Video Article

Assessing Working Memory in Children: The Comprehensive Assessment Battery for Children – Working Memory (CABC-WM)

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Abstract

The Comprehensive Assessment Battery for Children - Working Memory (CABC-WM) is a computer-based battery designed to assess different components of working memory in young school-age children. Working memory deficits have been identified in children with language-based learning disabilities, including dyslexia[1,2] and language impairment[3,4], but it is not clear whether these children exhibit deficits in subcomponents of working memory, such as visuospatial or phonological working memory. The CABC-WM is administered on a desktop computer with a touchscreen interface and was specifically developed to be engaging and motivating for children. Although the long-term goal of the CABC-WM is to provide individualized working memory profiles in children, the present study focuses on the initial success and utility of the CABC-WM for measuring central executive, visuospatial, phonological loop, and binding constructs in children with typical development. Immediate next steps are to administer the CABC-WM to children with specific language impairment, dyslexia, and comorbid specific language impairment and dyslexia.

Video Link

The video component of this article can be found at https://www.jove.com/video/55121/

Introduction

Working memory is the limited capacity system that enables an individual to mentally hold and manipulate incoming information while completing cognitive tasks[5,6]. Individual differences in working memory impact cognitive, scholastic, and professional performance in adults[7,8] and children[9,10]. Despite the connection between working memory and learning, few diagnostic tools are available to comprehensively assess working memory in children[11,12].

The Comprehensive Assessment Battery for Children - Working Memory (CABC-WM) was designed to assess working memory at its most elemental level, as envisioned by multiple prominent working memory models, including those proposed by Baddeley and colleagues[5,13,14] and Cowan and colleagues[15,16,17]. Baddeley[14] proposes four separate working memory components: a central executive/attention controller that focuses, switches, and divides attention and links long-term and working memory; a visuospatial sketchpad that holds visual and spatial information; a phonological loop that holds speech-based and other acoustic information; and an episodic buffer that forms an interface among working memory components and binds information from subsystems and long-term memory. On the other hand, Cowan posits that working memory may be part of a larger, more unitary construct primarily guided by the focus of attention, in addition to central executive and phonological storage and rehearsal subsystems[15,16,17]. The CABC-WM includes 13 working memory tasks that measure the central executive (or focus of attention), visuospatial, phonological, and binding subsystems of working memory. We aimed for three measures of each construct to support the use of latent variables. Several of the tasks included in the CABC-WM were modeled after tasks originally designed for adults, who typically have a higher tolerance than children for complex tasks. We adapted the tasks to make them motivating for children by presenting them in a pirate-themed computer game with visually-appealing graphics, virtual rewards, and a touch-screen interface. We also limited the number of tasks presented in a single research session and the number of trials in each task to decrease the likelihood of fatigue. Finally, to increase the reliability of the battery, tasks were designed to be easy to administer and score. All tasks included standardized instructions presented by the computer as part of each game. Most of the tasks have automated scoring that reduces the opportunity for human error during data processing. Details of the tasks can be found in **Table 1** and are described below.

Central Executive Tasks

N-back auditory, *N-back visual*, and *number updating* tasks assess central executive function. The *N-back* task is an updating task that presents a sequence of stimuli, after which subjects are asked to judge whether a stimulus is the same or different from the preceding stimulus. The *N-back auditory* task is presented in the context of a robot band playing different instruments with differing tones. Children listen to the tones in sequence. After each tone is heard the child decides whether the new tone is the same or different from the preceding tone and responds by pushing labeled same/different keys on the keyboard. Pilot data showed that a 1-back task was doable by elementary-age children. The *N-back Visual* task is presented in the context of robots playing a game with patterned game pieces. Each game piece is a black square with different patterns of white dots. Children see a series of individual game pieces. After each piece is shown, they decide whether the pattern is the same or different from the preceding piece and show their response by pushing labeled same/different keys on the keyboard. Again, pilot data showed that only a 1-back task was at the appropriate level for young children completing this battery. The *number updating* task assesses a child's ability to maintain information in working memory and to update it when additional information is provided. This task is presented in the context of a toy factory where the child's task is to keep track of the running total of yoyos and teddy bears manufactured. Initially, children are shown two digits to remember, one digit for the number of yoyos and the other for the number of teddy bears. The children are then shown an addition operation (*e.g.,* +1, +2, *etc.*) for one of the digits, which they use to update the digit total. Children are given five operations in sequence before the numbers are reset and they begin again.

