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What Does a Verbal Working Memory Task Measure? The Process-Specific and Age-Dependent Nature of Attentional Demands in Verbal Working Memory Tasks

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Most models of verbal working memory (WM) consider attention as an important determinant of WM. The detailed nature of attentional processes and the different dimensions of verbal WM they support remains, however, poorly investigated. The present study distinguished between attentional capacity (scope of attention) and attentional control (control of attention) and examined their respective role for two fundamental dimensions of verbal WM: the retention of item versus serial order information and the simple versus complex nature of WM tasks. Three hundred four young and older adult participants performed simple or complex recall or reconstruction tasks involving the retention of item and/or serial order information, as well as attention tasks estimating scope and control of attention abilities. In young participants, scope of attention measures was most robustly associated with all WM tasks; control of attention measures were additionally involved when item and order information had to be maintained in more complex WM tasks. Older adult participants presented a similar pattern of results with, however, a tendency for increased reliance on control of attention already for the simple storage of information, and this most robustly for serial order information. These results reveal the task-dependent and partly age-dependent intervention of scope and control of attention in verbal WM measures, calling for dynamic models of verbal WM and attention.

Public Significance Statement

Working memory (WM) and attention are closely associated concepts in different theoretical frameworks of WM and this particularly in the context of complex WM tasks. Yet, the extent to which attentional capacity may influence performance in a broad set of WM tasks contexts remains poorly investigated. By distinguishing between scope of attention and control of attention, and by using WM tasks varying in type of memoranda and complexity, we show that young adults rely to a greater extent on scope of attention than control of attention abilities for WM task performance. Older adults instead tend to rely more strongly on control of attention, even for the least complex WM tasks. This study highlights the dynamic nature of WM by showing that a given WM task does not measure a uniform capacity, but differentially recruits aspects of attention as a function of task design and the age of the person being tested.

Keywords: working memory, attention, verbal, item, order

Most models of working memory (WM) consider attention to be a major component of WM. Many models view attention as a mechanism intervening in the most complex WM tasks and involving a strategic, top-down control function close to executive functioning (Baddeley, 1986; Baddeley & Hitch, 1974; Conway et al., 2002; Engle et al., 1999; Kane et al., 2001). Some WM models also consider an additional, nonstrategic aspect of attention, the scope of attention, reflecting the amount of information that can be held in the focus of attention at one point in time (Barrouillet & Camos, 2015; Barrouillet et al., 2011; Cowan, 1988, 1995, 1999; Cowan et al., 2024). Both aspects of attention have been identified via latent variable approaches to reflect distinct components and distinct predictors of other cognitive domains such as fluid intelligence (e.g., Chow & Conway, 2015; Shipstead et al., 2012, 2015). But there is

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Tasks, data, and analysis scripts are available at https://osf.io/2xg8e/?view_only=0adbc2c65bf547ac94de48507192592d. Part of this work was presented at the 61st Annual Meeting of the Psychonomic Society as well as at the 10th European Working Memory Symposium.

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currently very little direct evidence about the role of each attentional capacity in specific aspects of WM. The aim of the present study is to examine the role of scope and control of attention in verbal WM by examining their possible differential implication in verbal WM tasks as a function of different fundamental dimensions of WM, such as the type of information—item versus serial order—to be maintained and the complexity of the WM tasks.

WM and Attention

There is broad consensus about the close connections between attention and WM. A number of theoretical models consider that attention is a major determinant of WM, with recent views considering that attention and WM are at least partially overlapping concepts (Barrouillet et al., 2004; Cowan, 1988, 2024; Engle et al., 1999; Hitch et al., 2018; Kane et al., 2001), while initial models of WM considered attention as a specific cognitive process that would support temporary storage only in more complex situations (Baddeley, 1986). There is also general agreement that attention serves to control to-be-maintained information by safeguarding it against interference from nontarget stimuli or from secondary tasks. Attentional involvement is also considered allowing for further processing and manipulation of memoranda. In this sense, attention has a role of top-down and executive control, with some authors defining this aspect of attention as executive attention (Engle et al., 1999; Kane et al., 2001). This aspect of attention also has an intensity dimension, with individuals being able to deploy their attentional control over the entire duration of a task in a variably reliable and consistent manner (Unsworth & Robison, 2020). Moreover, a nonstrategic form of attention has been proposed by Cowan (1988, 1995; Cowan et al., 2024): the scope of attention. The scope of attention reflects the amount of information one can be aware of at one point in time. It has been defined as the amount of information we can hold in our focus of attention without the intervention of any active maintenance mechanism such as verbal rehearsal or attentional refreshing (Cowan et al., 2005, 2024). For some authors, this capacity is limited to about four units (Cowan et al., 2024), while other authors consider that at a given time point, we can be aware of only a single unit (Oberauer & Bialkova, 2009). This lower level, stimulus-driven aspect of attention is typically measured by tasks presenting a simultaneous set of multiple stimuli for a very brief period of time (e.g., presenting a set of colored squares during less than 1 s as in the visual array task) or by presenting a continuous set of stimuli at a very fast rate (e.g., presenting a sequence of digits of unpredictable length at the rate of >2 items per second as in the running span task; Cowan et al., 2005; Luck & Vogel, 1997; Shipstead et al., 2012). Participants are then asked to recognize or recall the stimuli they just experienced, with an observed limit of about four items in young adult (YA) participants (Cowan et al., 2005, 2024).

