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Implicit Working Memory: Implications for Assessment and Treatment

Arthur W. Joyce

Private Practice, Clinical Neuropsychology, Irving, Texas

Working memory (WM) impacts a gamut of cognitive abilities, but implicit WM is typically not considered in assessment or treatment, which may explain the variability of results in reviews of WM training. The role of implicit WM in adaptive behavior is reviewed. All we do is action based. Explicit WM plays a major role when we are required to “think”; that is, when we apply previously learned perception-action linkages in new ways to unique situations. Implicit WM is involved in the automation of behavior, which occurs through interaction with cortical and subcortical systems that guide sensory-motor anticipation and the prediction of reward. This article reviews evidence that implicit WM interacts with cortical-cerebellar and cortical-basal ganglia connections to form perception-action linkages. The cerebellum forms an internal model of cortical WM, corrects the content of this internal model, and then projects the improved representation back to the cortex, where it is retained for future use. The basal ganglia also form an anticipatory system, controlling cortical access to WM by allowing or restricting the information that is released based on the probability of reward. This framework is applied to the assessment and treatment of individuals with WM deficits. The ability to automate behavior can be assessed through repeated trials of existing testing instruments, such as the Trails B and Stroop tasks. Application of skill learning emphasizing automation as an end goal offers a model for the development of new types of WM training.

Key words: basal ganglia, cerebellum, neuropsychological testing, working memory

Working memory is a component of the joint and orderly activation of posterior and anterior cortical networks in the perception–action cycle. (Fuster, 2015, p. 280)

A fundamental aspect of our view of declarative knowledge is that it derives from procedural knowledge encoded in internal models. (Pezzulo, 2011, p. 99)

Our motivation is to keep the field of neuropsychology moving forward. In order to move forward, information from the various neurosciences needs to be better integrated, and accommodating this information results in abandoning the prevailing cortico-centric model of cognition. (Koziol & Budding, 2009, p. 363–364).

Working memory (WM) impacts a wide variety of cognitive abilities, from planning and problem solving (Richardson, 1996) to academic skills, such as reading and mathematics (Pickering, 2006). WM is involved in multiple facets of cognition, so the groundswell of research that has arisen to look for ways to improve WM is not surprising. Early research examining computerized WM training of children identified transfer effects to other attention tasks (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002). However, later researchers were unable to replicate the effects (Holmes, Gathercole, & Dunning, 2010). WM training of people with schizophrenia reveals a similar pattern, with initial findings of successful transfer of effects (McGurk, Twamley, Sitzler, McHugo, & Mueser, 2007) but a subsequent well-constructed large-scale study found no transfer (Owen et al., 2010).

A PubMed search of the term “working memory training” conducted on August 15, 2015 resulted in 1,288 publications, including 376 publications since January 2014. Progress has been limited, with questions about efficacy and validity (Shipstead, Redick, & Engle, 2012). Despite the volume of research being conducted, the underlying mechanisms of WM training remain surprisingly unclear. WM training has been guided by a dominant theory, whereby WM is conceptualized as an explicit construct involving a phonological loop contained within areas of the left cerebral “language” hemisphere, a visuospatial sketchpad contained within the right cerebral hemisphere, and a central executive thought to reside in prefrontal cortices (Baddeley, 2003). This theory is consistent with a cortico-centric view of the brain. However, Baddeley’s view may not fully encompass how working memory “works.”

Accumulating evidence shows that WM involves ongoing and dynamic interactions between the cerebral cortex and subcortical structures, including the basal ganglia and cerebellum. The basal ganglia is a set of structures that controls access to WM (McNab & Klingberg, 2008), filtering and releasing the most relevant information to be processed by the cortex (Awh & Vogel, 2008). Increased activation of the basal ganglia and the cerebellum occurs with high load WM tasks (Luis et al., 2015). Cerebellar activation occurs during verbal and visuospatial n-back tasks (Thurling et al., 2012). As the n-back level of difficulty increases, an increase in cerebellar activation occurs (Küper et al., 2015), a finding that indicates cerebellar involvement in WM processing. Despite these and many other findings, neuropsychological texts maintain a cortical bias and a somewhat localized focus regarding WM, excluding subcortical contributions (see Kent, 2015, this issue).

The limited progress in WM training combined with a voluminous literature implicating subcortical structures in WM gives one pause. Perhaps there are additional ways to think about the construct of WM that, if consistent with known neuroanatomy and neural circuitry, might guide future research and treatment options. The aim of this manuscript is to offer fresh ideas about WM and to provide a general framework by which new questions could be investigated. Evidence of implicit WM is considered, followed by examining the role that subcortical structures play in WM processing. The novelty-routinization principle emphasizes the importance of anticipation in processing both novel (unexpected) and routine aspects of the environment (Goldberg & Costa, 1981; Koziol, 2014; MacNeilage, Rogers, & Vallortigara, 2009). This theory is applied to implicit WM. The integration of these ideas leads to a consideration of the role that WM plays in the formation of perception-action linkages. The paper concludes by

applying this framework to neuropsychological testing of WM and discussing the implications for WM training.

