andrews et al., 2003; Halford et al., 1998, 2007) proposed that the key factor that differentiates one cognitive level from another is the number of items that can be inter-associated in working memory. For example, learning sums can require the association of as few as three items (e.g., $2+3=5$), whereas learning ratios requires four (e.g., $2/3 = 4/6$).

In the neo-Piagetian view, the levels of complexity of thought follow Piaget's prescription only under a circumscribed set of processing demands, which determine the load on working memory. If the demands are reduced, such as by using eye movements as a measure of surprised reactions instead of intentional, manual choices, one can see the rudiments of object permanence by 5 months (Baillargeon et al., 1985). Piaget seemingly thought that a stage was reached when the correct concept was expressed independent of the processing demands, but there may be no such point according to a neo-Piagetian viewpoint.

Illustrating the enormous role of processing demands, once as a teaching assistant in graduate school I slightly complexified a test of concrete operations and found that college students then failed it. Specifically, a well-known Piagetian finding in preoperational children is that they will state that a ball of clay rolled out into a sausage shape has more clay. I asked students to imagine that there were two identical balls of clay heavier than water, that one of them was rolled out into a sausage shape, and that the two pieces of clay were then totally immersed in identical beakers of water. Many students judged that the level of water would rise higher in the beaker containing the sausage-shaped clay, a preoperational answer for a problem with just one extra processing step (judging clay volume indirectly, by the rise in water volume). The misconceptions in this task seem working-memory-related and may resemble what happens in more abstract, real-world problems (for related published evidence see Çalýk et al., 2005). In an example provided by Goldinger (2003), participants were to judge the amount of fiscal liability of a baseball stadium after injury of a spectator, given extenuating factors that were not logically relevant to the decision (Goldinger et al., 2003). Irrelevant factors influenced the liability decisions when working memory was overloaded.

Cognitivist advances in my own recent research.: I have already described how my earlier work showed age differences in decay and capacity. For some years, though, I was unable to get further to determine what processes may help to account for the apparent structural changes. They could be simple maturational differences consistent with a nativist view of the change in working memory. According to a cognitivist, and constructionist, view of working memory development, however, what changes with development need not be the structures that retain and process information. Instead, the mnemonic strategies that are used to make the most use of the structures may change. Recent work leans more toward mnemonic processing differences underlying at least the apparent capacity growth. These processes include the formation and use of knowledge, the use of metacognitive ability, the control of attention in dual-task situations, and the off-loading of information to preserve attentional capability. These will be described in turn and are highlighted in Figure 1 (bottom).

Formation and use of knowledge.: Above, I summarized research showing that, with knowledge equated among age groups, developmental differences in working memory still could be observed (Cowan et al., 2015; Gilchrist et al., 2009). The cognitivist and constructivist view includes knowledge, but the use of it depends on the processes of assimilation and accommodation, which depend in turn on the child's level of cognitive maturation. Adult findings of the use of patterns and rules to simplify or compress stimulus sets, increasing the apparent capacity (e.g., Brady & Alvarez, 2015; Chekaf et al., 2016) fit into the cognitivist and constructivist views under the assumption that individuals will differ in what patterns and rules they can find, and the assumption that the ability to find patterns relies on a type of executive function that generally improves with age (Cowan et al., 2018).

Demetriou et al. (2014) proposed a relevant theory in which children 2 years and older go through developmental cycles. In the first part of each cycle, children learn to form representations of things in the environment. In a later phase of the cycle, they integrate the new representations into a wider system of knowledge. Cowan (2021a) was able to test predictions of this cognitivist theory in a large-scale sample of data on children 2–7 years old, who were tested to create norms for the Wechsler Preschool and Primary Scales of Intelligence (WPPSI-IV). This test included two new visual working memory measures, one of which involved recognition of pictures of common objects and would be helped by better representations. In the age range of 2;6 to 3;11 years, the results suggest that better representations did help: the proportion of working memory variance shared with knowledge-based tests (Information, Receptive Vocabulary, and Picture Naming) was R^2=.16 to .22. In the age range of 4;0 to 6;0 years old, however, better representations did not play a major role: the proportions of variance dropped to the range of R^2=.08 to .11. This shift was specific to tasks that depended on the use of knowledge. For tests that emphasized manipulations rather than knowledge-based representations, there was no comparable drop across the age groups in shared variance between working memory and the other tests. The pattern is in accord with Demetriou et al. and a neo-Piagetian, stage-like approach involving the combination of working memory and knowledge.

Use of metacognitive ability.: A key aspect of working memory performance according to the cognitive view is the use of problem-solving to figure out how to make the most of working memory retention abilities of the brain. Performance depends on deliberate strategies of the individual, which in turn depend on the individual's understanding of his or her cognition, or metacognitive knowledge. Forsberg et al. (2021) examined the metacognitive ability of elementary school children and adults in a working memory task (method Figure 2, Interim Task D; results, Figure 3D). On every trial, an array of colored spots was followed by a retention interval of several seconds and then a probe color to be judged present in the array or absent from it. On some trials, during the retention interval, the participant was queried regarding how many items they thought they retained in mind. Whereas actual performance levels increased throughout development to a level of about three items in adults, children from the early elementary school years incorrectly indicated that they thought they held an average of about three items. This pattern (along with the infant evidence discussed previously) suggests that perhaps, in some sense, working memory capacity remains fixed at about three items at all developmental stages. If so, however, there must be a developmental improvement in the representation of the task-relevant features of the objects (Cowan, 2017b). The younger children of Forsberg et al. may have retained three items in some sense, but perhaps some of the representations of these items did not actually contain the color features needed to respond appropriately to the probe. The idea of an object file (Kahneman et al., 1992) could be relevant because metacognition in children may detect object files that are not complete and may even be empty, perhaps except for a location feature. This is an interesting topic for continuing research.

Control of attention in dual-task situations.: The world is a lively place and working memory must navigate it. Encapsulating these aspects of the world, Cowan et al. (2021) reported on an experiment in which a visual memory load (an array of colors to be remembered for a later probe item recognition test) was followed by a retention interval that sometimes included a speeded task, pressing a button on the same side as a visual or acoustic signal or, in a more difficult situation, pressing a button on the opposite side (method, Figure 2, Interim Task C; Results, Figure 3C). The pattern of results across development during the elementary school years, and with college students, was clear. Younger children responded as if they often stopped trying to maintain the memory load when they had to carry out the speeded task. They showed a profound effect of the speeded task on the memory task compared to a memory-task-alone condition, but little or no effect of the memory task on the speeded task. In contrast, older children and adults did try to maintain the memory load and therefore demonstrated a mild impairment of performance on both tasks, compared to when only one task was required. The age differences are consistent with the notion of younger children operating with a reactive stance, as if they invest effort in each task only as it arrives, as compared to older participants operating with a proactive stance, as if they invest effort not only on the current speeded task, but also on the probe recognition phase of the trial that will follow. There is other, converging evidence for a developmental shift from reactive to proactive stances in the childhood development of working memory (Chevalier et al., 2015; Morey et al., 2018).

Off-loading of information to free up attention.: Sometimes, it is impossible to share attention well across two tasks but, according to a hypothesis of Cowan (2019) and Rhodes and Cowan (2018), another possibility is to off-load some information out of the focus of attention to be saved in activated long-term memory (with new learning about associations between items and their serial or spatial positions). Relevant to this process, Cowan et al. (2018) examined the development of the ability to combine visual information from spatial arrays and acoustic information from tone or digit series, with the two sets of stimuli presented in succession (method, Figure 2, Interim Task B; result, Figure 3B). On some trials, the task was to retain both sets in working memory whereas, on other trials, only one set was to be retained. The reduction in performance resulting from the requirement of retaining both sets was considered a central, attention-intensive part of capacity, whereas the portions of visual and acoustic memory that were not affected by the instructions were considered peripheral, feature-specific aspects of capacity based on activation of long-term memory elements. The capacity of feature-specific portions increased markedly with age from the early elementary school years through adulthood, whereas the central, attention-intensive portion did not increase. The implication is that, as participants mature, they do not hold more information in the focus of attention at once. Instead, they somehow learn to hold more information in a manner that does not stress the focus of attention. Cowan et al. proposed that the more mature participants do this by memorizing patterns that could be retained for the duration of the trial without very much use of attention. More research on the mechanism is warranted.

The cognitivist and constructivist approaches and working memory training.: One difference between my research program and many others is that, unlike many other laboratories, I have not addressed the question of whether aspects of working memory can be trained. This has been done by others to examine whether it is possible to improve indices of brain power, intelligence, aptitude, or scholastic performance (for reviews see Diamond &

Lee, 2011; Holmes & Gathercole, 2014; Melby-Lervåg & Hulme, 2013; Morrison & Chein, 2011; Sala & Gobet, 2017). This is essentially the same question of how much working memory adheres to the empiricist agenda, with experience altering processing abilities, or the nativist agenda, with experience having little or no effect.

The consensus from this research is that it is certainly possible to improve performance on a task but that, at least in typically developing children, that training will not much change performance across task components more than ordinary daily life would do. Any one kind of training does not display much in the way of “far transfer” to other task skills that were not directly trained. It may still be possible that some children with learning deficits do not get optimal training in daily life or educational settings and might benefit from working memory training. There also may be changes in brain physiology from training, which would suggest that the brain is not an indication of wholly genetic traits; we already know this from earlier studies of environmental enrichment in animals (e.g., Kempermann et al., 1997).