The distinction between scope and control of attention is supported by a significant number of studies. The main bulk of evidence stems from latent variable approaches, examining the association between tasks supposed to involve scope of attention (such as the running span and visual array tasks mentioned above), tasks supposed to involve control of attention (mainly storage and processing complex WM span tasks such as the listening span or operation span tasks; Daneman & Carpenter, 1980; Turner & Engle, 1989) and tasks measuring another cognitive domain thought to be associated with WM such as fluid intelligence. These studies showed that estimates of scope of attention and control of attention generally load on distinct factors and show specific associations with fluid intelligence measures (e.g., J. D. Martin et al., 2021; Shipstead et al., 2012, 2015). Similar results have also been observed in developmental studies. By using a regression approach, Cowan et al. (2006) observed that scope of attention (as measured by a visual array task) and control of attention (as measured by a dual modality memory task involving attentional prioritization on one of the modalities) were independent predictors of an estimate of a combined verbal–visual intelligence score in adults while in children, most variance was accounted for by scope of attention. Neuroimaging and neurostimulation studies further showed that distinct neural mechanisms support the scope and the control of attention, and this more specifically in frontoparietal cortices (Li et al., 2014; Majerus et al., 2018; Postle et al., 2006). Postle et al. (2006), using transcranial magnetic stimulation, observed that stimulation of the prefrontal cortex selectively disrupted manipulation of information in WM (i.e., control of attention) while stimulation in the posterior parietal cortex disrupted both manipulation and retention aspects. This latter result could be interpreted as reflecting the disruption of the scope of attention, which should impact performance more broadly. More recently, Majerus et al. (2018) showed that scope of attention and control of attention can be dissociated within the posterior parietal cortex based on the type of attention (scope vs. control) involved in a WM task.

It should be noted here that the type of attention being probed and its association with WM may further depend on task design. For example, some significant overlap between scope of attention and control of attention has been observed if the scope of attention tasks include a dimension of selectivity and hence also a dimension of top-down control (e.g., instructing participants to focus their attention exclusively on the left side of the stimulus display in a visual array task, J. D. Martin et al., 2021). Regarding complex WM tasks, by virtue of task design, these tasks are likely to involve control of attention ability to a larger extent than scope of attention ability. In many of these tasks, such as the reading or listening complex span tasks, focalization and retention of target stimuli are continuously interrupted by the processing part of the task (e.g., sentence anomaly judgment), retention of information being possible only via controlled strategies such as blocking nontarget stimuli, as well as actively refreshing and rehearsing stored target information while new information is being processed and memoranda are extracted. While in some of the abovementioned studies, complex WM measures have sometimes been used as a proxy of attentional control, it should also be noted here that J. D. Martin et al. (2021), using more direct measures of attentional control (e.g., antisaccade or flanker tasks), showed that complex WM tasks cannot be reduced to an attentional control construct (see also Wilhelm et al., 2013). It remains to be examined to what extent scope of attention and control of attention naturally intervene in different types of WM tasks, independently of the attentional control requirements that may have been imposed or not. In order to answer this question, we need to examine the different dimensions that characterize WM tasks.

The Different Components of WM and Their Association With Attentional Processes

In order to examine natural associations between different aspects of attention and WM tasks, we need to examine the different components of WM and their intervention as a function of WM task context. Given the complexity of this question and the specificity of the components involved, we will limit this discussion as well as the present study to verbal WM exclusively. Note, however, that similar questions have been addressed in the visual WM domain, with studies also assuming the intervention of bottom-up versus top-down aspects of attention (Hu et al., 2014). A first critical element is the distinction between item and serial order components in verbal WM (Lee & Estes, 1977). Given the sequential nature of verbal information, memoranda in a typical verbal WM task are presented in temporal succession, and both the memoranda and their serial position need to be maintained and recalled. The item component has been shown to strongly interact with underlying linguistic knowledge, with item recall being enhanced for verbal memoranda that can be represented quicker, more strongly and in a richer manner in phonological, lexical, and semantic knowledge bases, as evidenced by higher item recall ability for familiar, frequent, and concrete words as opposed to unfamiliar, low-frequency, or abstract words (e.g., Hulme et al., 1991, 1997; Kowialiewski & Majerus, 2018; Walker & Hulme, 1999). These findings have led many authors to consider strong connections between WM and the language system in models of WM (e.g., Acheson & MacDonald, 2009; Burgess & Hitch, 1999, 2006; Majerus, 2009; N. Martin & Saffran, 1992). On the other hand, serial order information (i.e., the order of a word within a list) is considered to be coded by distinct processes such as temporal, spatial, or other types of contextual codes (e.g., Burgess & Hitch, 1999; Hartley et al., 2016; Majerus, 2019). The distinction between item and serial order components is supported by studies showing that order information is less influenced than item information by language knowledge as well as by the observation of order-specific or item-specific interference effects in dual-list encoding conditions (Guitard et al., 2021; Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996; Saint-Aubin & Poirier, 1999). This distinction is also supported by neuropsychological studies showing the existence of item-specific or serial order-specific verbal WM impairment, with serial order WM capacity being a specific predictor of performance in other domains involving the processing of sequential information such as reading, mental calculation, spelling, and novel word learning (Attout et al., 2014; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus et al., 2007, 2015; Ordonez Magro et al., 2021; Perez et al., 2012). Neuroimaging studies have also shown that the maintenance of item information involves coding of memoranda in linguistic processing areas (Kowialiewski et al., 2020; Majerus et al., 2010), while the maintenance of serial order information recruits specific frontoparietal networks associated with attentional, spatial, and/or temporal processing (Cristoforetti et al., 2022; Majerus et al., 2010).

Regarding the association between attentional processes and WM for item versus serial order information, several predictions can be made. On the one hand, we may assume that low-level, scope of attention abilities is necessary for the retention of any type of information, given that any WM task will require that to-be-memorized stimuli are held in the scope of attention. Hence, simple maintenance at item levels and serial order levels should involve scope of attention abilities to the same extent. On the other hand, it could be argued that the maintenance of serial order information is more demanding than the maintenance of item information and might therefore additionally recruit control of attention abilities as the limits of scope of attention capacity will be more quickly reached. Guitard and Cowan (2023a, 2023b; Guitard et al., 2021, 2022) recently showed asymmetrical switch costs between item and serial order retention requirements, suggesting indeed that retention of serial order may be more demanding at the level of attentional control processes than the retention of items. This situation could be explained by the fact that memory for items is supported by temporary activation of already existing representations (e.g., familiar words), while serial order information is typically arbitrary and needs to be represented as a novel and hence less stable representation that furthermore needs to be temporarily bound to the item representations, a set of operations that may be more challenging in terms of attentional cost and control (Cowan et al., 2024). Other studies have shown that the retention of serial order information is associated, at the neural level, with increased recruitment of specific parts of fronto-parietal cortices associated with attentional processes (Cristoforetti et al., 2022; Majerus et al., 2010; van Dijck & Fias, 2011). On the other hand, some neuroimaging studies observed similar involvement of left intraparietal cortices associated with control of attention in item and serial order WM tasks (Majerus et al., 2010). A developmental study based on a variance partitioning method also did not find larger portions of shared variance between selective attention and serial order WM measures than between selective attention and serial order WM measures (Majerus et al., 2009).