EVIDENCE OF IMPLICIT WORKING MEMORY

Despite flying “under the radar,” there are several lines of evidence which suggest that WM operates implicitly, doing its most important work beyond the realm of conscious awareness. Hassin and colleagues (Hassin, Bargh, Engell, & McCulloch, 2009) reviewed five studies which demonstrated that WM processes often operate outside of conscious awareness. Additionally, even children are able to apply the rules of language before the full development of the declarative, explicit memory system (Lavenex & Banta Lavenex, 2013). Four-year-old children retain and use rules of language, long before they can explicitly state those rules (Ullman, 2001). Furthermore, increased levels of activity in subcortical structures which are known underpinnings of implicit learning predict improvements in WM capacity 2 years later (Darki & Klingberg, 2015).

The attentional eye blink phenomenon occurs when two visual stimuli are presented in rapid succession and attentional resources are not available to detect the second visual stimulus presented in the same location within 500 milliseconds of the first stimulus (Shapiro, Raymond, & Arnell, 1994). Bergström and Eriksson (2014) used the attentional eye blink phenomenon to evaluate implicit WM, rendering previously perceived letters as non-conscious. Behavioral performance was better than chance up to 15 seconds, indicating that information outside the level of conscious awareness is maintained over several seconds. The researchers also used the blood-oxygen-level dependent (BOLD) signal to examine neural correlates during the nonconscious delay phase. Sustained BOLD signal change during maintenance of the nonconsciously perceived information activated the right lateral prefrontal cortex, the orbitofrontal cortex, and Crus II of the cerebellum (Bergström & Eriksson, 2014). This research demonstrates that non-conscious signals can be maintained for much longer time periods than had been noted and that frontal-cerebellar circuitry connections play a role in implicit WM processes. These findings are consistent with other data demonstrating Crus I and II regions of the lateral cerebellum are involved in regulation of the default mode network, which is primarily anchored within the cerebral cortex (Halko, Farzan, Eldaief, Schmahmann, & Pascual-Leone, 2014). Therefore, there is unequivocal, persuasive evidence for implicit WM. Cortical and subcortical structures must interact with implicit WM to form perception-action linkages. The nature of these interactions is explored in the following section.

THE CEREBELLUM AND WORKING MEMORY: SENSORY-MOTOR ANTICIPATION

The cerebellum and the cerebral cortex communicate with each other through a consistent pattern of extensive reciprocal connections (Schmahmann & Pandya, 1997). The cerebellum participates in both motor and non-motor functions (Ito, 2011). Extensive parietal and temporal connections provide the anatomic underpinning for a cerebellar influence on perception (Ramnani, 2012); reciprocal connections with motor and pre-motor frontal cortex support cerebellar involvement in motor planning and motor action (Middleton & Strick, 2000). Within neuroscientific disciplines, it is generally accepted knowledge that the cerebellum is involved in language, executive planning, learning, and memory. For in-depth reviews of these connections, see Schmahmann (1997) and Schmahmann and Pandya (1997). For in-depth reviews of functional involvement, see the 2014 consensus paper on the role of the cerebellum in cognition (Koziol et al., 2014). This manuscript focuses only upon “how” the cerebellum participates in WM.

Cerebellar activation has been established during explicit WM tasks. In the n-back task frequently used to evaluate WM, cerebellar activity increases as the difficulty of the task increases from 1-back to 2-back (Küper et al., 2015). Similarly, cerebellar activation occurs during explicit verbal WM tasks of increasing levels of difficulty. For example, multiple regions of the cerebellum are recruited during verbal working memory high load conditions but not low load conditions (Desmond, Gabrieli, Wagner, Ginier, & Glover, 1997). What might be the nature of cerebellar involvement in implicit working memory?

The operations of the cerebellum occur outside of conscious awareness (Ito, 2005). As cited by Ito, electrical stimulation of the cerebellum does not evoke conscious experience (Koch et al., 2007), whereas electrical stimulation to the cerebral cortex does generate the sense of conscious experience (Penfield & Perot, 1963). Furthermore, the cerebellum can initiate goal-directed, purposeful activity, implicitly, outside of conscious awareness (Thach, 2014).

The cerebellum is an anticipatory control mechanism. Ito (2008, 2011) and others (Higuchi, Imamizu, & Kawato, 2007; Imamizu & Kawato, 2012) characterize this mechanism as a generator of “internal models”. These models allow the cerebellum to function as a self-correcting learning machine. For example, the reciprocal connections between the cerebellum and the cerebral cortex allow the cerebellum to generate a copy of the WM content which is maintained within the cortex. This “copy” is an “internal model,” which includes all the sensory and motor information necessary to perform the behavior—literally, the cortical WM content.