Phonological Working Memory

'Phonological working memory' is responsible for mentally holding and manipulating acoustic and speech-based information. Phonological working memory is assessed using 'digit span', 'digit span-running', and 'nonword repetition' tasks. The 'digit span' task requires children to repeat lists that vary in length from 2-8 digits. This task is presented to children in the context of playing a copycat game with a robot. The child repeats what the robot says, trying to remember as many digits in the sequence as possible. The 'digit span-running' task is presented in the context of playing a copycat game with sea monsters who read lists of numbers 7-10 digits in length; however, children do not know how many digits will be presented in a list. When the list is completed, the child is prompted to recall as many digits as possible, in forward order, from the end of the list. In the 'nonword repetition' task, children repeat novel words (*e.g.*, 'genfad' and 'yitvodgoom'), which help the pirate build a candy bridge over a river.

Visuospatial Working Memory

'Visuospatial working memory' is the component of working memory that mentally holds and manipulates visual and spatial information. Visuospatial working memory is assessed with 'location span', 'location span-running', 'visual span', and 'visual span-running' tasks. The location span task requires children to remember the endpoint location of a series of arrows that direct a pirate to buried treasure. The locations are displayed in an array of eight dots radiating from the center of the screen at equidistant angles. After children see the series, they point to as many locations as they can remember in sequence. The 'location span-running' task is the same as the location span task except that children do not know how many locations will be presented. The 'visual span' task is similar to the 'location span' task. Children see a series of 1-6 individual black polygons (*i.e.*, 'gems' in the context of the game) appear on the screen, one at a time. After seeing each series, six polygons appear in a line on the screen. Children select the order in which they appeared, using the touchscreen. The 'visual span-running' task is similar to the visual span task except that children do not know how many polygons will appear. At the end of the sequence, children recall the polygons in forward order. The span lengths vary from 3 to 6 polygons.

Binding Tasks

'Binding tasks' refer to the component of working memory that forms a temporary interface among the various working memory components (*e.g.*, phonological and visuospatial) and binds information within and across these subsystems and long-term memory. Binding tasks include 'phonological binding span', 'visual binding span', and 'cross-modal binding'. The 'phonological binding span' task requires children to learn pairings of non-speech sounds (*e.g.*, beeps and tones) with single-syllable nonwords (*e.g.*, vope and meck). This task is presented in the context of robots speaking a special 'robot language' to order candy at a candy store. Children start by hearing one sound with one nonword in a sequence, but the task increases in difficulty until they hear up to four sound-nonword pairings in a sequence. The 'visual binding span' task requires children to remember two paired pieces of visual information, such as where individual polygons are located in a 4 x 4 grid. Span length increases from 1 to 6 polygons. After the last polygon in each trial has been displayed, an identical, blank 4 x 4 grid appears on the screen next to a field of the six optional polygons. Children use the touchscreen to select and drag the polygons to their proper location within the grid. Children are allowed to move polygons around the grid until they are satisfied with their selection. 'Cross-modal binding' requires the binding of auditory nonwords (*e.g.*, koov and geem) with black polygon shapes. This task is presented in the context of learning the name of game pieces. As each individual polygon is shown in the center of the screen, children hear a 1-syllable nonword paired with that polygon. Each trial varies in the number of pairs presented, ranging from 1 to 6. After the last pair is presented, a selection screen showing the field of six polygons appears. Children hear each nonword, one at a time, and use the touchscreen to indicate the polygon that goes with that nonword. The nonwords are not replayed in the order in which they were presented.

CABC-WM Administration and Results

The protocol for administering the CABC-WM is described below. Following this, results of the CABC-WM measures and reported task reliability are provided for a sample of typically-developing children. The presented CABC-WM battery is administered on a desktop computer with a touchscreen monitor using a pirate-themed context for the games. The child sits directly in front of the touch screen. A research assistant sits beside the child to monitor the child's attention or need for breaks. The assistant also records data for the tasks that are not automatically recorded by the computer program (see below). At the conclusion of each task, the CABC-WM prompts the child to select the next task. After the last task has been completed in the research session, the CABC-WM concludes by allowing the child to purchase items for his pirate avatar in a virtual store.

All tasks begin with a set of training trials that the child is required to pass before proceeding to the test trials. If a child cannot pass the training trials after five attempts, the task is discontinued. Please see **Table 1** for individual task details including: stimuli used, conditions, number of training trials and task trials, average task length, and dependent variables.

Protocol

All procedures described below were approved by the human research ethics review boards at the participating institutions.

1. Preparation and Seating

1. To begin, seat the child in front of the computer and fit him with an adjustable headphone/microphone combination set. Use a headphone splitter to connect a set of headphones that the assistant will wear during the administration of the battery.
   NOTE: Throughout the administration of the protocol, an assistant sits beside the child to monitor the child's attention to the tasks; to enter response data, as described below; and to ensure the child's fidelity to the CABC-WM protocol (*e.g.,* to ensure that the child uses his dominant hand to respond, attends to the computer screen, *etc.*).