Another dimension of verbal WM is the complexity dimension of the task. As we have already noted earlier, complex WM tasks involving the storage and processing of information have been explicitly designed to engage control of attention (Barrouillet et al., 2004; Conway et al., 2002; Engle et al., 1999). These tasks should thus maximally depend on control of attention abilities in addition to scope of attention abilities. In line with J. D. Martin et al. (2021), we assume that scope of attention abilities is involved in complex WM tasks, at least to some extent, given that these tasks require keeping memoranda within the scope of attention, even if the latter is made more challenging due to the presence of nontarget, interfering information. Conversely, simple storage and recall tasks should rely more exclusively on scope of attention abilities.

The Present Study

The present study examined the associations between scope of attention, control of attention, and verbal WM as a function of the type of information to be maintained—item versus serial order information—and as a function of the complexity of the task. For measuring simple retention at the item level, a nonword delayed repetition task and an item recall score for a word list immediate serial recall task were chosen, allowing to assess phonological and lexico-semantic levels of item retention (Majerus et al., 2008; Poirier & Saint-Aubin, 1996). Serial order retention abilities were assessed via a serial order reconstruction task and the order recall score on the word list immediate serial recall task (e.g., Majerus et al., 2008; Whiteman et al., 1994). Finally, two complex WM tasks were presented in which item and serial order information had to be protected against interference coming from nontarget stimuli presented during recall or from a concurrent processing task. A first task was a combined item and serial order reconstruction task in which participants were presented, at the recall stage, target and nontarget stimuli and had to discard the latter to select the targets and then arrange them in their correct order. A second task was the listening span task, which is an auditory adaptation of the largely used reading span measures for assessing complex WM (Daneman & Carpenter, 1980; Draheim et al., 2022).

Scope of attention abilities was measured using the running span and visual array tasks, which have been widely used in previous studies to assess this ability (Cowan et al., 2005; J. D. Martin et al., 2021). We should note here that for the visual array task, we used the standard, nonselective version in order to minimize confounds with control of attention (J. D. Martin et al., 2021). This type of task has also been shown to be very minimally affected by cognitive load or active maintenance mechanisms (Kreither et al., 2022; Ricker & Vergauwe, 2020). Control of attention was assessed by two final tasks, a visual search task and a strategic running span task. The visual search task, involving the detection of a target visual figure among distractor figures, was adapted from Treisman and Gelade (1980); this type of task has also been frequently used in studies examining the role between WM and control of attention (Oberauer, 2019). The strategic running span task was an adaptation of the running span used to assess the scope of attention but, critically, imposed top-down attentional control. In the scope of attention version of the task, participants passively listened to a continuous and quickly presented string of alternating letters and digits and then were asked to produce the items they had in their mind when the sequence stopped. In the control of attention version of the task, the participants were instructed to selectively focus their attention on either the letter or the digit stimuli (i.e., every second item), both enabling and imposing top-down attentional control. This procedure had been validated in a previous study, where we showed that the nonstrategic and strategic running span tasks lead to different estimates of attentional capacity, with higher relative performance levels for the strategic version; furthermore, the two tasks are characterized by distinct neural activity patterns in the frontoparietal dorsal attentional network (Majerus et al., 2018). Note that by contrasting auditory-verbal and visual tasks for both aspects of attention, we were able to determine whether each aspect of attention is modality-independent as assumed by a number of theoretical frameworks of WM and attention (Barrouillet et al., 2004; Conway et al., 2002; Cowan, 1988; Engle et al., 1999).

Furthermore, in order to examine our hypotheses with maximal sensitivity, we included young and older healthy adults. Reduced verbal WM abilities, for both simple and complex span tasks, have been demonstrated in healthy aging (e.g., Belleville et al., 1996; Qin & Basak, 2020). Interestingly, Greene et al. (2020) recently showed that estimates of top-down attentional control capacity were not diminished in older versus YAs, but peripheral and modality-dependent attention estimates showed age-related decline. Greene et al. (2020) estimated these different attentional components by comparing bimodal attention instructions, in which all available and quickly presented visual and auditory items needed to be attended to versus a unimodal condition, where only the auditory or the visual stimuli needed to be attended to. Note that these two different conditions are very similar to the standard running span and strategic running span conditions used in the present study. For the older adult (OA) participant group in the present study, we may therefore expect that the association between performance on the different WM tasks and scope of attention abilities is diminished relative to young, healthy participants, while the association between WM task performance and control of attention abilities may be preserved or even increased.

The present study used a Bayesian correlation and multiple regression approach in order to assess evidence for the association but also evidence for the *lack* of association between the different WM and attentional components, based on the predictions described above. We did not use a latent variable design (although note that post hoc latent variable analyses are provided in the Appendix), as we were interested in determining the role of scope of attention and control of attention in each specific WM task as a function of the different characteristics of each task (item level, serial order level, simple, complex), and by considering that tasks sharing characteristics should not necessarily be reduced to a single latent variable. More specifically, for the nonword delayed recall and the immediate serial recall item recall measure, although both measures were intended to maximize item recall abilities, item-level maintenance mainly reflected sublexical phonological representations for the first measure, and lexical/semantic representations for the second measure, thus differing in the type of item information to be maintained and recalled. Furthermore, the articulatory suppression task presented during the delay between item encoding and recall in the nonword recall task distinguished this task from the direct recall procedure in the immediate serial recall, potentially leading to an enhanced association with control of attention abilities for the first item measure relative to the second one. Therefore, reducing these measures to a single latent variable may obscure important task differences and their possible impact on the association with the different attentional tasks. A similar situation characterized the two serial order WM measures, with the serial order reconstruction task measure being based on a raw recall performance measure for serial order information exclusively, while the immediate serial recall order measure was based on a serial order score corrected for item recall performance (see the Method section) in a task that involved recall of both item and serial order information. Serial order WM capacity estimates may not necessarily be the same for the two tasks, and this may affect their associations with the different attentional measures.