Therefore, the internal model “knows” what the cortex wants to do, and it contains every element necessary to execute the intended behavior. All of the sensory feedback and motor output necessary to eventually execute an efficient, accurate, rapid and “new” behavior at first consumes considerable time and precious energy. The brain needs a way to function in “real time.” Nature’s answer to this problem is the cerebral-cerebellar circuitry system.

By making an internal model of the contents of WM, slowly operating cortical feedback systems are bypassed. The internal model of the cerebellum is focused on anticipatory control; based upon its copy of cortical content, the cerebellum predicts behavioral, or sensory-motor outcomes. With repeated execution of the behavior, the cerebellum continually refines the behavior, so that the behavior becomes efficient, effortless, automatic—and implicit—outside of conscious guidance and control. Error corrections occur rapidly, with minimal reliance on incoming sensory data (Shadmehr, Smith, & Krakauer, 2010). The cerebellum “corrects” the contents of its own internal model each time the action is executed. This results in an increasingly efficient representation of the behavior; this efficient behavior is projected back to the premotor cortex, allowing the pre-motor cortex to retain what the cerebellum learned (Galea, Vazquez, Pasricha, de Xivry, & Celnik, 2011). When a new but similar situation is encountered, the cerebellum copies the “revised” cortical WM content and modifies its own previously established “model.” As a result, the cerebellum is able to adapt learned behavior across similar settings/situations; the automatic behavior is adjusted, but it never has to be re-learned again.

This brain mechanism “replaces long and unavoidable feedback delays” (Ito, 2011, p. 169). The internal model allows for dynamic, moment-to-moment responding to changing environmental demands. The behavior becomes independent from initial cortical WM content. This results in gradual improvements in various abilities, through practice and repetition. The cerebellum performs the same operation upon all input it receives; so emotional input and output is automated and adjusted to meet situational demands; the same operation is performed for thought and language. Thinking and verbal expression is rapid and usually effortless. In fact, we can think and express ourselves so quickly that implicit thought expression interacts with new explicit situational input to rapidly adjust to changing circumstances. Consider the implicit adjustments that are required for successful interactions at a lively social gathering. Multiple implicit communication adjustments occur in response to rapid changes in topic. Subtle adjustments in verbal and non-verbal interactions are required based upon one’s relationships with various people encountered at

the gathering. This dynamic ability to respond in the moment to changing demands is at the heart of implicit/explicit perception-action linkages (Christensen et al., 2014; Mendez, Perez, Prado, & Merchant, 2014).

THE BASAL GANGLIA AND WORKING MEMORY: RELEASE OF BEHAVIOR IN ANTICIPATION OF REWARD

Optimal adaptation involves learning what to do and what not to do within the environment. Cortical-basal ganglia circuitry releases dopaminergic reward signals through multiple pathways impacting motor, cognitive, and emotional functioning. Tonic and phasic dopamine changes influence WM maintenance and updating (Awh & Vogel, 2008; Frank, Santamaria, O'Reilly, & Willcutt, 2007; Paladini & Roeper, 2014). The critical involvement of cortical-basal ganglia circuitry in WM updating is also demonstrated in positron emission tomography (PET) scan studies (Frank, 2005). Similarly, Chang and colleagues (Chang, Crottaz-Herbette, & Menon, 2007) mapped the temporal dynamics of various regions of the basal ganglia during the performance of a verbal WM task, finding that the anterior region of the caudate signals distinct functional networks during different phases of the WM task.

The basal ganglia are involved in sequencing tasks associated with WM. The head of the caudate updates the cortex regarding each next step in a sequence. Consider the Trails B, a test involving connecting alternating sequences of numbers and letters on paper. The Trails B requires several cognitive and motor skills to be held in mind and applied concurrently. These skills include updating of number-letter sequences, holding a sequencing rule in mind (e.g., next letter, next number, etc.); and applying automated motor skills associated with tool use (pencil). The basal ganglia gating mechanism releases the appropriate set of cognitive sequences and motor skills at just the right time to complete the Trails B task (Koziol & Budding, 2009).