I think that the finding of little or no far transfer of working memory training effects has had a dampening effect on the field of working memory, as far as the public is concerned. People have thought, if working memory cannot usefully be trained, then why study it? Of course, one reason to study it is to assess what educational materials are best suited to children of a certain age or ability level (Cowan, 2014). Also, training of working memory even without far transfer can be important for meaningful tasks that involve working memory, such as mathematics. My educated guess at present is that working memory should be trained by making sure to include problems in a topic area such as math or science with sufficiently challenging (but not overly difficult) working memory demands resembling the demands encountered in important activities.

According to the cognitivist and constructivist views, the most important environmental input would be expected to be input making the individual think, reflect, or adapt better to the environment, and it may well be that working memory training is too repetitive and sterile to stimulate much intellectual growth. What might work better is training that does more to help guide participants in the effective construction of new mnemonic strategies, and to help increase the metamemory needed to know where improvement is most possible, so as to develop strategies usable given the child’s current abilities (cf. Demetriou & Spanoudis, 2018).

Summary and prognosis for the cognitivist and constructivist influences on working memory development.: It appears that the structures of working memory do not show tremendous, obvious specialization for different domains (e.g., see common functions across various tasks administered to children 4 to 15 years by Gathercole et al., 2004). They do not markedly change with development, at least during the elementary school years and possibly earlier. Thus, for example, infants and adults both show signs of a core working memory faculty that can retain only about 3 items, despite developmental change in performance using adult procedures (e.g., Cowan et al., 2005a; Simmering, 2016). What seems to improve most with development is the active construction of mnemonic strategies and knowledge to enrich working memory encoding and to handle and process information better (e.g., see Figure 3), changes that appear to underlie the increased ability to understand and construct concepts (Halford et al., 2007). Several suggestions for understanding the results and carrying out future research from a cognitivist standpoint will be suggested below.

Working memory and attention.: If there is a single biological development related to the various advancements of working memory, along with increasing knowledge, it is the way in which attention can be used to initiate and carry out mnemonic strategies. Many have pointed out the close relationship between attention and working memory in children (e.g., Alloway et al., 2009; Bertrand & Camos, 2015; Karatekin et al., 2007; Magimairaj & Montgomery, 2013; Rogers et al., 2011; Siegel & Ryan, 1989), even though attention does not account for everything that working memory scores do (for example, with a separate role of working memory in reading achievement shown by Slattery, et al., 2021). What was unclear previously was the degree to which the role of attention in working memory was one of storage or mnemonic processing. Several of the recent studies reviewed here suggest that a major aspect of development is the use of attention for mnemonic processing rather than storage. It is an improved use of executive control akin to what is found in other procedures examining the development of attention (e.g., for reviews see Ristic & Enns, 2015; Shore et al., 2006). In contrast, I have not seen strong evidence of developmental change in the more automatic aspects of working memory storage or in the number of items that can fit in the focus of attention at once, which is a revision of a hypothesis that I used previously to explain why it is attention-intensive aspects of working memory are the ones that change most with development (Cowan et al., 2005a). Thus, the central storage component of working memory exists but did not change magnitude with age, whereas the ability to use attention for better encoding and memorization of the materials apparently did (Cowan et al., 2018), as Figure 3b shows; and the ability to coordinate storage with a separate processing task showed children taking a more proactive stance with development, indicating improved ability to share attention between two tasks (Cowan et al., 2021), as Figure 3c shows.

Forsberg et al. (in press) recently examined the role of attention in working memory and long-term learning of pictures of common objects. The ratio between working memory capacity for objects in an array and the number of them later recognizable in a long-term memory test depended on whether the items were presented in sub- or super-capacity sets. Nevertheless, the ratios were very similar across the elementary school years and adulthood; younger children remembered fewer items in both tests but the working-memory to long-term-memory ratio did not change. As suggested by Cowan (2014), it appears that working memory underpins learning directly, so that the amount learned depended on maturation because working memory depended on maturation. However, the degree of learning depended on attention in that sub-capacity sets were better encoded into working memory and better learned in each age group.

Working memory and neo-Piagetian theory.: The opportunity to apply a neo-Piagetian approach to an understanding of the role of working memory in cognition is under-utilized. For example, theory-of-mind studies (e.g., Andrews, 2003) could be combined with measures of working memory for the underlying premises to determine the role of memory failure in performance. We now have a good idea that what changes with development is largely the ability to manage attention more efficiently, for example by applying knowledge and noticing patterns that can be used to help ease the load (Rhodes & Cowan, 2018). This kind of attention-based theory is consistent with Case et al. (1982) and work from a neo-Piagetian perspective (e.g., Pascual-Leone & Johnson, 2021). It remains to be determined just what biological maturation may occur to allow this improved management of attention. Clearly, the frontal lobes help in managing attention and are some of the latest portions of the brain to mature (Casey et al., 2000).

Understanding u-shaped developmental changes.: There are various cases in which u-shaped developmental grown is observed (e.g., Gershkoff-Stowe & Thelen, 2004), such as the apparent indication of more working memory capacity in infancy than in the early elementary school years (Cowan, 2016) or the change from the correct word form like *went* to an invented word form like *goed*. Fundamentally, though, the theoretical expectation is that increases in knowledge and ability are monotonic across infant and child development, not u-shaped. To demonstrate monotonic development despite u-shaped behavioral change, working memory and the child's conceptual level could be indexed through physiological measures (e.g., alpha suppression measures of attention to items: Wang et al., 2021) in a wide range of ages.

The specific uses of working memory in other cognitive tasks.: More research is needed to understand just what working memory is used for. Here is one example in which the findings about the use of working memory were clear, but counter to our expectations. Adams and Cowan (2021) went beyond the usual correlational approach, examining 4- and 5-year-old children's delayed imitation of passive-sentence descriptions of pictures ("speaking in a new way," they were told), sometimes while under a memory load. The results were counterintuitive, indicating that children ventured more passive sentences under load than not under load. In the process, they occasionally made some silly mistakes, such as saying *The girl was watered by the flower*. The results make sense with the notion that working memory was used to check the semantic accuracy of the repetition, with children often abandoning the assigned task of speaking in the new way for the sake of semantic accuracy. In contrast, under a working memory load, this reformulation of the idea to be sure of its semantic accuracy was not feasible, so what predominated was simply mimicking the presented sentence as well as possible, despite errors.

Summary.: In sum, there are various ways in which children's working memory improves with age, largely having to do with management of attention. The improvement of working memory triggers improved learning from the environment and the ability to handle more complex ideas. The findings underlying these statements provide invitations for further research, with many new avenues now open.

Working Memory Development and Dynamic Systems Theory

Work with dynamic systems theory has explained working memory development in terms in which basic changes in neural functioning, with environmental input, lead to the developmental growth of capacity (e.g., Perone et al., 2021; Simmering, 2016; Spencer, 2020; Thelen & Smith, 1994). The approach has relied heavily on computational models to show how very basic neural processes combined with knowledge can create developmental changes, for example in working memory capacity. The strength of the approach is to show neural interactions through computations with emergent consequences for the child's processing capabilities that might not be obvious from verbal arguments alone.

In principle, the dynamic systems approach seems friendly to cognitivism as it may be providing a different level of analysis to understand the interactions between heredity and environment more fully. It can serve as a check on behavioral investigations. In a related approach, Westermann et al. (2011) describe the new field of neuroconstructivism, saying (p. 723) that "Neuroconstructivism builds on the Piagetian view that development constitutes a progressive elaboration in the complexity of mental representations via experience—dependent processes. However, neuroconstructivism is also informed by recent theories of functional brain development, under the view that the character of cognition will be shaped by the physical system that implements it."

The basic difficulty in developmental study is that age is not an experimental manipulation; many processes improve with age at once and it is difficult to disentangle them, as I have been trying to do. Is metamemory is important in the efficient use of working memory? Do older participants remember more through their increased ability to encode patterns in the stimuli? I can investigate whether those processes occur, but the dynamic systems approach can provide input into whether there is an elegant way to conceive of the connection between them and working memory capacity development, or whether instead they seem unessential correlates of that capacity.

As Witherington and Margett (2011) discussed, there is a wide range of variability between possible dynamic systems approach, with some of them more consistent with a view that the main task is to absorb structure from the environment and other dynamic systems approaches more consistent with a view that the main task is to understand inherited maturational changes, or to coordinate both of these things.