2. Initial Instructions to the Subject

1. Instruct the child to use the touchscreen interface to select a pirate avatar that he will use throughout the game.
   NOTE: Within the game, the child will traverse a virtual ocean to complete 13 working memory tasks, distributed across four islands (each island is completed on a different day to prevent fatigue). See **Figure 1**. Individual tasks are represented by icons (*e.g.*, different icons of toys on Toy Island). Tasks are randomized across children; thus, the computer randomly selects the order of task presentation for each child.

3. Selection of the Avatar

1. **After selecting the pirate avatar, direct the child to select an island to complete. Instruct the child to select one of the picture icons on his selected island, which will start a task.**
   NOTE: Each island has 3-5 tasks (see **Figure 1**), each of which are represented by picture icons. Tasks are randomly presented by the CABC-WM so a particular picture icon is not necessarily associated with a particular task. For each task, an introduction screen appears first, which signals to the assistant what materials are needed (*e.g.,* removing the keyboard, placing labels on the keyboard, etc.) for that specific task.
    1. When the materials are arranged appropriately, ask the assistant to press the *9* key on the 10-key number pad to start the task. Once a child has completed a task (as described in the protocol below), the selected island reappears and the child selects the next task. The session continues until all tasks on the island have been completed.
       NOTE: All tasks within the CABC-WM are narrated by a pirate who provides standardized verbal instructions for each task. Each task is categorized below according to each working memory component, including: 1) central executive, 2) phonological working memory, 3) visuospatial working memory, and 4) binding. Comprehensive descriptions of each task were provided above in the introduction of the manuscript.

4. Central Executive Tasks

1. **N-back Auditory**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard in front of the child, and place a green sticker on the *C* key and a red sticker on the *M* key. Press *9* on the 10-key number pad to start the task for the child. Ensure that the child indicates his response by selecting the respective labeled key on the keyboard.
       NOTE: The red sticker represents *different* and the green sticker represents *same;* this is how the child indicates the same/difference response in this task. The CABC-WM narrator instructs the child to judge whether an auditory stimulus (*i.e.,* atone) is the same or different from the preceding stimulus.

2. **N-back Visual**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard in front of the child, and place a green sticker on the *C* key and a red sticker on the *M* key. Press *9* on the 10-key number pad to start the task for the child
       NOTE: The red sticker represents 'different' and the green sticker represents *same;* this is how the child indicates the same/difference response in this task. The CABC-WM narrator instructs the child to judge whether a visual stimulus (*i.e.*, a 'game piece') is the same or different from the immediately preceding visual stimulus.
    2. Ensure that the child indicates his response by selecting the respective labeled key on the keyboard.

3. **Number updating**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Direct the child to visually attend to two numbers presented on the computer screen and to the subsequent addition operations. Press *9* on the 10-key number pad to start the task for the child.
       NOTE: The child is shown two numbers on the screen. The child is given, in sequence, a series of five addition operations that are applied to the numbers. After each operation, the child provides a verbal running total of the two numbers.

2. After the child verbally provides the running total (*e.g.,* 2, 3 or 2,4) for each trial, key the child's response on the 10-key number pad, which will automatically advance the task to the next trial.

5. Phonological Working Memory Tasks

1. **Digit Span**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session.
    NOTE: The CABC-WM narrator instructs the child to listen to sequences of digits that increase in length and to repeat as many digits as he can recall.
    2. Place the keyboard out of reach of the child (the assistant will key the child's responses). Press '9' on the 10-key number pad to start the task for the child. After each trial, enter the digits that the child repeats into the 10-key number pad, regardless of the correctness of his response, on the keyboard.
    NOTE: The CABC-WM scores the child's responses as correct if the repeated numbers are in the correct order. The assistant does not judge the accuracy of the child's response, but simply keys the child's response into the program for the computer to analyze and score.
2. **Digit Span - Running**
NOTE: The CABC-WM narrator instructs the child to listen to lists of numbers that range in spans from 7-10 digits in length, and then to repeat as many numbers (in forward order) at the end of the sequence.
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child (the assistant will key the child's responses). Press '9' on the 10-key number pad to start the task for the child. After each trial, enter the digits that the child repeats into the 10-key number pad on the keyboard.
    NOTE: The CABC-WM scores the child's responses as correct if the repeated numbers are in the correct order. The assistant does not judge the accuracy of the child's response, but simply keys the child's response into the program for the computer to analyze and score.
3. **Nonword Repetition**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session.
    NOTE: The CABC-WM narrator instructs the child to repeat a series of nonwords (*e.g.,* genfad and yitvadgoom) as accurately as possible.
    2. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child. After the child makes an attempt at repeating each nonword, press the 'C' key to indicate an attempt was made and advance to the next trial. If the child does not make a reasonable attempt (*e.g.*, child says, 'I don't know' or does not respond), press the *M* key to indicate an attempt was not made and the next trial will begin.