The amount of activity in a basal ganglia structure that receives cortical projections predicts future WM ability. Darki and Klingberg (2015) conducted a longitudinal study of 89 individuals aged 6–25 years who received functional magnetic resonance imaging (fMRI) scans at 2-year intervals during performance of a visual-spatial WM task. Frontal-parietal network connections were related to current WM capacity, while activity in the caudate of the basal ganglia predicted future improvements in WM capacity. The head of the caudate receives projections from prefrontal and orbitofrontal regions of the cortex, while the caudate tail receives projections from temporal and parietal regions. The central role of the caudate in receiving projections from frontal

and parietal regions involved in WM implicate this structure, and the neural circuitry with which it is associated, in all aspects of WM gating and release (Hazy, Frank, & O'Reilly, 2006). The cerebellum, basal ganglia, and cerebral cortex have reciprocal loops of communication that influence the brain's ability to adapt through anticipatory control (Bostan & Strick, 2010; Koziol, 2014). WM interacts with cortical-cerebellar anticipatory perceptual motor control through the cerebellar circuits that copy the contents of cortical WM in order to correct errors. WM interacts with cortical-basal ganglia anticipatory reward processes through the basal ganglia's release of WM contents based on the greatest likelihood of reward. The way that implicit WM interacts with these anticipatory systems to form perception-action linkages is best understood through application of the novelty-routinization principle of brain functioning.

NOVELTY AND ROUTINIZATION: AN ORGANIZING PRINCIPLE OF BRAIN FUNCTIONING

The traditional understanding of brain functioning is an information processing theory. This model is perceive-decide-act, with divisions between perceptual, cognitive, and motor aspects of brain functioning. The information processing theory posits that the brain turns sensory data into perceptual information that is used to build knowledge, make decisions, and take action (Atkinson & Shiffrin, 1971). However, as outlined by Cisek and Kalaska (2010), collected data contradicts the information processing theory in multiple areas. The authors review many examples of these contradictions. For example, the associative functions of the posterior parietal cortex (PPC), according to the information processing theory, should only be involved in perception. However, PPC cells activate in response to cognitive and motor signals, as well as perceptual. The PPC also constructs "salience networks" and represents action intentions, functions that are the traditional domain of cognition (Cisek & Kalaska, 2010). These findings are difficult to reconcile with the rigid divisions between perceptual, cognitive and motor signals associated with information processing theory.

Brains evolved to control sensory-motor interaction through dynamic, moment-by-moment responses to a changing environment. The purpose of living organisms is to adapt and survive. This occurs through brain networks that respond selectively to familiarity and novelty within the environment (Bargh & Chartrand, 1999; Cisek & Kalaska, 2010). Behavioral flexibility is a key factor for successful adaptation, with optimal adaptation associated with rapid response to changes in the environment. Automatic behavior frees brain

resources to respond when unexpected environmental changes occur.

Principles of novelty and routinization apply to lateralization of brain function (hemispheric specialization). The left hemisphere is specialized for organization and maintenance of well-established behavior under ordinary circumstances and the right hemisphere is specialized for identification of novel, unfamiliar stimuli within the environment (Goldberg & Costa, 1981; Goldberg, Podell, & Lovell, 1994; Wang, Buckner, & Liu, 2014).

The PPC represents action intentions (Cisek & Kalaska, 2010). Spatial information specifies the parameters for action control. This means the dorsal stream provides pragmatic representation of the opportunity for action that objects afford, rather than accurate representations of the objects. The extensive reciprocal connections between the cerebellum and the PPC implicate the role of the cerebellum in anticipation (Schmahmann, 1997). The cerebellum sends feedback to the sensory systems about where to place attentional resources. In this respect, WM guides attention through cerebral-cerebellar circuitry (Ito, 2011).

The basal ganglia processes routine as well as novelty signals within the environment. A recent study examined the role of the caudate, a primary input structure of the basal ganglia, in finding objects of value and in manipulating those objects. Dopaminergic signaling is differentiated in these two processes. The rostral (head) and caudal (tail) of the caudate encode the reward value of visual objects. Flexibility and response to novelty in the environment is coded in the caudate head while stability and response to familiarity is coded in the caudate tail. While both parts of the caudate project to the superior colliculus and contribute to visual gaze, circuitry of the caudate head controls voluntary saccades while the caudate tail circuitry controls automatic saccades (Kim & Hikosaka, 2015). These findings lend strong support to the novelty-routinization principle of brain functioning. This system enables rapid identification of environmental changes that may necessitate quick and decisive action. A practical illustration may bring home the point.

Consider what happens when you are driving home through a familiar neighborhood. You may drive on “automatic pilot” and your car “knows the way home.” However, your right hemisphere novelty detection system rapidly detects a basketball rolling across the road, resulting in the basal ganglia issuing an emergency command to brake hard in anticipation of a child running into the road. You hit the brake long before you “think through” the problem. Your right hemisphere prefrontal and parietal cortex communicates with the basal ganglia, resulting in this rapid, possibly lifesaving behavior (MacNeilage et al., 2009).