Method

Participants

Three hundred five participants were recruited for this study, with the data of one participant being discarded due to extreme values on several measures. All participants were native French speakers. The final sample consisted of 153 YA participants and 151 OA participants. The YA group had a mean age of 23.84 years (SD = 2.85), a mean number of years of education of 15.17 years (SD = 1.98) and was composed of 87/66 female/male participants. The OA group had a mean age of 69.62 years ($SD = 3.51$), a mean number of years of education of 13.31 years ($SD = 2.50$) and was comprised of 80/71 female/male participants (demographic data based on free self-report). Both groups were matched for mood levels (Beck Depression Inventory, Beck et al., 1988; YA = 3.10 ± 2.87, OA = 3.29 ± 2.84; Bayesian t test Bayes factor [BF_{01}] = 6.76; no participant reached the threshold for major depressive disorder) but as expected, the YA group exceeded the OA[1] group for nonverbal intellectual efficiency as measured by Raven's standard progressive matrices (Raven et al., 1998; YA = 51.36 + 4.64, OA = 37.39 ± 4.64; Bayesian t test BF_{10} = 2.37e + 54), while the OA group exceeded the YA group for verbal knowledge as measured by the Mill

[1] Note that the data for the Raven matrices were missing for one participant.

Hill test (Raven & Deltour, 1998; YA = 24.58 + 3.46, OA = 26.85 ± 4.22; Bayesian t test BF_{10} = 23,086.77). All participants in the OA group were screened for signs of age-related dementia, and they all performed above the threshold (>123) for the Mattis Dementia Rating Scale (Llebaria et al., 2008; Mattis, 1976; M = 141.01 ± 3.63). This study was approved by the local ethics committee. All participants reported having no major physical illness or psychological disorder, nor any history of neurological or neurodevelopmental disorder. Participants were wearing their usual visual or auditory correction devices as needed. The minimal number of participants to be recruited for this study had been estimated by a Bayesian sensitivity analysis (see the General Procedure and Statistical Analysis section).

Material and Procedure

Retention of Item Information

Nonword Delayed Repetition Task. This task involved the repetition of a single nonword item after a 5-s delay, during which rehearsal was blocked via backward counting by steps of three and by starting at 95. The task consisted of 30 monosyllabic nonwords with a consonant–vowel–consonant structure and respecting French phonotactic rules. The nonwords had been recorded by a female human voice and were presented in isolation. Each nonword was followed after 5 s by a beep tone inviting the participant to stop counting backward and to recall the nonword. Four practice trials were presented at the beginning of the task. A new nonword was presented on every trial, maximizing the processing and retention demands of phonological item information relative to serial order information. The only serial order errors that could occur were intra-stimulus phoneme exchanges, but the likelihood of this type of error was greatly reduced given that all nonwords had the same consonant–vowel–consonant structure and hence a predictable syllabic structure. Past studies with this task showed that the given type of serial position exchanges represents 0.4% of all errors in this task (Leclercq & Majerus, 2010). The task instructions were the following (English translation of text given in French):

> You will hear a word that doesn't exist, and I ask you to memorize the word. Immediately after hearing the word, you will start counting backward by steps of 3 and by starting at 95. As soon as you hear a beep tone, you stop counting backward, and you recall the word you memorized.

The participants' responses were recorded and transcribed for later scoring. The number of nonwords correctly recalled was retained as a score.

Word Immediate Serial Recall Task—Item Score. One hundred eight monosyllabic nouns were selected from the Brulex lexical database for their high medium to high lexical frequency (Content et al., 1990). The words were randomly assigned to lists of two to seven words, with four lists per length. They were prerecorded by a female voice at the rate of one word per second for presentation via E-Prime 2 software. The participants received the following instruction (translation of the text presented in French to the participants):

> You will hear sequences of 2 to 7 words. After each sequence, you need to repeat the words in the same order as during list presentation. If, for a given sequence, you do not remember the word, say "forgotten" for that word.

Participants were informed when the sequence length increased. For isolating item WM performance, we determined the total number of words correctly recalled, independently of output serial position.

Retention of Serial Order Information

Serial Order Reconstruction Task. The serial order reconstruction task consisted of the auditory presentation of digit lists of increasing length. The lists, containing three to nine digits, were sampled from digits 1 to 9, with four lists per length. For list length three, only the digits 1, 2, and 3 were used. For list length four, only the digits 1, 2, 3, and 4 were used, and so forth for other list lengths. This procedure ensured that item knowledge was known in advance and that participants only had to remember the position in which each item occurred. The lists were recorded by a female voice at the rate of one stimulus per second. The lists were presented (see the General Procedure and Statistical Analysis section for details) with increasing length. At the end of each trial, the participants were given cards (size: 5 × 5 cm) on which the digits presented during the trial were printed in black font. The number of cards corresponded to the number of digits presented and were presented in numerical order to the participants. The participants were requested to arrange the cards on the desk horizontally, following their order of presentation. At the end of each trial, the cards were removed. The participants received the following instruction (translation of the text presented in French to the participants):

> You will hear a sequence of digits. For a sequence of three digits, only the digits 1, 2, and 3 will occur. For a sequence of four digits, only the digits 1, 2, 3, and 4 will occur. After each sequence, you need to recall the order of the sequence of digits by using the cards on which the digits are printed.