Concluding Remarks: A Long Perspective

A lot has happened since the field of working memory development began. Nevertheless, there are many gems of the past that have not been fully integrated into the current-day outlook. Bolton (1892) reported on written digit spans of about 1,500 children between 8 and 15 years old, but without a clear theoretical rationale. Following that study of norms long ago, working memory research has been influenced by big theories. The important thing for us now is to be aware of the major influences and to use a disconfirming stance to allow room for the other influences. If one is examining working memory or its effects in infancy, one must allow for early learning along with neurobiology. If one is assessing what children know, or their tendency to follow directions, one must consider that failure can come from working memory or attention limitations in replying or trying to carry out directions (Holmes et al., 2014; Jaroslawska et al., 2016; Ristic & Enns, 2015; Shore et al., 2006). When we evaluate unexpectedly early skills in infancy, we need to ask whether neo-Piagetian ideas can explain the progression in infancy, with theories that preserve some aspects of Piaget's theory while revising the timeline and task-specific processing demands. We must ask children what they think they know to assess what strategies they will judge to be helpful. We should use cognitive level and processing limits mainly to tune the learning material to the children (Cowan, 2014), not to try to push the children to where they are not. If there is nothing as practical as a good theory, as is often said, still perhaps there is nothing as useful as several contrasting theories, which have pushed research on working memory development in different directions for the past half-century.

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References

Adams EJ, & Cowan N (2021). The girl was watered by the flower: Effects of working memory loads on syntactic production in young children. Journal of Cognition and Development, 22, 125–148. 10.1080/15248372.2020.1844710 [PubMed: 34584497]

Alloway TP, Gathercole SE, Kirkwood H, & Elliott J (2009). The cognitive and behavioral characteristics of children with low working memory. Child development, 80, 606–621. [PubMed: 19467014]

Andrews G, Halford GS, Bunch KM, Bowden D, & Jones T (2003). Theory of mind and relational complexity. Child Development, 74, 1476 – 1499. [PubMed: 14552409]

Atkinson RC, & Shiffrin RM (1968). Human memory: A proposed system and its control processes. In Spence KW & Spence JT (Eds.), The psychology of learning and motivation: Advances in research and theory (Vol. 2, pp. 89 195). New York: Academic Press.

Baddeley A (2000). The episodic buffer: a new component of working memory? Trends in Cognitive Sciences, 4, 417–423. DOI: 10.1016/S1364-6613(00)01538-2 [PubMed: 11058819]

Baddeley A (2001). The magic number and the episodic buffer. Behavioral and Brain Sciences, 24, 117–118.

Baddeley AD (1986). Working memory. Oxford Psychology Series #11. Oxford: Clarendon Press.

Baddeley AD, & Hitch G (1974). Working memory. In Bower GH (Ed.), The psychology of learning and motivation, Vol. 8. New York: Academic Press. (pp. 47–89)

Baddeley AD, & Scott D (1971). Short-term forgetting in the absence of proactive interference. Quarterly Journal of Experimental Psychology, 23, 275–283.

Baddeley AD, Hitch G, & Allen R (2021). A multicomponent model of working memory. In Logie RH, Camos V, and Cowan N (eds.), Working Memory: State of the Science, Oxford University Press. (pp. 10–43)

Baddeley AD, Thomson N, & Buchanan M (1975). Word length and the structure of short-term memory. Journal of Verbal Learning and Verbal Behavior, 14, 575–589.

Baillargeon R, Spelke E, & Wasserman S (1985). Object permanence in five-month-old infants. Cognition, 20, 191–208. [PubMed: 4064606]

Barrouillet P, Portrat S, & Camos V (2011). On the law relating processing to storage in working memory. Psychological Review, 118, 175–192. [PubMed: 21480738]

Bayliss DM, Jarrold C, Gunn DM, & Baddeley AD (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. Journal of Experimental Psychology: General, 132, 71–92. [PubMed: 12656298]

Belsky J, Bakermans-Kranenburg MJ, & van Ijzendoorn MH (2007). For better and for worse: Differential susceptibility to environmental influences. Current Directions in Psychological Science, 16, 300–304.

Bertrand R, & Camos V (2015). The role of attention in preschoolers' working memory. Cognitive Development, 33, 14–27.

Biography Newsletter, Downloaded from the worldwide web on 23 December, 2021. https://www.biography.com/scientist/jean-piaget

Bjork RA, & Whitten WB (1974). Recency-sensitive retrieval processes in long-term free recall. Cognitive Psychology, 6, 173–189.

Bolton TL (1892). The growth of memory in school children. American Journal of Psychology, 4, 362–380.

Brady TF, & Alvarez GA (2015). No evidence for a fixed object limit in working memory: Spatial ensemble representations inflate estimates of working memory capacity for complex objects. Journal Of Experimental Psychology: Learning, Memory, And Cognition, 41, 921–929.

Braine MD (1976). Children"s first word combinations. Monographs of the Society for Research in Child Development, 41, 104. 10.2307/1165959

Braine MDS, Brooks PJ, Cowan N, Samuels MC, & Tamis-LeMonda C (1993). The Development of categories at the semantics/syntax interface. Cognitive Development, 8, 465–494.

Broadbent DE (1958). Perception and communication. New York: Pergamon Press.

Broadbent DE (1975). The magic number seven after fifteen years. In Kennedy A & Wilkes A (eds.), Studies in long-term memory. Oxford, England: John Wiley & Sons. (pp. 3–18)

Brown J (1958). Some tests of the decay theory of immediate memory. Quarterly Journal of Experimental Psychology, 10, 12–21.

Bruner JS, Goodnow JJ, & Austin GA (1956). A study of thinking. John Wiley and Sons.

Buchsbaum BR, & D'Esposito M (2019). A sensorimotor view of verbal working memory. Cortex, 112, 134–148. [PubMed: 30639088]

Çalýk M, Ayas A, & Ebenezer JV (2005). A review of solution chemistry studies: Insights into students' conceptions. Journal of Science Education and Technology, 14, 29–50.

Camos V, & Barrouillet P (2011). Developmental change in working memory strategies: From passive maintenance to active refreshing. Developmental Psychology, 47, 898–904. Doi: 10.1037/a0023193 [PubMed: 21417518]

Camos V, & Barrouillet P (2018). Working memory in development. Routledge.

Case R, Kurland DM, & Goldberg J (1982). Operational efficiency and the growth of short-term memory span. Journal of Experimental Child Psychology, 33, 386–404.

Casey BJ, Giedd JN, & Thomas KM (2000). Structural and functional brain development and its relation to cognitive development. Biological Psychology, 54(1–3), 241–257. [PubMed: 11035225]

Chater N, & Brown GDA (1999). Scale-invariance as a unifying psychological principle. Cognition, 69, B17–B24. 10.1016/S0010-0277(98)00066-3 [PubMed: 10193053]

Chekaf M, Cowan N, & Mathy F (2016). Chunk formation in immediate memory and how it relates to data compression. Cognition, 155, 96–107 [PubMed: 27367593]

Cherry EC (1953). Some experiments on the recognition of speech, with one and with two ears. The Journal of the Acoustical Society of America, 25, 975–979. Doi: 10.1121/1.1907229

Chevalier N, Martis SB, Curran T, & Yuko Munakata. (2015). Metacognitive processes in executive control development: The case of reactive and proactive control. Journal of Cognitive Neuroscience, 27, 1125–1136. [PubMed: 25603026]

Cheie L, MacLeod C, Miclea M & Visu-Petra L (2017). When children forget to remember: Effects of reduced working memory availability on prospective memory performance. Memory & Cognition, 45, 651–663. 10.3758/s13421-016-0682-z [PubMed: 27987114]

Chomsky N (1957). Syntactic structures. The Hague: Mouton.

Chomsky N (1965). Aspects of the theory of syntax. MIT Press.

Conrad R (1964). Acoustic confusion in immediate memory. British Journal of Psychology, 55, 75–84.

Cowan N (1984). On short and long auditory stores. Psychological Bulletin, 96, 341–370. [PubMed: 6385047]

Cowan N (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. Psychological Bulletin, 104, 163–191. 10.1037/0033-2909.104.2.163 [PubMed: 3054993]

Cowan N (1995). Attention and memory: An integrated framework. Oxford Psychology Series, No. 26. New York: Oxford University Press. (Paperback edition: 1997)

Cowan N (1999). An embedded-processes model of working memory. In Miyake A & Shah P (eds.), Models of Working Memory: Mechanisms of active maintenance and executive control. Cambridge, U.K.: Cambridge University Press. (pp. 62–101)

Cowan N (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. Behavioral and Brain Sciences, 24, 87–185. DOI: 10.1017/S0140525X01003922

Cowan N (2010). Multiple concurrent thoughts: The meaning and developmental neuropsychology of working memory. Developmental Neuropsychology, 35, 447–474. [PubMed: 20721769]

Cowan N (2014). Working memory underpins cognitive development, learning, and education. Educational Psychology Review, 26, 197–223. DOI: 10.1007/s10648-013-9246-y.Cowan 2019 [PubMed: 25346585]

Cowan N (2015). George Miller's magical number of immediate memory in retrospect: Observations on the faltering progression of science. Psychological Review, 122, 536–41. [PubMed: 25751370]

Cowan N (2016). Working memory maturation: Can we get at the essence of cognitive growth? Perspectives on Psychological Science, 11, 239–264. DOI: 10.1177/1745691615621279 [PubMed: 26993277]

Cowan N (2017a). The many faces of working memory and short-term storage. Psychonomic Bulletin & Review, 24, 1158–1170. DOI: 10.3758/s13423-016-1191-6 [PubMed: 27896630]

Cowan N (2017b). Mental objects in working memory: Development of basic capacity or of cognitive completion? Advances in Child Development and Behavior, 52, 81–104. Doi: 10.1016/bs.acdb.2016.12.001 [PubMed: 28215289]

Cowan N (2019) Short-term memory based on activated long-term memory: A review in response to Norris (2017). Psychological Bulletin, 145, 822–847. DOI: 10.1037/bul0000199 [PubMed: 31328941]

Cowan N (2021a). Differentiation of two working memory tasks normed on a large U.S. sample of children 2 to 7 years old. Child Development, 92, 2268–2283. DOI: 10.1111/cdev.13562 [PubMed: 33783825]

Cowan N (2021b). Empiricism, Nativism, Cognitivism, and Working Memory Development: A 50-Year Research Assessment. Open Science Framework site, https://osf.io/xg6j3/.