INTERIM SUMMARY

Novelty-routinization is an organizing principle of brain functioning that can usefully be applied to better understand WM. This principle is consistent across 500 million years of phylogeny and involves brain structures present in all vertebrate animals. The large majority of our behavior occurs automatically, beneath the level of conscious awareness. “Thinking” occurs only when faced with a novel problem that has no obvious solution (Cisek & Kalaska, 2010; Koziol, Budding, & Chidekel, 2012). The novelty-routinization principle requires automation of learned behavior and anticipation of behavioral outcomes within the environment. These abilities are inherent in cortical-cerebellar and cortical-basal ganglia circuitry. WM “works” within these systems to form perception-action linkages, the topic of the next section.

WORKING MEMORY AND THE FORMATION OF PERCEPTION-ACTION LINKAGES

WM is involved in the formation of perception-action linkages, through the cerebellar copying of WM contents (Christensen et al., 2014) and the basal ganglia gating mechanisms that release the contents of WM for cortical processing (Leisman, Braun-Benjamin, & Melillo, 2014). The result is an adaptive system that can rapidly respond to changes within the environment while gradually forming knowledge of the world (e.g., learning what works and what does not). Adaptive associations requires anticipation of sensory-motor outcomes (Shadmehr et al., 2010) and identification and release of behaviors that have the highest probability of a rewarding outcome (Yu, FitzGerald, & Friston, 2013).

Behavioral choices are continuously made by all vertebrate animals on a moment-by-moment basis (Cisek & Kalaska, 2010). WM plays an important and remarkable role in the selection of behavior, holding and processing potential perception-action linkages, with choices occurring in an ongoing manner. When an organism can identify behavior with the greatest chance of success and act within the environment to access that behavior, the result is optimal adaptation. This process occurs early in development, allowing for the gradual build-up of an extensive “knowledge base” of successful perception-action linkages, which are stored within a distributed brain network for future access when needed (Amso & Davidow, 2012; Davidson, Amso, Anderson, & Diamond, 2006). The basal ganglia and cerebellum are active from early infancy. An fMRI analysis of healthy infants during natural sleep identified a resting state network that encompassed the bilateral basal ganglia (Fransson et al., 2009). Similarly, a recent study revealed a dramatic myelination growth of the pons (the primary

structure through which cortical projections enter the cerebellum) during early infancy (Tate et al., 2015).

Development progresses from reflexive behavior to perception-action linkages and is based on interaction with the environment (Johnson, Ok, & Luo, 2007; Konicarova & Bob, 2013a, 2013b; Leisman et al., 2014; Tau & Peterson, 2010). Early experiences of “behavioral success” expand and build throughout infancy, childhood, adolescence and into adulthood. Infants are born with reflexes that help them to survive. Initially, a reflex is an adaptive response to a stimulus with no WM to guide it. The reflex is quickly reinforced, meaning the cortical-basal ganglia system identifies something that “works.” For example, consider how the sucking reflex becomes linked with food reward through a basic pattern that repeats and builds upon itself. And what is the pattern?

1. The action (e.g., sucking), becomes associated with a high probability of obtaining food, through the dopaminergic cortical-basal ganglia system.
2. At the same time, the cortical-cerebellar system makes a copy of the contents of cortical WM associated with the suck reflex as experienced within the environment. This results in the formation of anticipatory sensory and motor cues (e.g., sight and feel of the nipple; formation of the mouth movement for sucking).
3. Implicit WM processes combine with cortical-subcortical systems to form a perception-action linkage, resulting in a strong and lasting association between the sensory-motor behavior of sucking and the high probability of obtaining food.
4. The perception-action linkage is applied when new situations are encountered, leading to the formation of new perception-action linkages, such as using the mouth to suck from a straw or to chew.

There are many real-life illustrations of how WM is involved in the formation of perception-action linkages. The formation of mouth movements to smile or the vocal intonations to coo lead to warmth (e.g., body contact) and pleasurable social interactions (e.g., being picked up, played with, attended to). These likely lead to basal ganglia recognition of anticipatory reward combined with cerebellar automation of sensory-motor aspects of these behaviors, resulting in the storage of perception-action linkages within cortical structures.

Consider the role of implicit WM in applying previously learned perception-action linkages to a new skill. When a toddler learns to tie her shoes, implicit

WM is required to hold a set of previously learned, fully automated skills to solve the new problem. For example, the pincer grasp is required to tie shoes. However, the pincer grasp was previously a completely novel task that required repeated practice to master. This practice involved a series of grasping movements and progressive approximations in preparation for mastery of the pincer grasp (Wallace & Whishaw, 2003). With practice and effort, the pincer grip becomes automated and effortless, a perception-action linkage called upon when faced with a new and unfamiliar task, like shoe tying. Certain cognitive concepts must also be automated prior to learning shoe tying, such as the spatial concepts of front and back. The child no longer has to “think” about these motor (pincer grasp) and spatial (front, back) skills, allowing her to focus effortful processing on learning the shoe tying skill. WM “holds” the previously learned perception-action linkages that are needed for mastery of the current novel task.