The number of positions correctly reconstructed, by polling over all trials and sequence lengths, was determined for a maximal sensitivity of the score.

Word Immediate Serial Recall Task: Serial Order Score. For the word immediate serial recall task described above, we retained the number of items recalled in the correct serial position, pooled over all list lengths and trials, as a score. In subsequent analyses, we furthermore subtracted this serial order score (which is actually a serial order + item recall score) from the item score to obtain a purer estimate of serial order retention and recall performance.

Complex WM

Item and Serial Order Reconstruction Task. The design and structure of this task were identical to the serial order reconstruction except that digits were sampled from the digits 1 to 9 for each trial independently of sequence length, meaning that item information was not predictable anymore. Furthermore, at the moment of recall, participants were presented cards with all nine digits, ordered horizontally in increasing numerical order, and they had to select first the cards with the digits that had been presented in the memory list and then order them following their order of presentation. Hence, this task involved additional interference stemming from the item selection process. The participants received the following instruction (translation of the text presented in French to the participants):

> You will hear sequences of digits from 1 to 9. The length of the sequences will progressively increase. After each sequence, you will

> use the cards with the printed digits in front of you. You need to select the digits in the order you heard them.

The number of digits correctly selected in order was retained as a score by pooling again over all trials and lengths.

Listening Span Task. A computerized French-language version of the listening span task (Delaloye et al., 2008; Stawarczyk et al., 2014) was administered. In the first introductory part, participants heard 16 prerecorded sentences and judged them for semantic coherence by pressing a yes ("k" key) or no ("d" key) button. This part was preceded by four practice trials. The goal of this first part was to familiarize the participants with the semantic judgment task. In the storage and processing part (main task), participants had to carry out the same semantic judgments on the sentences, but in addition, they were instructed to memorize the final word of each sentence. The sentences were presented in blocks of two to five sentences, and participants were instructed to recall the final words in correct serial order (from the first to the *N*th sentence for a block of *N* sentences). The appearance of a white triangle on a black background on the computer screen indicated that the participants needed to recall all the final words of the just-presented sentence block. There were 56 prerecorded sentences divided into 16 blocks (four blocks for each sequence length), and block length varied in pseudorandom order by avoiding the immediate succession of two blocks of the same length. Half of the sentences were semantically correct, and the number of syllables of the final words to be memorized was controlled (i.e., only mono or trisyllabic words). Half of the sentences contained two nouns (e.g., "Children love chocolate"), and half contained one noun (e.g., "One can buy the moon"). Participants received the following instructions (translation of the text presented in French):

> In this part of the task, you will again need to determine whether the sentences are plausible ("yes") or not ("no"). But in addition, you need to memorize the final word of each sentence. The sentences are presented in blocks of 2, 3, 4 or 5 sentences. At the end of each sequence. (indicated by a white triangle), you need to recall the words you memorized in their order of presentation.

Two practice blocks were presented before starting the main task and could be repeated, if necessary. We determined the number of final words recalled in the correct serial position over all blocks as the score for this task.

Scope of Attention

Running Span. Sequences with alternating letter and digit names were presented auditorily at the speed of four items per second. The length of the sequences was 12, 16, 18, or 20 items, with five trials per sequence length. The letter and digit names had been individually prerecorded by a neutral female voice. Each sequence was preassembled and presented as a single.wav audio file to avoid any temporal irregularities in stimulus presentation that can occur when assembling sequences online during task presentation. Participants were not informed about sequence length, and they had to repeat back all stimuli they had in mind when the sequence stopped. Participants received the following instructions (translation of the text presented in French):

> You will hear sequences with quickly alternating letter and digit names. Listen carefully to them, as you will need to recall as many letters and digits as possible when the sequence stops. Take care in recalling them in the same order you heard them, from the most recent part of the sequence.

The task started with five practice trials that could be repeated if necessary. We determined the mean number of items recalled in correct order.

Visual Array Task. Arrays containing two, four, six, or eight colored squares were presented for a very brief duration (250 ms) in order to avoid any strategic attentional control processes or verbalization. For each array, the colors of the squares were sampled without replacement from a set of eight different colors. The arrays were presented on a gray background, which remained on the screen for a further 1,000 ms after the presentation of the array. Then the same array was represented with one circled square, which in 50% of the trials had changed color. Participants had to decide whether the circled square was of the same or a different color within 3,000 ms by pressing "yes" ("k" button) or "no" ("d" button). The probe display was cleared after the participant's response. There were 16 trials for each array size condition. Each trial started with the appearance of a cross in the center of the screen for 750 ms. Participants received the following instructions (translation of the text presented in French):

> You will see a first array containing 2, 4, 6 or 8 squares of different colors. You will then see a second array configured in the same manner as the first one. On this second array, one square will be circled. You need to decide whether the circled square is of the same color as the square in the same location in the first array. You respond by pushing the "yes" button if the color is the same (no change) and the "no" button if the color is different. (there is a color change)

The task started with four practice trials that could be repeated if necessary. We determined the overall amount of correct responses over all trials and array sizes.

Control of Attention

Running Span-Controlled. The structure and stimuli of this task were nearly identical to the *Running Span* task, including the presentation of alternating letter and digit names at the pace of four items per second. The main difference was that participants were instructed to focus exclusively on either the letters or the digits, thereby imposing attentional selection and top-down attentional control. The sequences were also shorter to allow for continuous top-down attentional control on target stimuli over the entire sequence. The sequences contained eight or 12 items. The task was divided into two parts, with participants being instructed to focus on the letters (or digits) in the first part and on the digits (or letters) in the second part. There were five trials per sequence length and target stimulus. Participants received the following instructions (translation of the text presented in French):