6. Visuospatial Working Memory Tasks

NOTE: At the start of each task, the CABC-WM narrator provides instructions to the child.

1. **Location Span**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child. Monitor the child's attention to the task which requires him to recall a series of locations on the computer screen and while he responds by touching the screen to make his selections.
2. **Location Span - Running**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child.
    2. Monitor the child's attention to the task while he recalls, in forward order, as many locations presented from the end of a sequence of unpredictable length. After the child touches the screen to respond, ensure that the child selects the *NEXT* button, a circle in the lower-right corner of the screen that is labeled *NEXT,* to advance the CABC-WM to the next trial.
3. **Visual Span**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child. Monitor the child's attention to the task while, when prompted, he uses the touchscreen to select the order of presented polygons in spans of 2-6 lengths.
4. **Visual Span - Running**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child.
    2. Monitor the child's attention to the task while, when prompted, he uses the touchscreen to select the order of polygons that he can recall in forward order, as many polygons as possible from an unpredictable span length. After the child touches the screen to respond, ensure that the child selects the 'NEXT' button, a circle in the lower-right corner of the screen that is labeled 'NEXT', to advance the CABC-WM to the next trial.

7. Binding Tasks

1. **Phonological Binding Span**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child.
    2. Listen for the child's verbal response when he is asked for the nonword that was paired with the non-speech sound. If the child makes a reasonable attempt, press the C key to indicate that an attempt was made and to advance the task to the next trial. If the child does not make a reasonable attempt (*e.g.*, the child says 'I don't know' or does not respond), press the 'M' key to indicate that an attempt was not made and to allow the next trial to begin.
2. **Visual Binding Span**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child.
    2. After the child is presented with polygons in their respective locations on the screen (increasing in span length from 1 to 6 polygons at a time for each trial), monitor the child while he uses the touchscreen to move the polygons into the grid locations he recalls. After the child finishes his selections, ensure that the child selects the 'NEXT' button, a circle in the lower-right corner of the screen that is labeled 'NEXT', to advance the CABC-WM to the next trial.
3. **Cross-Modal Binding**
    1. Read the instruction screen that appears after the child selects the task icon on the selected island of the session. Place the keyboard out of reach of the child. Press '9' on the 10-key number pad to start the task for the child.
    2. As the child is presented with a polygon to label after learning the polygon-nonword pairings in spans of 1-6 pairings, monitor the child's responses. If the child makes a reasonable attempt, press the 'C 'key to indicate that an attempt was made and to advance the task to the next trial. If the child does not make a reasonable attempt (*e.g.*, the child says 'I don't know' or does not respond), press the 'M' key to indicate that an attempt was not made and to allow the next trial to begin

Representative Results

The CABC-WM was administered to 168 children with typical development who were enrolled in or had just completed second grade (mean age = 7; SD = 4.99 months). Children also met the following inclusionary criteria: a) had no history of neuropsychiatric disorders (*e.g.*, ADHD or autism spectrum disorder), b) had no history of receiving special education services, c) spoke monolingual English, d) had not repeated a grade, e) had a standard score >30th percentile on the Goldman-Fristoe Test of Articulation -2 (GFTA)[18], f) had a standard score >87 on the core language composite of the Clinical Evaluation of Language Fundamentals-Fourth Edition (CELF-4)[19], g) had a 2nd grade composite standard score >95 on the Test of Word Reading Efficiency, Second Edition (TOWRE-2)[20], and h) had a standard score >74 on the Nonverbal Index of the Kaufman Assessment Battery for Children (K-ABC)[21]. Table 2 presents the pass rates, means, standard deviations, and range of scores across each task. Some children did not complete all tasks. In some cases, this was due to equipment failure (about 4%) or because the child was unable to pass the training phase of a task. For children who successfully passed the training phase, we observed no floor or ceiling effects, suggesting that the tasks were developmentally appropriate for capturing a range of performances across children. Based on training success, the most difficult tasks to pass were 'digit span-running' and 'visual span-running', with pass rates of 70.7% and 80.4%, respectively. All other tasks were passed by at least 90% of the children.