Explicit WM is also called upon as the child applies a “shoe tying rule” learned from her mother: “Cross the laces, one over the other.” This rule must be held in mind while attempting the task. WM is also involved in mastering a sequence of complex steps that must be held in during each attempt to practice the task. Sequencing involves the cortical-basal ganglia system (Hazy et al., 2006; Koziol & Budding, 2009; McNab & Klingberg, 2008). The ultimate goal is to fully automate the shoe tying skill. This occurs through practice and repetition, resulting in slow and gradual improvements in performance, a process that directly involves the cortical-cerebellar system. The cerebellum copies the contents of cortical WM, resulting in an internal model of shoe tying, and then gradually corrects errors, sending correction signals to the cortex, where the improvements are stored. As error correction results in continued improvements in performance, cerebellar activation decreases (Flament, Ellermann, Kim, Ugurbil, & Ebner, 1996). The learning process may involve mastery of multiple smaller steps in a hierarchical fashion, such as learning to cross the laces, learning to make the loop for tying, and so forth.

At each step, both explicit and implicit WM is involved. The explicit WM involvement may include a verbal rule held in mind, or a mental image of the modeled ability. The implicit WM involvement includes the application of previously learned perception-action linkages that are held in mind while working towards mastery of the entire task. At each step in the learning process, the basal ganglia release the necessary information into WM and inhibit unnecessary information. Anticipatory reward is also involved; the child previously earned praise from her mother when she successfully learned other skills, enabling the basal ganglia to predict future reward once the current shoe tying skill is mastered. Anticipatory reward may serve as a motivating

factor as the child struggles with such a difficult and challenging task.

All behaviors involve chains of perception-action linkages. The “links in the chain” must be held in mind as new perception-action linkages are formed. This is a potentially useful idea that can be applied in a variety of clinical and research settings to better understand and treat problems associated with WM. The chains of perception-action linkages involve holding previously learned associations (e.g., various combinations of perceptions, ideas, and actions) in mind as newly learned associations are formed, resulting in the gradual increase of behavioral repertoire. These perception-action linkages develop through repetition. New behavior must be attempted many times before the behavior becomes routine.

REDEFINING WORKING MEMORY: ASSESSMENT AND TREATMENT

The profession of neuropsychology needs to incorporate practice and theory based on what is known and understood about the neuroanatomical correlates of brain functioning. Current test paradigms need to be reconsidered and new test paradigms developed based on sound understanding of neuroanatomical circuitry and application of relevant principles of brain functioning. While questions remain, what is clear is that the old paradigm of perception-thought-action is incomplete. WM does not just “hold” an action possibility, await decisions by the prefrontal cortex, and then act. Instead, the brain is geared to anticipate the perceptual-motor actions that are most likely to lead to rewarding outcomes (Cockburn & Frank, 2011). Multiple potential action plans are made ready, right up to the point that a specific perceptual-motor action plan is released (Cisek & Kalaska, 2010). Within this model, there is no specific brain structure or area that houses or contains “working memory.” Instead, WM is continuously involved in multiple aspects of environmental adaptation, from the practice steps involved in dynamic learning of new behaviors, to the “holding in mind” several possible perceptual-motor actions when faced with unexpected novelty.

There is no commercially available test to measure implicit WM. Instead, the focus of neuropsychological test construction has remained on explicit and static aspects of WM. This state of affairs within the neuropsychological field is particularly unfortunate, given the compelling evidence that adaptive behavior is based on brain-wide functional hub connectivity patterns across practiced and novel tasks (Cole et al., 2013).

Nature has built into all animals the necessity of practice and repetition to automate behavior, from the foal shakily learning to stand to the human toddler learning

to communicate through speech. Many neurological and psychological disorders have in common a decreased ability to efficiently automate behaviors. The term “developmental delay” reflects delays in skill learning as compared to peers at similar age levels. Persons with developmental delays exhibit a decreased ability to benefit from practice and repetition, as evidenced by their limited ability to efficiently form new perception-action linkages as compared to same-aged peers.

Ironically, the discipline of neuropsychology consistently warns practitioners to be on the lookout for “practice effects” when administering the same test over recent time periods. This, we are cautioned, can impact validity of the results (Strauss et al., 2006). However, “practice” is a crucial part of skill learning, as outlined in this paper. Repeated practice results in improved performance. Dynamic interactions of implicit WM with cortical and subcortical structures leads to the formation of perception-action linkages. Therefore, using the concept of “practice” might be a good place to start as we consider ways to evaluate and treat implicit WM.

Koziol and Budding (2009) were the first practicing neuropsychologists to identify ways to incorporate the concept of “practice” by using traditional tests in new ways. For example, repeating the Trails B neuropsychological test up to five times was suggested by these authors. Because the effects of skill learning include increased speed and accuracy, deficits in implicit WM might be measured through analysis of change scores across trials, including time to completion and errors. Intact performance would be expected to include decreased time to task completion (indicating automation) and decreased errors (indicating error-correction).