Cowan N, AuBuchon AM, Gilchrist AL, Blume CL, Boone AP, and Saults JS (2021). Developmental change in the nature of attention allocation in a dual task. Developmental Psychology, 57, 33–46. Doi: 10.1037/dev0001134 [PubMed: 33271032]

Cowan N, AuBuchon AM, Gilchrist AL, Ricker TJ, & Saults JS (2011). Age differences in visual working memory capacity: Not based on encoding limitations. Developmental Science, 14, 1066–1074. Doi: 10.1111/j.1467-7687.2011.01060.x [PubMed: 21884322]

Cowan N, Blume CL, & Saults JS (2013). Attention to attributes and objects in working memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 39, 731–747. DOI: 10.1037/a0029687

Cowan N, Elliott EM, Saults JS, Morey CC, Mattox S, Hismjatullina A, & Conway ARA (2005a). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. Cognitive Psychology, 51, 42–100. Doi: 10.1016/j.cogpsych.2004.12.001 [PubMed: 16039935]

Cowan N, Elliott EM, Saults JS, Nugent LD, Bomb P, & Hismjatullina A (2006a). Rethinking speed theories of cognitive development: Increasing the rate of recall without affecting accuracy. Psychological Science, 17, 67–73. DOI: 10.1111/j.1467-9280.2005.01666.x [PubMed: 16371146]

Cowan N, Fristoe NM, Elliott EM, Brunner RP, & Saults JS (2006b). Scope of attention, control of attention, and intelligence in children and adults. Memory & Cognition, 34, 1754–1768. Doi: 10.3758/bf03195936 [PubMed: 17489300]

Cowan N, Hogan TP, Alt M, Green S, Cabbage KL, Brinkley S, & Gray S (2017). Short-term memory in childhood dyslexia: Deficient serial order in multiple modalities. Dyslexia, 23, 209–233. [PubMed: 28497530]

Cowan N, Johnson TD, & Saults JS (2005b). Capacity limits in list item recognition: Evidence from proactive interference. Memory, 13, 293–299. [PubMed: 15952261]

Cowan N, Li D, Moffitt A, Becker TM, Martin EA, Saults JS, & Christ SE (2011). A neural region of abstract working memory. Journal of Cognitive Neuroscience, 23, 2852–2863. DOI: 10.1162/jocn.2011.21625 [PubMed: 21261453]

Cowan N, Li Y, Glass B, & Saults JS (2018). Development of the ability to combine visual and acoustic information in working memory. Developmental Science, 21, e12635, 1–14. Doi: 10.1111/desc.12635. [PubMed: 29119661]

Cowan N, Morey CC, AuBuchon AM, Zwilling CE, & Gilchrist AL (2010). Seven-year-olds allocate attention like adults unless working memory is overloaded. Developmental Science, 13, 120–133. Doi: 10.1111/j.1467-7687.2009.00864.x. [PubMed: 20121868]

Cowan N, Nugent LD, Elliott EM, & Saults JS (2000). Persistence of memory for ignored lists of digits: Areas of developmental constancy and change. Journal of Experimental Child Psychology, 76, 151–172. [PubMed: 10788307]

Cowan N, Nugent LD, Elliott EM, Ponomarev I, & Saults JS (1999). The role of attention in the development of short-term memory: Age differences in the verbal span of apprehension. Child Development, 70, 1082–1097. DOI: 10.1111/1467-8624.00080 [PubMed: 10546336]

Cowan N, Ricker TJ, Clark KM, Hinrichs GA, & Glass BA (2015). Knowledge cannot explain the developmental growth of working memory capacity. Developmental Science, 18, 132–145. Doi: 10.1111/desc.12197 [PubMed: 24942111]

Cowan N, Saults JS, & Nugent LD (1997). The role of absolute and relative amounts of time in forgetting within immediate memory: The case of tone pitch comparisons. Psychonomic Bulletin & Review, 4, 393–397. http://www.psychonomic.org/psp/publications-resources.html

Cowan N, Suomi K, & Morse PA (1982). Echoic storage in infant perception. Child Development, 53, 984–990. [PubMed: 7128263]

Cowan N, Wood NL, Wood PK, Keller TA, Nugent LD, & Keller CV (1998). Two separate verbal processing rates contributing to short-term memory span. Journal of Experimental Psychology: General, 127, 141–160. DOI: 10.1037//0096-3445.127.2.141 [PubMed: 9622911]

Craik FI (2020). Remembering: An activity of mind and brain. Annual review of psychology, 71, 1–24. DOI: 10.1146/annurev-psych-010419-051027

Craik FIM, & Lockhart RS (1972). Levels of processing: A framework for memory research. Journal of Verbal Learning and Verbal Behavior, 11, 671–684. DOI: 10.1016/S0022-5371(72)80001-X

Crowder RG (1976). Principles of learning & memory. Hillsdale, NJ: Erlbaum.

Crowder RG (1982). The demise of short-term memory. Acta Psychologica, 50, 291–323. [PubMed: 7124433]

Deary IJ (2012). Intelligence. Annual Review of Psychology, 63, 453–482.

Demetriou A, & Spanoudis G (2018). Growing minds: A developmental theory of intelligence, brain, and education. Routledge. NY

Demetriou A, Spanoudis G, Shayer M, Van der Ven S, Brydges CR, Kroesbergen E, Podjarny G, & Swanson HL (2014). Relations between speed, working memory, and intelligence from preschool to adulthood: Structural equation modeling of 14 studies. Intelligence, 46, 107–121. 10.1016/j.intell.2014.05.013

Diamond A, & Lee K (2011). Interventions shown to aid executive function development in children 4 to 12 years old. Science, 333, 959–964. [PubMed: 21852486]

Efron R (1970a). The relationship between the duration of a stimulus and the duration of a perception. Neuropsychologia, 8, 37–55. [PubMed: 5522546]

Efron R (1970b). The minimum duration of a perception. Neuropsychologia, 8, 57–63. [PubMed: 5522547]

Efron R (1970c). Effects of stimulus duration on perceptual onset and offset latencies. Perception and Psychophysics, 8, 231–234.

Farah MJ, Wilson KD, Drain M, & Tanaka JN (1998). What is ""special"" about face perception? Psychological Review, 105, 482–498. Doi: 10.1037/0033-295x.105.3.482. [PubMed: 9697428]

Forsberg A, Blume C, and Cowan N (2021). The development of metacognitive accuracy in working memory across childhood. Developmental Psychology, 57, 1297–1317. DOI: 10.1037/dev0001213 [PubMed: 34591573] Forsberg A, Blume C, and Cowan N (in press). The development of metacognitive accuracy in working memory across childhood. Developmental Psychology.

Forsberg A, Guitard D, Adams EJ, Pattanakul D, & Cowan N (in press). Children's long-term retention is directly constrained by their working memory capacity limitations. Developmental Science. 10.1111/desc.13164Forsberg A, Guitard D, Adams EJ, Pattanakul D, & Cowan N (in preparation). Children's long-term retention is directly constrained by their working memory capacity limitations.

Friedman NP, Miyake A, Young SE, DeFries JC, Corley RP, & Hewitt JK (2008). Individual differences in executive functions are almost entirely genetic in origin. Journal of Experimental Psychology: General, 137, 201–225. [PubMed: 18473654]

Gaillard V, Barrouillet P, Jarrold C, & Camos V (2011). Developmental differences in working memory: Where do they come from? Journal of Experimental Child Psychology, 110, 469–479. 10.1016/j.jecp.2011.05.004 [PubMed: 21664622]

Galton F (1865) Hereditary talent and character. Macmillan's Magazine, 12, 157–166, 318–327

Gathercole SE, Pickering SJ, Ambridge B, & Wearing H (2004). The structure of working memory from 4 to 15 years of age. Developmental Psychology, 40, 177–190. Doi: 10.1037/0012-1649.40.2.17 [PubMed: 14979759]

Geary DC, Hoard MK, Byrd Craven J, & DeSoto MC (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. Journal of Experimental Child Psychology, 88, 121–151. [PubMed: 15157755]

Gershkoff-Stowe L, & Thelen E (2004). U-Shaped changes in behavior: A dynamic systems perspective. Journal of Cognition and Development, 5, 11–36. Doi:10.1207/s15327647jcd0501_2

Gibson EJ & Pick AD (2000). An ecological approach to perceptual learning and development. Oxford: Oxford University Press.

Gibson EJ (1969). Principles of perceptual learning and development. New York: Appleton-Century-Crofts.