Tasks of the CABC-WM have been used to test the fit of prominent models of working memory[22]. Based on confirmatory factor analyses, the tasks of the CABC-WM were used to define a final model of working memory that can best be described as a combination of Cowan's three-factor embedded processes model[15,16] of central executive, focus of attention, and phonological storage and rehearsal with Baddeley and Hitch's three-factor model[5] of central executive, visuospatial sketchpad, and phonological loop (see **Figure 2**). The first identified factor in the combined model, the central executive, included the *n*-back tasks and the updating task. The second factor was the focus of attention/ visuospatial sketchpad. Tasks loading onto this factor included traditional visually based tasks, such as visual span and location span, but also included running tasks which, as described above, are those tasks that have an unpredictable list length that does not allow for rehearsal[23,24]. The third identified factor, the phonological storage and rehearsal/phonological loop, included those tasks involving speech and auditory stimuli, such as digit span, phonological binding, and non-word repetition. See Gray *et al.*[22] for a complete review. These representative results confirm the utility of the tasks of the CABC-WM for measuring discrete components of working memory in the current sample of children.

Reliability

The reliability of the CABC-WM[22] tasks were assessed by calculating split-half and split-third coefficients (which are special cases of the more general K-split coefficient[25,26,27]). A complete description of how we split items may be obtained from the first author. Reliability for each task is shown in **Table 3**. Most reliabilities were moderate to high in value, providing evidence that the majority of the individual tasks in the CABC-WM are reliable. The binding tasks showed lower reliabilities, which warrants further investigation.

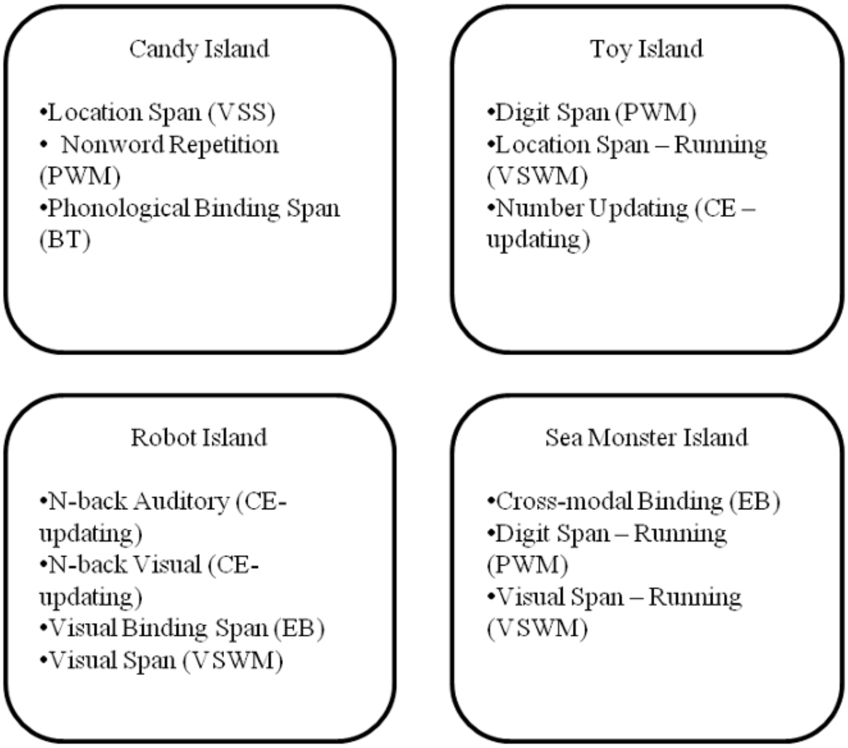

Figure 1: Distribution of Working Memory Tasks Across the Islands of the CABC-WM. Island order and task order were randomized for each child. Tasks were distributed across islands to counterbalance presentation and to standardize the amount of time required for island completion. (Abbreviations: VSS: Visuospatial working memory; PL: Phonological working memory; CE: Central Executive; BT: Binding Tasks

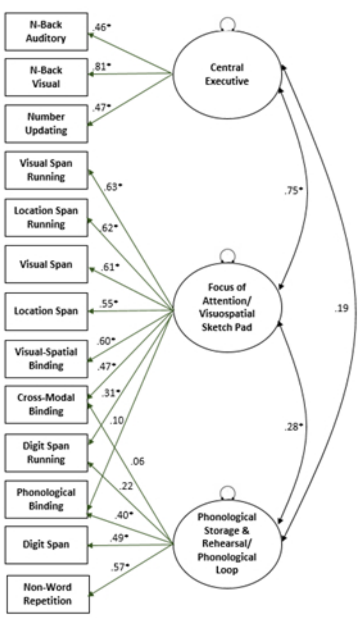

Figure 2: Combined Model of Working Memory with Standardized Coefficients. This figure shows the factors and factor loadings for tasks of the CABC-WM. Standardized coefficients are presented in the figure. See Gray *et al.*[22] for further details. (*Reprinted with permission from Gray *et al.*)[22].