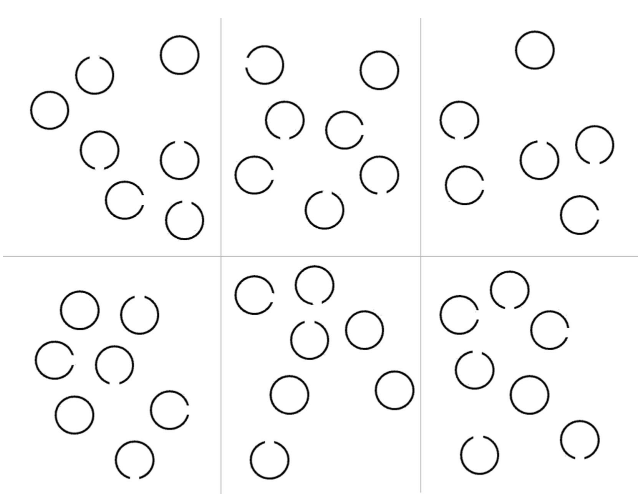
> You will hear sequences with quickly alternating letter and digit names. Listen carefully to them, as you will need to recall as many letters or digits as possible when the sequence stops, in the same order you heard them. There will be two parts to the task. In the first part, you need to focus exclusively on the digits (or letters) and recall only the digits (or letters). In the second part of the task, you need to focus exclusively on the letters (or digits) and recall only the letters. (or digits)

Within each part, the two sequence lengths were varied in random order. Participants were informed when the second part of the test started and the target stimulus changed. The task started with five practice trials that could be repeated if necessary. We determined the mean number of items recalled in correct order.

Visual Search Task. Each trial consisted of the presentation of six arrays containing each —six to seven black-colored circles on a white background, with three arrays appearing on the upper half of the screen, organized from left to right, and the other three arrays appearing on the lower part of the screen, organized from left to right (see Figure 1). The circles had random openings (no, top, bottom, left, right). Participants were presented with a circle with a target opening, and they then had to select the array that contained a circle with the same opening. For each trial, only one of the six arrays contained one instance of the target opening. There were 12 trials for each target type presented in blocks. The target circle was presented at the beginning of each block, followed by the presentation of the 12 six-array displays, each display having a maximal duration of 9,000 ms, and the next six-array display appearing immediately after the participant's response for the previous trial. Participants responded via the numerical keypad based on the spatial correspondence of the keys and the six-array display (7 = up left, 8 = up middle, 9 = up right, 4 = down left, 5 = down middle, 6 = down right). To avoid any confusion, stickers with adapted number labels were put on the keys to make the number successions agree with the left-to-right and top-to-down organization of the display (the "up left" key received the label "1," the "up" middle key received the label "2," the "up right" key received the label "3," etc.). The participants received the following instructions (translation of the text presented in French):

> Five types of circles will appear on the screen (closed, left opening, top opening, right opening, bottom opening) [the circles are shown on the screen]. The task is divided into five parts. For each part, a set of circles will appear on the screen. Your task is to detect, as quickly as possible, the target circle among the four other circle types. The target circle to be detected will be shown to you at the beginning of each part. The screen will be divided into six quadrants. For responding, you push on the corresponding button on the numerical keyboard [the quadrants and the correspondences on the keyboard are shown].

Figure 1
Example of a Trial Display for the Visual Search Task



Note. The example shown here required the response "2," the second quadrant (from left to right and top to bottom) containing the target "circle with left opening."

The task started with one practice trial that could be repeated if necessary. We determined the number of correct detections by pooling over all trials and target types.

General Procedure and Statistical Analysis

All tasks were presented via mobile workstations running E-Prime 2.0 (https://www.pstnet.com/) stimulus presentation software. Audio stimuli were presented at individually adjusted, comfortable loudness levels via high-quality audio speakers connected to the workstations. Auditory responses were recorded for subsequent transcription and scoring. The tasks were presented in two sessions in different pseudorandom orders by starting the first session with the background measures (Mattis Dementia Rating Scale, Beck Depression Inventory, Mill Hill vocabulary scale) and by alternating between WM and attentional focalization/control tasks. Note that the study was part of a larger study including additional response-speed-based measures of general attention and processing speed not reported here, this study focusing on performance-based measures for optimal between-task comparison.

A Bayesian statistical approach was used (see, e.g., Dienes, 2011; R. D. Morey & Rouder, 2011). This approach has the advantage of relying on a model comparison rationale to select and quantify the strength of evidence associated with each model, and crucially, it allows testing the strength of evidence for and against an effect of interest (i.e., positive evidence for the null hypothesis). The Bayesian framework does not involve traditional p values, thereby avoiding multiple testing problems such as α inflation (Wagenmakers et al., 2018). All analyses were based on BFs, which can be considered a relative measure of statistical evidence (R. D. Morey et al., 2016). Although there are no fixed thresholds for BF values, we used the following categories for describing the strength of evidence: a BF of at least one is considered to indicate anecdotal evidence; a BF of at least three is considered to indicate moderate evidence; a BF of at least 10 is considered to provide strong evidence; a BF of at least 30 is considered to provide very strong evidence; and a BF of at least 100 is considered to indicate decisive evidence (Jeffreys, 1961). We determined the minimal sample size based on a statistical sensitivity analysis estimating the probability of obtaining a specific BF value for a specific statistical test as a function of simulated sample sizes and an a priori estimation of the effect size (Schönbrodt & Wagenmakers, 2018). By using the BFDA (Bayes factor design analysis) package (Schönbrodt, 2016), we determined that a sample size of 150 participants allows obtaining a BF value > 10 in favor of a minimally meaningful correlation of $R > .30$ in 100% of simulated samples, if such an association exists and a BF value > 10 for the absence of such a correlation in >70% of cases if this association does not exist (for a stretched β prior value of 1.0 as used in subsequent analyses).

Transparency and Openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study, and we follow Journal Article Reporting Standartds (Kazak, 2018). All data, analysis code, and tasks are available at https://osf.io/2xg8e/?view_only=0adbc2c65bf547ac94de48507192592d (Majerus, 2024). Data were analyzed using JASP software package (https://jasp-stats.org/; Version 0.17.2 for all Bayesian analyses; Version 0.19.1 for latent variable analyses). Sample size calculations were run within R, Version 3.6.1 (R Development Core Team, 2019). This study's design and its analysis were not preregistered.