Similar reasoning can be applied to tasks involving the ability to inhibit a prepotent stimulus, such as the Stroop task. When a lack of performance improvement is identified across trials (e.g., limited decrease in time to completion; continued mistakes across trials), a deficiency in implicit WM may be indicated. A related application, with more emphasis on accuracy than time, might involve repeated drawing trials of a complex figure. Increased accuracy would be expected at each successive trial, with limited change in scores reflecting an implicit WM deficit.

The Tower of London-DX (TOL; Culbertson & Zillmer, 1998) is a tower puzzle task that contains an “embedded” measure of implicit working memory. Test takers sometimes have difficulty during the initial two or three problems of the TOL, then “get” the task, resulting in improved performance across subsequent trials (as evidenced by decreased time to completion, improved accuracy, and lack of rule violation). The test takers have implicitly learned the underlying basis of the task, although they are often unable to verbalize what they learned. It would be useful to quantify change scores

across TOL-DX trials, which might provide evidence of intact implicit WM. In each of these examples, a novel task was introduced and, through repeated trials, the ability to benefit from practice was examined. All of the aforementioned tests evaluate aspects of implicit WM. There seems little reason alterations in these traditional neuropsychological measures could not occur.

Implicit WM functioning can also be disrupted by basal ganglia deficits associated with reward prediction. Deficits in the ability to predict reward have been observed in many conditions, including obsessive-compulsive disorder (Kaufmann et al., 2013); autism (Larson et al., 2011); cocaine addiction (Morie et al., 2014); cigarette smoking (Potts et al., 2014); attention-deficit/hyperactivity disorder (Frank et al., 2007; Koziol, Budding, & Chidekel, 2013); Parkinson's disease (Frank, Seeberger, & O'Reilly, 2004); and schizophrenia (Horan et al., 2012). Researchers have begun to consider ways to evaluate the integrity of reward pathways (Apkarian et al., 2004; Frank & Claus, 2006; Kano, Ito, & Fukudo, 2011).

Probabilistic category learning tasks, such as the Weather Paradigm (Knowlton, Squire, & Gluck, 1994) and its variants have been used in research settings to understand how various clinical populations identify reward and avoid risk, including populations with Parkinson's disease (Frank et al., 2004) and ADHD (Frank et al., 2007). However, the only commercially available test of reward processing available to date is the Iowa Gambling Task (Bechara, Damasio, Damasio, & Anderson, 1994). Rating scale data can also provide information about the integrity of frontal-basal ganglia systems. For example, the Frontal Systems Behavior Scale (Grace & Malloy, 2001) provides information about the three primary prefrontal circuits, including the dorsolateral prefrontal circuit, orbitofrontal circuit and anterior cingulate circuit.

Measures of adaptive functioning may provide the most accurate commercially available estimate of implicit WM impairment, as reflected by delays in skill learning. Problems with perception-action linkages can be inferred in a 5-year-old who cannot tie her shoes, or a 7-year-old who cannot ride a bicycle. Likewise, speech and language impairments reflect skill learning difficulties associated with delays in perception-action linkage formation. Academic learning disabilities typically involve deficits in the ability to automate and build upon behavior (Dehn, 2008). For example, consider the "scaffolding" that must occur when building math skills. Furthermore, WM deficits are found in children with math and reading difficulties (Alloway, 2007; Pickering, 2006).

New measures of implicit WM functioning should also be developed. Evaluation of the integrity of the ability to form perception-action linkages may provide important information about brain functioning and may lead to new treatment interventions to improve

the functioning of persons with a variety of neurological and psychological conditions.

WM training researchers have begun to consider contributing factors to WM performance that are associated with implicit WM. Tang and Posner (2014) argued that WM training involves repetitive practice that exercises and strengthens specific brain networks. Dunning and Holmes (2014) conducted open-ended interviews about strategy use after administering untrained WM tasks. The authors concluded that training related improvements might be mediated by implicit changes in strategy use.

Finally, other disciplines appear to have developed interventions that tap into implicit WM without necessarily having awareness of the brain science behind their success. Consider, for example, the sea of literature documenting strategy use with individuals that have learning disabilities. For example, the Self-Regulation Strategy Development (SRSD) process has been utilized to help students learn writing skills. The SRSD process involves teacher support of the steps necessary to automate skills related to writing, including the following steps (from Graham, Harris, & Mckeown, 2013):

1. Develop it: involves discussion and exploration of the writing strategies to be learned.
2. Discuss it: Initiate graphing as a self-monitoring mechanism. Act as collaborative partner.
3. Model it: Teacher modeling and collaborative modeling of writing and self-regulation strategies. Discuss use of skills in other settings to support generalization.
4. Memorize it: Require and confirm memorization of strategies and self-instructions.
5. Support it: Gradual increase of criterion levels until goals are met. Prompts, guidance and collaboration gradually reduced until student can compose alone.
6. Independent performance: Students use writing and self-regulation strategies independently and overt self-regulation strategies are faded (e.g., graphing discontinued).