Gilchrist AL, Cowan N, & Naveh-Benjamin M (2009). Investigating the childhood development of working memory using sentences: New evidence for the growth of chunk capacity. Journal of Experimental Child Psychology, 104, 252–265. Doi:10.1016/j.jecp.2009.05.006 [PubMed: 19539305]

Glenberg AM, & Swanson NC (1986). A temporal distinctiveness theory of recency and modality effects. Journal of Experimental Psychology: Learning, Memory, & Cognition, 12, 3–15.

Goldinger SD, Kleider HM, Azuma T, & Beike DR (2003). Blaming the victim under memory load. Psychological Science, 14, 81–85. [PubMed: 12564759]

Gossaries O, Yu Q, LaRocque JJ, Starrett MJ, Rose NS, Cowan N, & Postle BR (2018). Parietal-occipital interactions underlying control- and representation-related processes in working memory for nonspatial visual features. Journal of Neuroscience, 38, 4357–4366. [PubMed: 29636395]

Goulet LR (1968). Verbal learning in children: Implications for developmental research. Psychological Bulletin, 69, 359–376. 10.1037/h0025713 [PubMed: 4873056]

Gray S, Green S, Alt M, Hogan T, Kuo T, Brinkley S, & Cowan N (2017). The structure of working memory in young school-age children and its relation to intelligence. Journal of Memory and Language, 92, 183–201. DOI: 10.1016/j.jml.2016.06.004 [PubMed: 27990060]

Halford GS, Cowan N, & Andrews G (2007). Separating cognitive capacity from knowledge: A new hypothesis. Trends in Cognitive Sciences, 11, 236–242. Doi: 10.1016/j.tics.2007.04.001 [PubMed: 17475538]

Halford GS, Wilson WH, & Phillips S (1998). Processing capacity defined by relational complexity: Implications for comparative, developmental, and cognitive psychology. Behavioral and Brain Sciences, 21, 803–865.

Hanley JR, & Young AW (2019). ELD revisited: A second look at a neuropsychological impairment of working memory affecting retention of visuo-spatial material. Cortex, 112, 172–179. [PubMed: 30527927]

Hebb DO (1949). Organization of behavior. New York: Wiley.

Hitch GJ, Towse JN, & Hutton U (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. Journal of Experimental Psychology: General, 130, 184 198. [PubMed: 11409098]

Hollingworth A (2004). Constructing visual representations of natural scenes: The roles of short- and long-term visual memory. Journal of Experimental Psychology: Human Perception and Performance, 30, 519–537. 10.1037/0096-1523.30.3.519 [PubMed: 15161384]

Holmes J, & Gathercole SE (2014). Taking working memory training from the laboratory into schools. Educational Psychology, 34, 440–450. DOI: 10.1080/01443410.2013.797338 [PubMed: 26494933]

Holmes J, Hilton KA, Place M, Alloway TP, Elliott JG, & Gathercole SE (2014). Children with low working memory and children with ADHD: same or different? Frontiers in Human Neuroscience. 10.3389/fnhum.2014.00976

Hulme C, & Tordoff V (1989). Working memory development: The effects of speech rate, word length, and acoustic similarity on serial recall. Journal of Experimental Child Psychology, 47, 72–87. 10.1016/0022-0965(89)90063-5

James W (1890). The principles of psychology. NY: Henry Holt.

Jaroslawska AJ, Gathercole SE, Logie MR, & Holmes J (2016). Following instructions in a virtual school: Does working memory play a role? Memory & Cognition, 44, 580–589. [PubMed: 26680246]

Jiang Y, Olson IR, & Chun MM (2000). Organization of visual short-term memory. Journal of Experimental Psychology: Learning, Memory, And Cognition, 26, 683–702

Joanisse MF, & McClelland JL (2015). Connectionist perspectives on language learning, representation and processing. WIREs Cognitive Science. Doi: 10.1002/wcs.1340Jonassen DH (1991). Objectivism versus constructivism: Do we need a new philosophical paradigm? Educational Technology Research and Development, 39, 5–14

Kahneman D, Treisman A, & Gibbs BJ (1992). The reviewing of object files: Object-specific integration of information. Cognitive Psychology, 24, 175–219. [PubMed: 1582172]

Kail RV, Lervåg A, & Hulme C (2016). Longitudinal evidence linking processing speed to the development of reasoning. Developmental Science, 19, 1067–1074. [PubMed: 26537631]

Kail R, & Park YS (1994). Processing time, articulation time, and memory span. Journal of Experimental Child Psychology, 57, 281 291. 10.1006/jecp.1994.1013 [PubMed: 8169582]

Kallman HJ, & Massaro DW (1979). Similarity effects in backward recognition masking. Journal of Experimental Psychology: Human Perception and Performance, 5, 110–128. [PubMed: 528921]

Kane MJ, Hambrick DZ, Tuholski SW, Wilhelm O, Payne TW, & Engle RE (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. Journal of Experimental Psychology: General, 133, 189–217. [PubMed: 15149250]

Karatekin C, Marcus DJ, & Couperus JW (2007). Regulation of cognitive resources during sustained attention and working memory in 10-year-olds and adults. Psychophysiology, 44, 128–144. [PubMed: 17241149]

Kausler DH (1974). Psychology of verbal learning and memory. New York: Academic Press.

Keller TA, & Cowan N (1994). Developmental increase in the duration of memory for tone pitch. Developmental Psychology, 30, 855–863.

Kempermann G, Kuhn H & Gage F (1997). More hippocampal neurons in adult mice living in an enriched environment. Nature, 386, 493–495. 10.1038/386493a0 [PubMed: 9087407]

Keppel G (1964). Verbal learning in children. Psychological Bulletin, 61, 63–80. 10.1037/h0043153 [PubMed: 14104616]

Keppel G, & Underwood BJ (1962). Proactive inhibition in short-term retention of single items. Journal of Verbal Learning and Verbal Behavior, 1, 153–161.

Lemaire B, Pageot A, Plancher G, & Portrat S (2018). What is the time course of working memory attentional refreshing? Psychonomic Bulletin & Review, 25, 370–385. [PubMed: 28364345]

Li D, Christ SE, & Cowan N (2014). Domain-general and domain-specific functional networks in working memory. Neuroimage, 102, 646–656. [PubMed: 25178986]

Li Y, & Cowan N (2021). Attention effects in working memory that are asymmetric across sensory modalities. Memory & Cognition, 49, 1050–1065. 10.3758/s13421-021-01142-9 [PubMed: 33694052] Li Y, & Cowan N (in press). Attention effects in working memory that are asymmetric across sensory modalities. Memory & Cognition. 10.3758/s13421-021-01142-9

Logie RH (2019). Converging sources of evidence and theory integration in working memory: A commentary on Morey, Rhodes, and Cowan (2019). Cortex, 112, 162–171. 10.1016/j.cortex.2019.01.030 [PubMed: 30824117]

Luck SJ, & Vogel EK (1997). The capacity of visual working memory for features and conjunctions. Nature, 390, 279–281. DOI: 10.1038/36846 [PubMed: 9384378]

MacKay DG (2019). The earthquake that reshaped the intellectual landscape of memory, mind and brain: Case H.M. In MacPherson SE & Sala S. Della (eds.), Cases of Amnesia: Contributions to Understanding Memory and the Brain. Routledge. (pp. 16–39)

Magimairaj BM, & Montgomery JW (2013). Examining the relative contribution of memory updating, attention focus switching, and sustained attention to children's verbal working memory span. Child Development Research, Article ID 763808. 10.1155/2013/763808.

Majerus S (2019). Verbal working memory and the phonological buffer: The question of serial order. Cortex, 112, 122–133. [PubMed: 29887208]

Majerus S, Cowan N, Péters F, Van Calster L, Phillips C, & Schrouff J (2016). Cross-modal decoding of neural patterns associated with working memory: Evidence for attention-based accounts of working memory. Cerebral Cortex, 26, 166–179. DOI: 10.1093/cercor/bhu189 [PubMed: 25146374]

Marcus GF, Pinker S, Ullman M, Hollander M, Rosen TJ, Xu F, & Clahsen H (1992). Overregularization in language acquisition. Monographs of the society for research in child development, i–178.

Massaro DW (1975b). Backward recognition masking. Journal of the Acoustical Society of America, 58, 1059–1065.

McCrink K, & Wynn K (2004). Large-number addition and subtraction in infants. Psychological Science, 15, 776–781. [PubMed: 15482450]

McGeoch JA (1932). Forgetting and the law of disuse. Psychological Review, 39, 352–370.

Melby-Lervåg M, Hulme C. (2010). Serial and free recall in children can be improved by training: evidence for the importance of phonological and semantic representations in immediate memory tasks. Psychological Science, 21,1694–700. Doi: 10.1177/0956797610385355. [PubMed: 20921571]

Melby-Lervåg M, & Hulme C (2013). Is working memory training effective? A meta-analytic review. Developmental Psychology, 49, 270–291. [PubMed: 22612437]

Melton AW (1963). Implications of short-term memory for a general theory of memory. Journal of Verbal Learning and Verbal Behavior, 2, 1–21.

Miller GA (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63, 81–97. [PubMed: 13310704]

Miller GA (1989). George A. Miller. In Gardner Lindzey, ed., A history of psychology in autobiography, Vol. VIII. Stanford, CA: Stanford University Press. (pp. 391–418)

Miller GA, Galanter E, and Pribram KH (1960). Plans and the structure of behavior. New York: Holt, Rinehart and Winston, Inc.