Results

Table 1 shows the descriptive statistics and split-half reliability coefficients for all experimental measures. The measures showed normal or close-to-normal distributions based on Q-Q plot analysis, with moderate to high split-half reliability values except for the serial order score in the word immediate serial recall task. This score is, as explained in the Method section, a difference score aimed at isolating order recall performance relative to item recall performance; difference scores are typically associated with lower reliability levels. Furthermore, as expected, task performance decreased across all measures in the OA group relative to the YA group (see Bayesian two-sample *t* tests in Table 1).

Correlation Analyses

A first set of analyses assessed general associations between the different WM and attentional measures. Bayesian correlation analyses were conducted within each group. Figure 2 reports the correlations, their credible interval, and the range of the associated BF_{10} value. As shown in Figure 2, for both age groups, the two measures within each WM domain of interest (item WM, order WM, complex WM) showed robust intercorrelation. This was also the case, even if to a lesser extent, for within-domain correlations for the attentional measures. The two scope of attention measures showed a more robust correlation in the YA group than in the OA group, while the reverse was observed for the two control of attention measures, with even evidence for the null in the YA group. Regarding between-domain correlations, item and order WM measures showed the expected low levels of association with evidence for the null in the OA group when considering associations between the serial order score for the immediate serial recall task and the two item WM tasks. When considering the serial order reconstruction task, robust associations were observed with both item WM tasks and in both groups. This discrepancy in associations as a function of order WM task likely reflects the fact that the serial order score in the immediate serial recall is already corrected for item recall performance, while this is not the case in the serial order reconstruction task. Although item WM recall requirements are minimized in the latter task, item WM is not completely absent, as maintenance of order information also implies maintenance of the associated items. Next, as expected, the complex WM measures, involving processing of both item and order information, showed robust association with the other item WM and serial order WM measures in both age groups. For the attentional measures, as predicted, scope of attention measures showed robust associations with all WM measures in both groups, these associations being weaker only for three out of the 24 correlations and involved the order score for the immediate serial recall task, the measure associated with the lowest reliability (see Figure 2; see also Figure A1 for correlations corrected for maximum possible correlation based on reliability estimates for each variable, showing that attenuation-corrected correlations increased correlations involving the order score measure and led to values closer to correlations for the other WM measures). Furthermore, in the YA adult group, the two control of attention measures showed overall small correlations with the simple order WM and item WM tasks ($0.13 \leq r \leq 0.18$ for six of eight correlations), while in the OA group, the correlations were higher ($0.26 \leq r \leq 0.43$ for six of eight correlations). When considering associations between the control of attention and the complex WM span tasks, both groups showed correlations of moderate size ($0.22 \leq r \leq 0.37$ for seven of eight correlations), as predicted. Finally, the scope of attention and control of attention also showed correlations of moderate size in both groups ($0.25 \leq r \leq 0.41$ for six of eight correlations).

Partial Correlation and Regression Analyses

After having examined the raw correlation profiles between the different WM and attention measures, we examined the specificity of these associations. We correlated the scope of attention and WM measures after partialling out control of attention measures, and we

Table 1
Descriptive Statistics for Experimental Measures

Task	Reliability[a]	YA group *M* (*SD*)	OA group *M* (*SD*)	BF_{10} value for age-group effect
Item WM				
Nonword delayed repetition	0.74	21.69 (4.54)	19.03 (4.52)	2.43×10^{4}
Word immediate serial recall-item	0.82	82.65 (7.88)	72.38 (8.92)	3.20×10^{19}
Order WM				
Serial order reconstruction	0.82	139.84 (15.70)	125.78 (15.65)	6.69×10^{10}
Word immediate serial recall-order	0.59	−6.79 (2.80)	−11.11 (6.09)	2.66×10^{27}
Complex WM				
Item and serial order reconstruction	0.90	139.40 (16.50)	117.72 (18.26)	1.63×10^{20}
Listening span	0.86	49.53 (4.03)	41.63 (5.85)	1.76×10^{30}
Scope of attention				
Running span	0.91	3.37 (0.78)	2.84 (0.62)	2.53×10^{7}
Visual array	0.87	51.18 (4.91)	37.97 (8.70)	7.50×10^{39}
Control of attention				
Running span-controlled	0.88	2.27 (0.58)	1.75 (0.52)	4.68×10^{11}
Visual search	0.85	42.48 (7.18)	28.08 (8.21)	4.62×10^{39}

Note. YA = young adult; OA = older adult; BF = Bayes factor; WM = working memory.
[a] Split-half reliability coefficient based on the Spearman–Brown prophecy formula (Brown, 1910; Spearman, 1910).

Figure 2

Raw Correlations and Associated 95% Credible Intervals for the YA Group (Upper Panel) and the OA Group (Lower Panel)

	Group YA	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10
WM item	Task 1	0.45 0.31 - 0.56	0.37 0.22 - 0.50	0.13 -0.03 - 0.28	0.40 0.26 - 0.52	0.34 0.19 - 0.47	0.29 0.14 - 0.43	0.31 0.16 - 0.44	0.14 -0.02 - 0.29	0.13 -0.03 - 0.28
	Task 2	1	0.44 0.30 - 0.55	0.16 -0.00 - 0.31	0.55 0.42 - 0.65	0.46 0.57- 0.32	0.56 0.44 - 0.66	0.36 0.21 - 0.49	0.24 0.08 - 0.38	0.18 0.02 - 0.32
WM order	Task 3		1	0.34 0.19 - 0.47	0.72 0.63 - 0.79	0.52 0.39 - 0.62	0.59 0.47 - 0.68	0.27 0.12 - 0.41	0.16 0.00 - 0.31	0.28 0.13 - 0.42
	Task 4			1	0.43 0.29 - 0.55	0.30 0.15 - 0.44	0.28 0.12 - 0.42	0.11 -0.05 - 0.26	0.18 0.02 - 0.33	0.13 -0.03 - 0.28
WM complex	Task 5				1	0.49 0.36 - 0.60	0.60 0.48 - 0.69	0.36 0.21 - 0.48	0.34 0.19 - 0.47	0.29 0.14 - 0.43
	Task 6					1	0.43 0.29 - 0.55	0.30 0.14 - 0.43	0.30 0.15 - 0.44	0.16 0.00 - 0.31
Attention scope	Task 7						1	0.32 0.16 - 0.45	0.29 0.14 - 0.43	0.10 -0.06 - 0.25
	Task 8							1	0.32 0.17 - 0.45	0.25 0.10 - 0.39
Attention control	Task 9								1	0.05 -0.11 - 0.21