Task Name	Stimuli Used	Conditions or Trial Types	Number of Training Blocks and Trials (in parentheses)	Criterion for Passing Training	Number of Trials	Task Length (minutes)	Dependent Variable(s)
Central Executive Tasks							
N-back Auditory (Updating)	• Tones • Image of robot band	• Same • Different	1 training block: • Same (3) • Different (3)	4/6	54 (3 blocks each with 9 Same, 9 Different)	6.5	Mean accuracy for same and different trials combined
N-back Visual (Updating)	• Images of black squares with white dots	• Same • Different	1 training block: • Same (3) • Different (3)	4/6	54 (3 blocks each with 9 Same, 9 Different)	7.5	Mean accuracy for same and different trials combined
Number Updating (Updating)	• Visual presentation of numbers and operations	n/a	2 training blocks: • Each block (5)	5/5 each block	15 (3 blocks each with 5 trials)	7.2	Mean accuracy for all trials
Phonological Working Memory Tasks							
Digit Span	• Auditory recordings of digits 1-9 (except 7 because it is 2 syllables)	Span length (2-8 digits)	1 training block: • 2 trials	2/2	14 (2 trials at each span length from 2-8 digits)	4.5	Number of trials correct at each span length x span length, then sum products
Digit Span – Running	• Auditory recordings of digits 1-9 (except 7 because it is 2 syllables)	Span length (7-10 digits)	3 training blocks: • 3 trials	At least 1 correct for each of 3 blocks	12 (3 trials at each span length from 7-10)	6	Average number of digits recalled in the correct order
Nonword Repetition	• Auditory recordings of nonwords	Word length (2-5 syllable nonwords)	1 training block: • 3 2-syllable nonwords)	3 attempted	16 nonwords (4 at 2-, 3-, 4-, and 5-syllable lengths)	3	Number of nonwords repeated with correct consonants at each syllable length x syllable length, then sum products
Visuospatial Working Memory Tasks							
Location Span	• An arrow pointing toward a location arranged in a circular pattern	Span length (2-6 locations)	3 training blocks: • 1 location (1) • 2 locations (2)	At least 1 at 1 location and 1 at 2 locations	12 (2 trials at each span length from 2-6 locations)	4.5	Number of trials correct at each span length x span length, then sum products
Location Span Running	• An arrow pointing toward a location arranged in a circular pattern	Span length (5-8 arrows)	3 training blocks: • 6 locations (1) • 7 locations (1) • 8 locations (1)	1/1 correct at each length	12 (3 trials at each span length from 5-8 locations)	7.5	Average number of locations correctly identified across all trials
Visual Span	• Black polygons	Span length (1-6 polygons)	1 training block • 1 polygon (1) • 2 polygons (2)	3/3	12 (2 trials at each span length from 1-6 polygons)	6.5	Correct number of trials at each span length x span length, then sum products
Visual Span - Running	• Black polygons	Span length (3-6 polygons)	1 training block • 3 polygons (1) • 4 polygons (1)	1 correct at each length	12 (3 trials at each span length from 3-6 polygons)	7	Average number of polygons correctly identified in

							order across all trials
Binding Tasks							
Phonological Binding Span	• Auditory non-speech sounds (e.g. mechanical noises) • Auditory recordings of nonwords	Span length (1-4)	1 training block • 1 sound-nonword pair (1) • 2 sound-nonword pairs (1)	2/2 attempted	20 sound/ nonword pairings (2 trials each of 1-4 pairs per trial)	5.2	Correct number of trials at each span length x span length, then sum products
Visual-Spatial Binding Span	• Image of a grid • Black polygons	Span length (1-6 polygons)	1 training block • 1 polygon (1) • 2 polygons (1)	2/2	12 (2 trials at each span length from 1-6 polygons)	5.2	Correct number of trials at each span length x span length, then sum products
Cross-Modal Binding	• Black polygons • Auditory recordings of nonwords	Span length (1-6 polygons)	1 training block • 1 nonword-polygon pair(1) • 2 nonword-polygons (2)	2/2	12 (2 trials at each span length from 1-6 polygons)	6.5	Correct number of trials at each span length x span length, then sum products

Table 1: Task Details for Working Memory Tasks Included in the CABC-WM. The table presents the stimuli used for each task, conditions tested, number of training trials, criteria for passing the training phase, number of task trials, average task length, and dependent variables for each task.