Mishkin M, & Delacour J (1975). An analysis of short-term visual memory in the monkey. Journal of Experimental Psychology: Animal Behavior Processes. 1, 326–334. [PubMed: 811754]

Moray N (1959). Attention in dichotic listening: Affective cues and the influence of instructions. Quarterly Journal of Experimental Psychology, 11, 56–60. Doi: 10.1080/17470215908416289

Morey C (2018). The case against specialized visual-spatial short-term memory. Psychological Bulletin, 144, 849–883 [PubMed: 29792442]

Morey CC, Mareva S, Lelonkiewicz JR, & Chevalier N (2018). Gaze-based rehearsal in children under 7: a developmental investigation of eye movements during a serial spatial memory task. Developmental Science, 21, 1–8. DOI: 10.1111/desc.12559

Morey CC, Morey RD, van der Reijden M, & Holweg M (2013). Asymmetric cross-domain interference between two working memory tasks: Implications for models of working memory. Journal of Memory and Language, 69, 324–348.

Morey CC (2019). Working memory theory remains stuck: Reply to Hanley and Young. Cortex, 112, 180–181. , 10.1016/j.cortex.2019.01.019 [PubMed: 30803740]

Morey CC, Rhodes S, & Cowan N (2019). Sensory-motor integration and brain lesions: Progress toward explaining domain-specific phenomena within domain-general working memory. Cortex, 112, 149–161. [PubMed: 30612701]

Morey CC, Rhodes S, & Cowan N (2020). Co-existing, contradictory working memory models are ready for progressive refinement: Reply to Logie. Cortex, 123, 200–202. [PubMed: 31916991]

Morrison AB, & Chein JM (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. Psychonomic Bulletin & Review, 18, 46–60. Doi: 10.3758/s13423-010-0034-0. [PubMed: 21327348]

Morrongiello BA, & Trehub SE (1987). Age-related changes in auditory temporal perception. Journal of Experimental Psychology, 44, 413–426.

Murdock BB (1967). Recent developments in short-term memory. British Journal of Psychology, 58, 421–433. [PubMed: 4870154]

Nairne JS (2002). Remembering over the short-term: The case against the standard model. Annual Review of Psychology, 53, 53–81.

Newell A, & Simon HA (1956). The logic theory machine: A complex information processing system. Santa Monica, CA: Rand Corporation,

Nicolas S, Andrieu B, Croizet J-C, Sanitioso RB, & Burman JT (2013). Sick? Or slow? On the origins of intelligence as a psychological object. Intelligence, 41, 699–711. Doi:10.1016/j.intell.2013.08.006

Oberauer K, & Eichenberger S (2013). Visual working memory declines when more features must be remembered for each object. Memory & Cognition, 41, 1212–1227. E-publication ahead of print, doi 10.3758/s13421-013-0333-6 [PubMed: 23716004]

Oberauer K, & Lewandowsky S (2008). Forgetting in immediate serial recall: decay, temporal distinctiveness, or interference? Psychological Review, 115, 544–576. [PubMed: 18729591]

Olton DS, Collison C, & Werz MA (1977). Spatial memory and radial arm maze performance of rats. Learning and Motivation, 8, 289–314.

Onishi KH, & Baillargeon R (2005). Do 15-month-old infants understand false beliefs? Science, 308, 255–258 [PubMed: 15821091]

OxfordLanguages (2021a). Definition of empiricism downloaded from web site, 10 May, 2021. https://www.google.com/search?client=firefox-b-1-d&q=empiricism.

OxfordLanguages (2021b). Definition of nativism downloaded from wet site, 12 May, 2021. https://www.google.com/search?client=firefox-b-1-d&q=nativism.

Pascual-Leone JA (1970). Mathematical model for the transition rule in Piaget"s developmental stages. Acta Psychologica, 32, 301–345.

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

Pascual-Leone J, & Smith J (1969). The encoding and decoding of symbols by children: A new experimental paradigm and a neo-Piagetian model. Journal of Experimental Child Psychology, 8, 328–355. DOI: 10.1016/0022-0965(69)90107-6

Penney CG (1989). Modality effects and the structure of short-term verbal memory. Memory & Cognition, 17, 398–422. [PubMed: 2668697]

Perone S, Simmering VR, & Buss AT (2021, online ahead of print). A dynamical reconceptualization of executive-function development. Perspectives on Psychological Science, 1–11. DOI: 10.1177/1745691620966792

Peterson LR & Peterson MJ (1959). Short term retention of individual verbal items. Journal of Experimental Psychology, 58, 193–198. [PubMed: 14432252]

Phillips WA (1974). On the distinction between sensory storage and short-term visual memory. Perception & Psychophysics, 16, 283–290.

Piaget on Piaget (2021). Available on web site, https://www.youtube.com/watch?v=I1JWr4G8YLM

Piaget J (1952). The origins of intelligence in children. (Cook M, Trans.). W W Norton & Co. 10.1037/11494-000

Piaget J (1977). Gruber HE; Voneche JJ, eds. The essential Piaget. New York: Basic Books.

Piattelli-Palmarini M (1980). Piattelli-Palmarini M (1980). Language and learning: The debate between Jean Piaget and Noam Chomsky. London: Routledge and Kegan Paul.

Plomp R (1964). Rate of decay of auditory sensation. Journal of the Acoustical Society of America, 36, 277–282.

Poulin-Dubois D, Rakoczy H, Burnside K, Crivello C, Dörrenberg S, Edwards K et al. (2018). Do infants understand false beliefs? We don't know yet – A commentary on Baillargeon, Buttelmann and Southgate's commentary. Cognitive Development, 48, 302–315.

Postman L (1975). Verbal learning and memory. Annual Review of Psychology, 26, 291–335.

Regal DM (1981). Development of critical flicker frequency in human infants. Vision Research, 21, 549–555. 10.1016/0042-6989(81)90100-0. [PubMed: 7269331]

Reznick JS, Morrow JD, Goldman BD, & Snyder J (2004). The onset of working memory in infants. Infancy, 6, 145–154. 10.1207/s15327078in0601_7

Rhodes S, & Cowan N (2018). Attention in working memory: Attention is needed but it yearns to be free. Annals of the New York Academy of Science, 1424, 52–63. Doi: 10.1111/nyas.13652

Ricker TJ, & Hardman KO (2017). The nature of short-term consolidation in visual working memory. Journal of Experimental Psychology: General, 146, 1551–1573. 10.1037/xge0000346 [PubMed: 28703619]

Ricker TJ, & Cowan N (2014). Differences between presentation methods in working memory procedures: A matter of working memory consolidation. Journal of Experimental Psychology: Learning, Memory, and Cognition, 40, 417–428.

Ricker TJ, Nieuwenstein MR, Bayliss DM, & Barrouillet P (2018). Working memory consolidation: insights from studies on attention and working memory. Annals of the New York Academy of Sciences, 1424, 8–18. Doi: 10.1111/nyas.13633. [PubMed: 29635694]

Ricker TJ, Spiegel LR, & Cowan N (2014). Time-based loss in visual short-term memory is from trace decay, not temporal distinctiveness. Journal of Experimental Psychology: Learning, Memory, and Cognition, 40, 1510–1523.

Riggs KJ, Simpson A, & Potts T (2011). The development of visual short-term memory for multifeature items during middle childhood. Journal of Experimental Child Psychology, 108, 802–809. Doi: 10.1016/j.jecp.2010.11.006 [PubMed: 21257180]

Riggs KJ, McTaggart J, Simpson A, & Freeman RPJ (2006). Changes in the capacity of visual working memory in 5 to 10yearolds. Journal of Experimental Child Psychology, 95, 18–26. [PubMed: 16678845]

Ristic J, & Enns JT (2015). The changing face of attentional development. Current Directions in Psychological Science, 24, 24–31. DOI: 10.1177/0963721414551165

Rogers M, Hwang H, Toplak M, Weiss M, & Tannock R (2011). Inattention, working memory, and academic achievement in adolescents referred for attention deficit/hyperactivity disorder (ADHD). Child Neuropsychology, 17, 444–458. [PubMed: 21390917]

Ross-Sheehy S, Oakes LM, & Luck SJ (2003). The development of visual shortterm memory capacity in infants. Child Development, 74, 1807–1822. [PubMed: 14669897]

Rovee-Collier C, & Cuevas K (2008). The development of infant memory. In The development of memory in infancy and childhood (pp. 23–54). Psychology Press.

Saint-Aubin J, & Poirier M (2000). Immediate serial recall of words and nonwords: Tests of the retrieval-based hypothesis. Psychonomic Bulletin & Review 7, 332–340. 10.3758/BF03212990 [PubMed: 10909142]

Sala G, & Gobet F (2017). Working memory training in typically developing children: A meta-analysis of the available evidence. Developmental Psychology, 53, 671–685. 10.1037/dev0000265 [PubMed: 28165253]

Shallice T, & Papagno C (2019). Impairments of auditory-verbal short-term memory: Do selective deficits of the input phonological buffer exist? Cortex, 112, 102–121.