The SRSD strategy contains several interventions that support implicit WM, including an emphasis on the importance of practice, external reminders which likely serve as external support for implicit WM during the learning of a complex task, and automation as an end goal. As reviewed by Graham et al. (2013), the SRSD strategy has shown impressive success in outcome studies of both learning disabled and general learners, typically showing a strong and positive effect on the quality of students' writing.

Automation of the skill of writing involves application of a number of previously learned perception-action

linkages, including word, sentence, and paragraph instruction, rules of spelling and grammar, sustained attention, and self-regulation skills. The SRSD strategy is interesting from a neuropsychological perspective because the intervention can be applied at remedial or advanced stages of learning, with no need for adjustment of the end-goal of automation. From this writer's perspective, the strategy is successful because it provides structured support for implicit WM processes, while allowing for the necessary practice (repetition) that leads to skill development. Considered from this perspective, this type of strategy could be successfully applied in a variety of settings, including populations with brain injury, ADHD, autism, schizophrenia, and dementia, to name only a few groups with notable working memory and skill learning deficits.

There is also a body of literature that involves similar application of supports and practice related to social skills training for persons with schizophrenia. The training includes breaking skills down into discrete steps; modeling; behavioral rehearsal (role-playing); social reinforcement; shaping (e.g., reinforcement of steps towards the eventual goal); and overlearning (e.g., practicing a skill until it becomes automatic; adapted from Bellack, 2004):

Similar to SRSD training, social skills training for schizophrenic populations has demonstrated efficacy. A 2012 meta-analysis found that training resulted in moderate to large effects on reduction of total symptoms and improvements in observer-rated community and institutional function (Kurtz & Richardson, 2012). The steps of social skills training are applicable to implicit WM training, including breaking down the overall skill, various aspects of skill practice (modeling; rehearsing; overlearning) and reward (social reinforcement; reinforcement for progress towards the goal).

Most interestingly, both the SRSD and social skills training interventions show remarkable parallels to the formation of perception-action linkages, as reviewed in this paper. Each of the interventions involved external supports put in place to assist in the gradual development of new skills, through practice and repetition. Perhaps these principles can be applied to increase the benefit of WM training.

What we are really talking about is a change in focus from a learning deficit to a "performance problem." How does a toddler develop cognitive control over speech musculature and its associations to sound? How does an infant learn how and when to bite? Or not bite? How does a 7-year-old learn appropriate social interactions? Treatments for these problems often fail, possibly because the problems are not learning failures but performance problems. If a performance deficit is present in any field, what is the best way to improve? By conceptualizing WM in terms of its role in

perception-action linkages, the role of practice comes to the forefront, coupled with emphasis on providing support and incentives designed to build up a reward system capable of learning what to do and when to do it. In this respect, WM represents the controlled activation of information (Hazy et al., 2006). To paraphrase an old saying, practice strengthens and rewards habit, and progress comes naturally.

SUMMARY

This manuscript reviewed elements of working memory conceptualization, evaluation, and training that are presently lacking in neuropsychological assessment. There is a dynamic interaction between cortical and subcortical structures in both explicit and implicit forms of WM. These circuitries can be understood through application of the novelty-routinization organizing principle of brain functioning. WM is involved in both the routine, automatic aspects of adaptation and when one is faced with unexpected situations that require new solutions and conscious problem solving. Through practice and repetition, unique behavioral adaptations are learned and become automated, at which point they are stored in the cortex and made available for future problem solving in new situations. In this way, adaptive functioning continues to occur throughout one's lifetime. Traditional neuropsychological assessment of WM has focused on explicit task analysis with limited generalization to real world settings. Extensive research efforts focused on WM training have met with variable results. However, the role of implicit WM has been virtually ignored in the psychological community.

Principles of novelty and routinization should be applied to the assessment and training of WM, beginning with the principle of automaticity through practice. The ability to automate behavior can be assessed through repeated presentation of existing neuropsychological instruments, such as Trails B, Stroop and drawings of complex figures. The expected finding on these tasks would be reductions in time and errors. Conversely, limited decreases in time across trials and continued errors would represent implicit WM deficits. Principles of skill learning have been utilized with success in educational settings (Graham et al., 2013) and in social skills training of individuals with severe mental illness (Kurtz & Richardson, 2012) and may provide a window through which new types of WM training could develop. The mechanisms that support WM are not sufficiently understood; perhaps other mechanisms are not yet identified. As a result, if a treatment technique fails, instead of blaming the technique, perhaps we need to pause and think in order to ask other questions.

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