Type of task	Pass Rate (%)[a]	N	Mean	SD	Minimum	Maximum
Number updating (accuracy)	91	155	0.8	0.28	0.14	1
N-Back Visual (accuracy)	94.8	147	0.77	0.17	0.3	0.96
N-Back Auditory (accuracy)	98.7	151	0.84	0.14	0.43	1
Location span (weighted sum)	100	151	10.59	5.99	0	30
Location span running (mean)	93.4	152	1.31	0.66	0.08	3.25
Visual span (weighted sum)	90.1	150	6.75	5.74	0	27
Visual span running (mean)	80.4	127	0.87	0.66	0.08	2.58
Digit span (weighted sum)	100	150	19.4	6.91	4	42
Digit span running (mean)	70.7	150	1.88	1.24	0.13	4.58
Nonword Repetition (weighted sum)	100	153	11.42	6.3	0	42
Cross-Modal binding (mean)	99.3	153	4.35	2.64	0	13
Phonological binding span	99.3	149	12.04	6.89	0	35
(weighted sum)						
Visual binding (weighted sum)	93.4	145	4.77	3.17	0	16
The percentages exclude data that were excluded because of equipment failure which occurred at a rate of 4.04% or participant issues which included withdrawal from the study or participant declining to complete an activity.						

Table 2: Performance on Each CABC-WM Task in Typically Developing Children in the 2nd Grade. The average pass rate is presented for each task. The means reported are raw scores for each task. The percentages exclude data that were discarded because of equipment failure, which occurred at a rate of 4.04%, or participant issues, which included withdrawal from the study or a participant declining to complete an activity.

Type of task	N	Reliability	95% CI of Reliability
Number updating (accuracy)	139	0.95	[.93, .96]
Number Back Visual (accuracy)	148	0.86	[.81, .90]
Number Back Auditory (accuracy)	151	0.82	[.75, .87]
Location span (weighted sum)	158	0.7	[.59, .78]
Location span run (mean)	146	0.93	[.91, .95]
Visual span (weighted sum)	140	0.73	[.62, .81]
Visual span run (mean)	99	0.84	[.78, .89]
Digit span (weighted sum)	159	0.67	[.55, .76]
Digit span run (mean)	109	0.85	[.79, .89]
Non-Word Rep (weighted sum)	153	0.6	[.45, .71]
Cross-Modal bind (mean)	153	0.38	[.15, .55]
Phonological bind span (weighted sum)	149	0.53	[.35, .66]
Visual bind (weighted sum)	145	0.51	[.32, .65]

Table 3: Reliability of CABC-WM Tasks. The reliabilities reported are derived from split-half and split-third coefficients, which are special cases of the more general K-split coefficient[25,26,27]. Most reliabilities were moderate to high in value.

Discussion

The CABC-WM was developed to comprehensively assess working memory in children based on prominent theories of working memory. Multiple tasks assess central executive, phonological working memory, visuospatial working memory, and binding functions.

Presently, the CABC-WM is undergoing additional refinement and testing. On occasion, the research assistant may encounter technical problems with the CABC-WM interface due to programming glitches or computer errors. The research team provides all assistants with a troubleshooting manual to address known problems (*e.g.,* the program may get stuck on a screen and need manual advancement), as well as extensive training regarding adherence to the troubleshooting protocol. Due to the duration of research sessions, child participants may become bored or frustrated with the program. Research assistants are trained to accommodate the child with breaks as necessary to maintain motivation and attention to the tasks. On rare occasions, the computer program has been known to require a reboot to continue. In those instances, if administration was interrupted mid-task, the task is not readministered, and that data is lost. The research team is diligently working to minimize these occurrences.

For now, the entire research battery should be administered, because children's performances on individual tasks presented outside the game environment have not been assessed. We are conducting studies to reduce the number of items in the battery, to assess the validity, and to determine how older elementary children perform on these measures. The research version of the CABC-WM requires five 30 to 45 min sessions to complete. This provides a comprehensive assessment of working memory for young elementary school children that may be of interest to researchers, but in its current form, the battery is not practical for practitioners. The validity of working memory models and task reliability have been reported for second graders in the U.S. The next steps are to test the battery in an expanded age range of children, to reduce the number of tasks in the battery, and to test concurrent validity.

There are only two known assessments specifically designed to measure working memory that are currently available for children[11,12]. The CABC-WM represents a more comprehensive alternative to these measures, administered in a child-friendly context (*e.g.,* a computer game) to increase motivation. Results suggest that CABC-WM tasks are reliable when administered to second graders with typical development.