Shore DI, Burack JA, Miller D, Joseph S, & Enns JT (2006). The development of change detection. Developmental Science, 9, 490–497. [PubMed: 16911451]

Siegel LS, & Ryan EB (1989). The development of working memory in normally achieving and subtypes of learning disabled children. Child development, 60, 973–980. [PubMed: 2758890]

Simmering VR (2016). Working memory capacity in context: Modeling dynamic processes of behavior, memory, and development. Monographs of the Society for Research in Child Development (SRCD Monographs), 81, 7–24.

Slattery EJ, Ryan P, Fortune DG, & McAvinue LP (2021). Contributions of working memory and sustained attention to children's reading achievement: A commonality analysis approach. Cognitive Development, 58, 101028. 10.1016/j.cogdev.2021.101028

Sokolov EN (1963). Perception and the conditioned reflex. NY: Pergamon Press.

Spelke ES, & Kinzler KD (2009). Innateness, learning, and rationality. Child Development Perspectives, 3, 96–98. [PubMed: 19768132]

Spencer JP (2020, online ahead of print). The development of working memory. Current Directions in Psychological Science, 1–9. DOI: 10.1177/0963721420959835

Spencer JP, Blumberg MS, McMurray B, Robinson SR, Samuelson LK, & Tomblin JB (2009). Short arms and talking eggs: Why we should no longer abide the nativist–empiricist debate. Child Development Perspectives, 3, 79–87. [PubMed: 19784383]

Spencer JP, Perone S, & Buss AT (2011). Twenty years and going strong: A dynamic systems revolution in motor and cognitive development. Child Development Perspectives, 5, 260–266. doi: 10.1111/j.1750-8606.2011.00194.x [PubMed: 22125575]

Sperling G (1960). The information available in brief visual presentations. Psychological Monographs, 74 (Whole No. 498.)

Teaching and Learning Resources (2021). Definition of cognitivism downloaded from web site, 13 May, 2021. https://www.google.com/search?client=firefox-b-1-d&q=cognitivism

Thelen E, & Bates E (2003). Connectionism and dynamic systems: Are they really different? Developmental Science, 6, 378–391.

Thelen E, & Smith LB (1994). A dynamic systems approach to the development of cognition and action. MIT Press.

Thomason ME, Race E, Burrows B, Whitfield-Gabrieli S, Glover GH, & Gabrieli JDE (2009). Development of spatial and verbal working memory capacity in the human brain. Journal of Cognitive Neuroscience, 21, 316–332. 10.1162/jocn.2008.21028 [PubMed: 18510448]

Towse JN, Hitch GJ, Horton N, & Harvey K (2010). Synergies between processing and memory in children's reading span. Developmental Science, 13, 779–789. [PubMed: 20712744]

Trehub SE, Schneider BA, & Henderson JL (1995). Gap detection in infants, children, and adults. Journal of the Acoustical Society of America, 98, 2532–2541.

Treisman AM (1960). Contextual cues in selective listening. Quarterly Journal of Experimental Psychology, 12, 242 248.

Vergauwe E, Barrouillet P, & Camos V (2010). Do mental processes share a domain-general resource? Psychological Science, 21, 384–390 [PubMed: 20424075]

Wang S, Megla EE, & Woodman GF (2021). Stimulus-induced alpha suppression tracks the difficulty of attentional selection, not visual working memory storage. Journal of Cognitive Neuroscience, 33, 536–562. Doi: 10.1162/jocn_a_01637 [PubMed: 33054550]

Watson JB (1913). Psychology as the behaviorist views it. Psychological Review, 20, 158–177.

Westermann G, Thomas MSC, & Karmiloff-Smith A (2011). Neuroconstructivism. In Goswami U (Ed.), The Wiley-Blackwell handbook of childhood cognitive development (pp. 723–747). Wiley-Blackwell.

Whitman A (1980, Sep 17). Jean Piaget Dies in Geneva at 84. New York Times. Retrieved from archive.nytimes.com/www.nytimes.com/learning/general/onthisday/bday/0809.html

Wikipedia (2021). Nativism. Wikipedia site, https://en.wikipedia.org/wiki/Psychological_nativism.

Witherington DC, & Margett TE (2011). How conceptually unified is the dynamic systems approach to the study of psychological development? Child Development Perspectives, 5, 286–290. 10.1111/j.1750-8606.2011.00211.x

Zhang W, & Luck SJ (2008). Discrete fixed-resolution representations in visual working memory. Nature, 453, 23–35.

Zosh JM, & Feigenson L (2012). Memory load affects object individuation in 18-month-old infants. Journal of Experimental Child Psychology, 113, 322–336. [PubMed: 22932473]

Zosh JM, & Feigenson L (2015). Array heterogeneity prevents catastrophic forgetting in infants. Cognition, 136, 365–380. [PubMed: 25543889]

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Open science practices:

The previously unposted data from Cowan et al. (2015) and means for all results replotted in Figure 3 are posted at Cowan (2021b), https://osf.io/xg6j3/. Original data for the other studies regraphed in Figure 3 are posted with those studies.

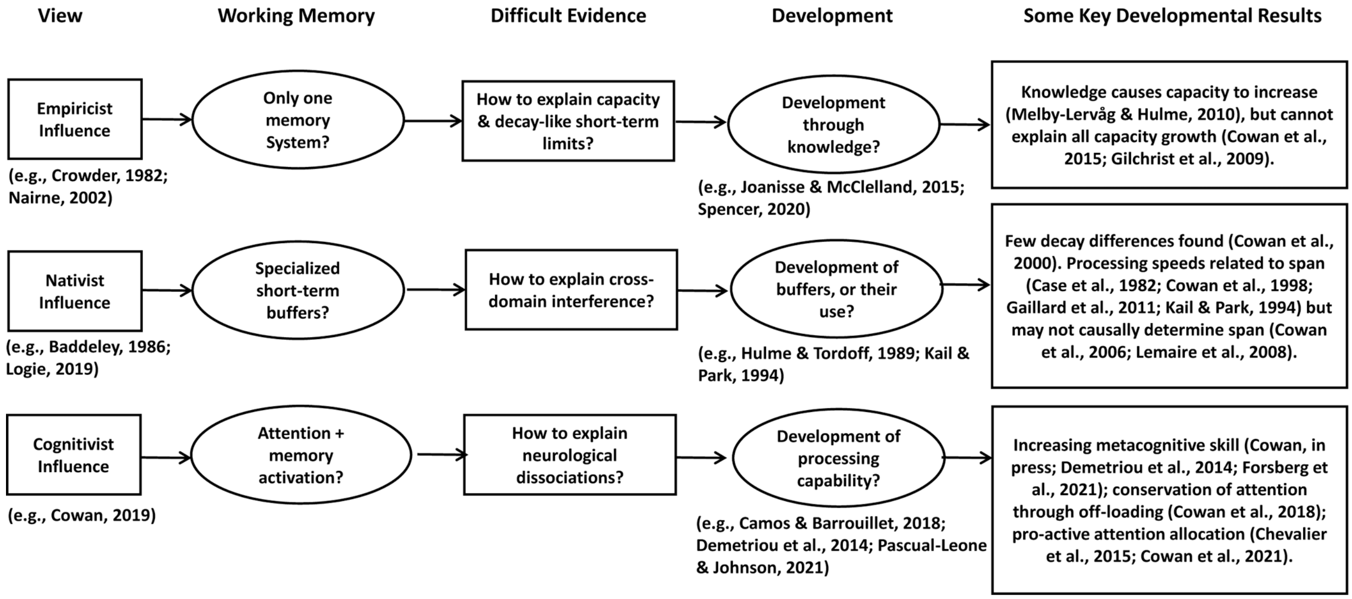

Figure 1.

A schematic illustration of the issues at stake and some key developmental evidence. The first column shows three theoretical views; the second column, implications of each view for the structure of working memory; the third column, evidence that presents a difficulty for each type of view; the fourth column, implications of each view for the nature of developmental change; and the fifth column, key evidence about that type of developmental change.

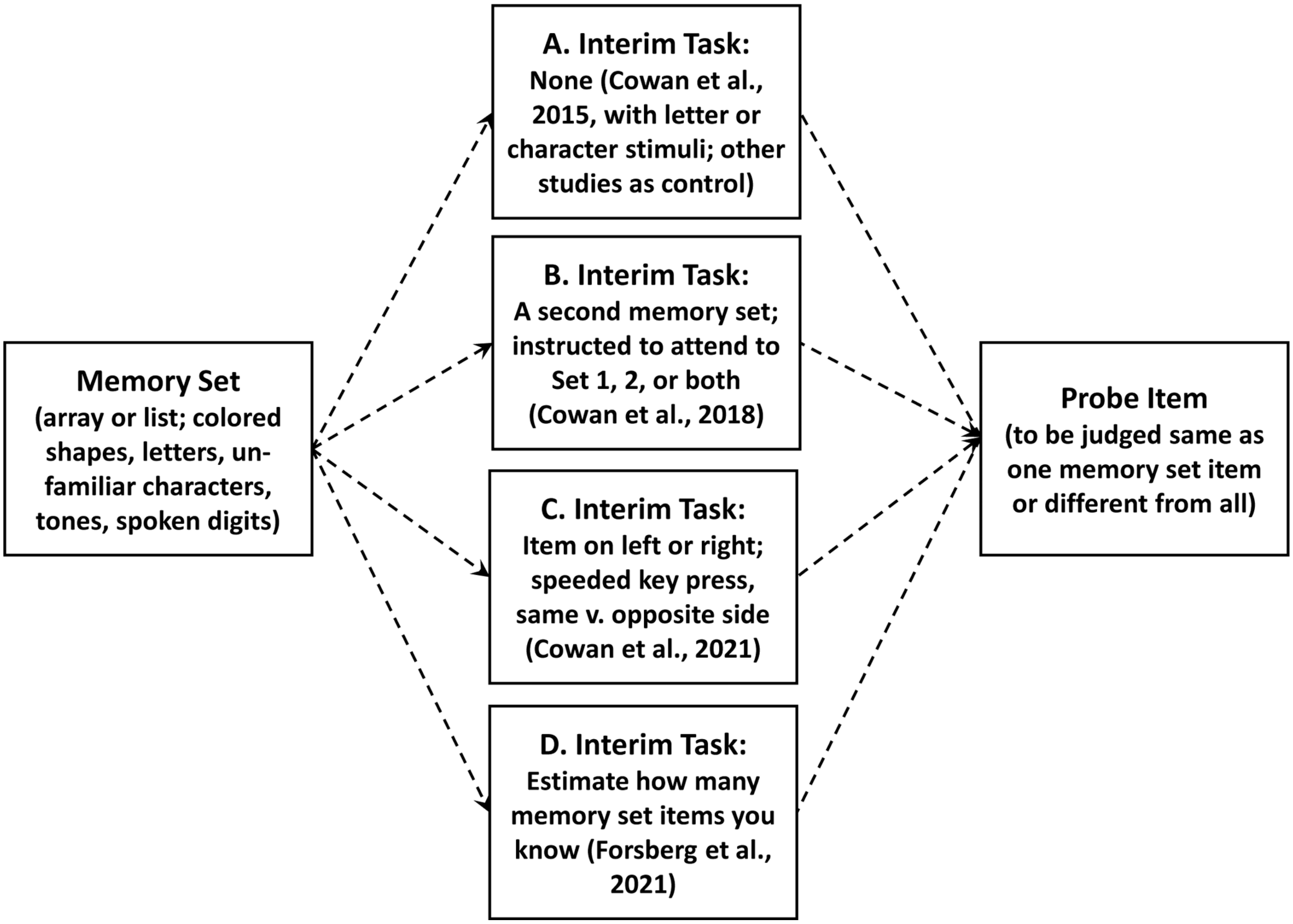

Figure 2.

A schematic diagram of the method in several studies indicating processing capabilities that develop in childhood. Studies differed in the types of materials presented in the set to be remembered (memory set) and the nature of the interim task (A-D) presented in the retention interval between the memory set and the probe item. The probe item was to be recognized as same as one memory item or different from all. In Cowan et al. (2018), the memory items were arrays of colored squares, lists of spoken digits, or lists of tones; in the later studies, arrays of colored squares.

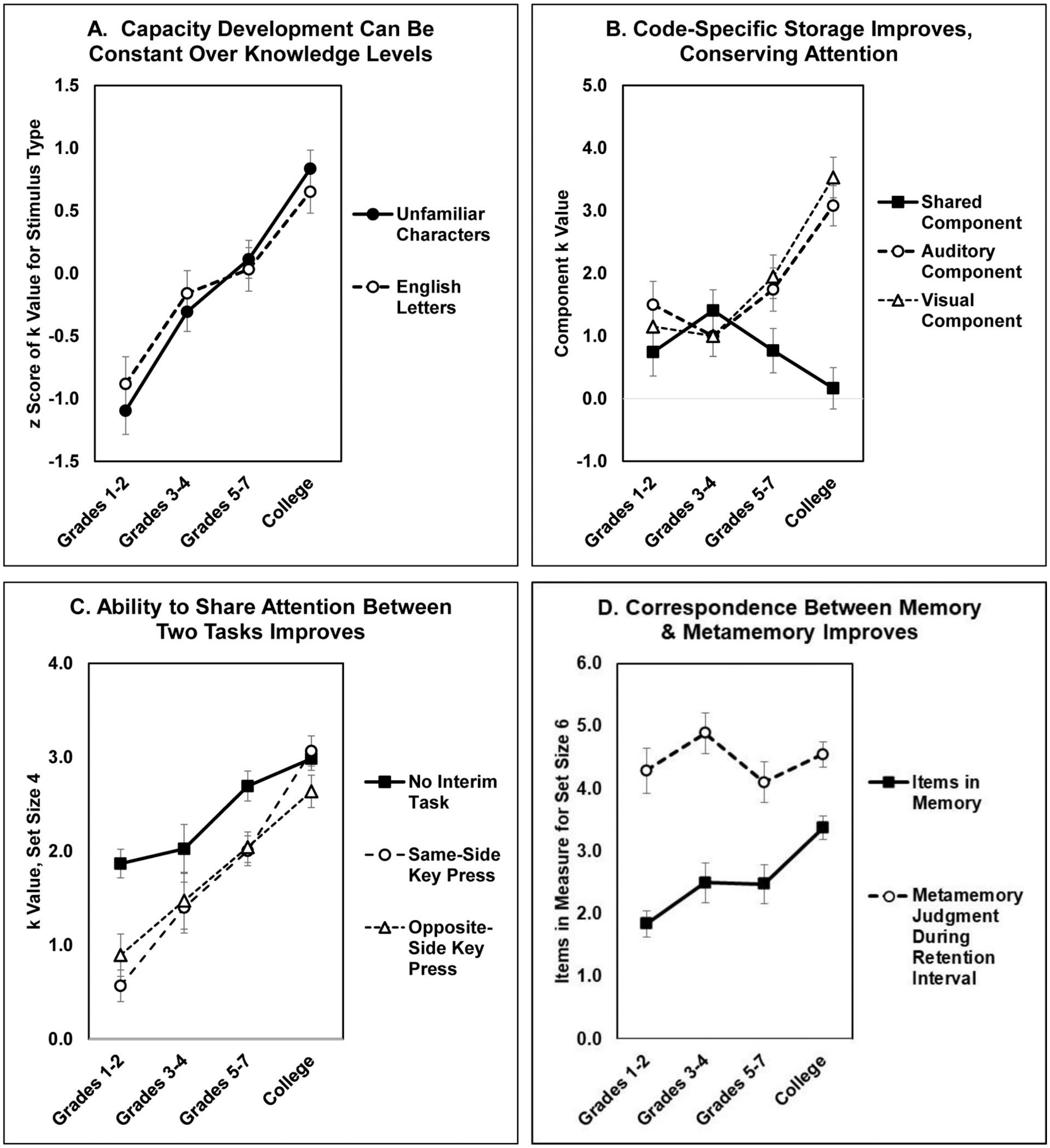

Figure 3.

Selected results of four studies corresponding to the different types of interim task (A-D) in Figure 2. **A**, replotted from Cowan et al., (2015); **B**, replotted from Cowan et al. (2018, Experiment 2); **C**, replotted from Cowan et al. (2021, Array Set Size 4); data posted with the article through the Open Science Framework link were used to regroup children to create age groups comparable to the other studies. **D**, replotted from Forsberg et al. (2021, Experiment 2, Array Set Size 6) using the “clean data” file posted at the Open Science

Framework site linked to the article. First grade corresponds to children 6–8 years old, with increasing age 1 grade per year. Error bars are ±1 standard error of the mean.

Table 1

Tenets of the Theoretical Views Under Consideration and Implications for Working Memory Development

Theoretical View	**Main Tenet of the Theoretical View**	**Potential Implications for Working Memory Development**
Scientific Empiricism	Observing behavior is the sole basis of psychological science.	It is convenient to start with the notion that behavior depends largely on the history of stimulation, not on internal neural differences between individuals.
Behaviorism	The measured relations between stimuli and responses are scientific; mental concepts are not discussed.	General principles of learning and memory can explain remembering in the short term. Developmental improvement of the ability to remember recent events could stem from the learning history of the child.
Nativism	The key factor determining behavior is the genetic factor.	Mechanisms of working memory are likely to arise from innate structures in the brain, with a built-in schedule of maturation.
Modularity	Individuals are endowed with separate mechanisms that have evolved to carry out different mental processes.	The development of working memory is likely to take place according to a relatively immutable developmental schedule. There would be interesting questions about the variability of maturation of these modules between individuals.
Cognitivism	Behavior and other sources of evidence can be combined to yield inferences about internal mental processes.	The most helpful understanding of working memory and its development should come from a description in terms of internal mental processes like activation, storage, attention, mnemonic rehearsal strategies, and the use of self-knowledge to adjust strategies.
Constructivism (of the cognitivist variety)	Ideas in the mind are not solely external to the person and then absorbed; they are largely constructed by the person as thought develops.	As a child matures, the development of ideas improves not only because of increasing knowledge, but also because an improved working memory capacity allows more complex ideas to be grasped and created from its component parts.
Dynamic Systems and Neuroconstructivism	Neural principles can be modeled to show how mental processes can emerge from neural activity, often in a self-organizing manner.	Working memory can develop because increasing knowledge allows neural processing of the input to retain more separate items; improvements in neural processing efficiency also contribute.