Findings from the initial sample of second-grade children are being used to refine the CABC-WM battery. The next steps are to assess the reliability and validity of the battery in a wider age range of children. The long-term goals of this research are to help educators and families understand the individual working memory strengths and weaknesses of children to support differentiated instruction and to help each child understand their working memory profile to empower their self-advocacy and use of strategies to increase academic achievement.

Disclosures

The authors have nothing to disclose.

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References

1. Jeffries. S., & Everatt, J. Working memory: Its role in dyslexia and other specific learning disabilities. *Dyslexia.* **10** (3), 196-214 (2004).
2. Smith-Spark, J., & Fisk, J.R. Working memory functioning in developmental dyslexia. *Memory.* **15** (1), 34-56 (2007).
3. Hoffman, L.M., & Gillam, R.B. Verbal and spatial information processing constraints in children with specific language impairment. *J Speech Lang Hear R.* **47**, 114-125 (2004).
4. Marton, K., & Schwartz, R.G. Working memory capacity and language processes in children with specific language impairment. *J Speech Lang Hear R.* **46**, 1138-1153 (2003).
5. Baddeley, A. D., & Hitch, G. Working Memory. In Gordon H. Bower (Ed.), *Psychol Learn Motiv.* **8**, 47-89. New York, NY: Academic Press (1974).
6. Miller, G. A., Galanter, E., & Pribram, K. H. *Plans and the structure of behavior.* New York, NY: Henry Holt and Co, Inc (1960).
7. Engle, R.W., Tuholski, S.W., Laughlin, J.E., & Conway, A.R.A. Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *J Exp Psychol Gen.* **128**, 309-331 (1999).
8. Silber, K. H., & Foshay, W. R. *Handbook of Improving Performance in the Workplace, Instructional Design and Training Delivery: Volume 1* .(1 edition.). Pfeiffer (2009).
9. Gathercole, S. E., Lamont, E., & Alloway, T. P. Chapter 8 - Working Memory in the Classroom. In S. J. Pickering (Ed.), *Working Memory and Education.* (pp. 219-240). Burlington, MA: Academic Press (2006).
10. Cowan, N. Working Memory Underpins Cognitive Development, Learning, and Education. *Educ Psychol Rev.* **26** (2), 197-223 (2014).
11. Alloway, T.P. *Automated Working Memory Assessment.* London: Pearson Assessment, (2007).
12. Pickering, S. J., & Gathercole, S. E. *Working Memory Test Battery for Children.* London: Psychological Corporation, (2001).
13. Baddeley, A.D. *Working memory.* Oxford Psychology Series #11. Oxford: Clarendon Press (1986).
14. Baddeley, A. The episodic buffer: a new component of working memory? *Trends Cogn Sci.* **4** (11), 417-423 (2000).
15. Cowan, N. Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychol Bull.* **104** (2), 163-191 (1988).
16. Cowan, N. The differential maturation of two processing rates related to digit span. *J Exp Child Psychol.* **72** (3), 193-209 (1999).
17. Cowan, N., et al. On the capacity of attention: its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychol.* **51** (1), 42-100 (2005).
18. Goldman, R., & Fristoe, M. *Goldman-Fristoe test of articulation -2.* Circle Pines, MN. American Guidance Service, Inc. (2000).
19. Semel, E., Wiig, E.H., & Secord, W.A. *Clinical evaluation of language fundamentals.* (4^{th} ed.). Circle Pines, MN: American Guidance Service Inc. (2003).
20. Torgesen, J., Wagner, R., & Rashotte, C. *Test of word reading efficiency.* (2^{nd} ed). Circle Pines, MN: American Guidance Service Inc. (2012).
21. Kaufman, A.S., & Kaufman, N.L. *Kaufman assessment battery for children.* (2^{nd} ed.). Circle Pines, MN: American Guidacne Service, Inc. (2004).
22. Gray, S., et al. The structure of working memory in young school-age children and its relation to intelligence. *J Mem Lang.* **92**, 183-201 (2016).
23. Crowder, R.G. Behavioral strategies in immediate memory. *J Verb Learn Verb Be.* **8**(4), 524-528 (1969).
24. Hockey, R. Rate of presentation in running memory and direct manipulation of input processing strategies. *Q J Exp Psychol.* **25**(1), 104-111 (1973).
25. Green, S., et al. Use of internal consistency coefficients for estimating reliability of experimental task scores. *Psychon B R.* 1-14, (2015).
26. Raju, N.S. A generalization of coefficient alpha. *Psychometrika. 42,*. 549-565 (1977).
27. Cronbach, L. J., & Furby L. How We Should Measure "Change"- or Should We? *Psychol Bull.* **74***,* 68-80, (1970).