	Group OA	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10
WM item	Task 1	0.50 0.37 - 0.61	0.30 0.15 - 0.44	0.03 -0.13 - 0.19	0.41 0.26 - 0.53	0.38 0.23 - 0.50	0.35 0.20- 0.48	0.27 0.12 - 0.41	0.28 0.12 - 0.42	0.26 0.11 - 0.40
	Task 2	1	0.33 0.17 - 0.46	-0.07 -0.23 - 0.09	0.41 0.27 - 0.53	0.47 0.33 - 0.58	0.36 0.21 - 0.49	0.27 0.11 - 0.41	0.31 0.15 - 0.44	0.30 0.14 - 0.43
WM order	Task 3		1	0.41 0.26 - 0.53	0.56 0.44 - 0.66	0.43 0.29 - 0.55	0.44 0.30 - 0.56	0.23 0.07 - 0.37	0.43 0.28 - 0.55	0.18 0.02 - 0.32
	Task 4			1	0.26 0.10 - 0.40	0.25 0.10 - 0.39	0.18 0.02 - 0.33	0.09 -0.07 - 0.24	0.31 0.16 - 0.44	0.03 -0.13 - 0.19
WM complex	Task 5				1	0.48 0.34 - 0.59	0.35 0.20 - 0.48	0.21 0.06 - 0.36	0.27 0.12 - 0.41	0.22 0.06 - 0.36
	Task 6					1	0.42 0.28 - 0.54	0.22 0.06 - 0.36	0.37 0.22 - 0.49	0.34 0.19 - 0.47
Attention scope	Task 7						1	0.17 0.01 - 0.32	0.41 0.26 - 0.53	0.27 0.12 - 0.41
	Task 8							1	0.19 0.03 - 0.34	0.29 0.13 - 0.43
Attention control	Task 9								1	0.28 0.12 - 0.41

$BF_{10}>100$; $BF_{10}>10$; $BF_{10}>3$; $BF_{10}<3$; $BF_{10}<0.33$

Note. BF_{10} value ranges are indicated by the color of each cell, according to the scale shown at the bottom of the figure. Task 1: nonword delayed repetition; Task 2: word immediate serial recall-item; Task 3: serial order reconstruction; Task 4: word immediate serial recall-order; Task 5: item and serial order reconstruction; Task 6: listening span; Task 7: running span; Task 8: visual array; Task 9: running span-controlled; Task 10: visual search. YA = young adult; WM = working memory; OA = older adult; BF = Bayes factor. See the online article for the color version of this figure.

correlated the control of attention and WM measures after partialling out the scope of attention measures. This allowed us to examine the specific contribution of each type of attention after controlling for the shared variance between the two attention measures, including variance related to memory load further shared with the WM tasks. The strength of each association was assessed via Bayesian multiple regression analyses that determined the incremental evidence associated with a regression model, including the predictor of interest, relative to a regression model including the predictor to be partialled out. More precisely, when assessing a partial correlation involving the verbal scope of attention task (running span), the verbal control of attention task was partialled out (running span-controlled), and when assessing a partial correlation involving the visual scope of attention task (visual array), the visual control of attention task (visual search) was partialled out. By comparing attentional tasks from the same stimulus domain, we were able to maximally control for the shared variance between the two attentional tasks. Figure 3 indicates partial correlations and credible intervals for the regression coefficients of each analysis, as well as associated BF_{10} value ranges. First, for both groups, we observed moderate to decisive Bayesian evidence for a specific role of the two scopes of attention measures in simple item and order WM as well as complex WM measures, after controlling for the influence of control of attention ($0.19 \leq r_p \leq 0.57$ for 19 of 24 correlations). These associations were again weaker for the order score of the immediate serial recall task, possibly due to the direct control of item recall abilities in this measure, removing the variance in scope of attention abilities that supports item WM—but, as noted previously, the lower reliability of this measure could also have contributed to this situation. Second, the partial correlation analyses supported the task-dependent intervention of control of attention abilities by revealing a specific association for the two controls of attention measures with the complex WM tasks (moderate to decisive Bayesian evidence for 11 of 16 correlations; $0.21 \leq r_p \leq 0.56$). Critically, this analysis showed very small partial correlations between control of attention and the simple item and order WM tasks in the YA group, with even evidence for an absence of specific association ($BF_{01} > 3$) for four of eight partial correlations ($-0.01 \leq r_p \leq 0.09$). This pattern of results was also supported by an analysis of the credible intervals of the regression coefficients. A comparison of these coefficients for the verbal scope of attention and control of attention predictors or for the visual scope of attention and control of attention predictors in the YA group (see Figure 3) showed nonoverlapping credible intervals of the regression coefficients for four of eight comparisons ("running span" vs. "running span-controlled" for regression on the item immediate serial recall and serial order reconstruction dependent variables; "visual array" vs. "visual search" for regression on the nonword delayed repetition and item immediate serial recall-dependent variables). On the other hand, in the OA group, only one partial correlation was associated with evidence for the null ("visual search"* "immediate serial recall-

Figure 3

Partial Correlations and Associated BF_{10} Value Range for the YA Group (Columns to the Left) and the OA Group (Columns to the Right; See Text for Details)

		YA				OA			
		Attention scope		Attention control		Attention scope		Attention control	
		Task 7	Task 8	Task 9	Task 10	Task 7	Task 8	Task 9	Task 10
WM item	Task 1	.26 0.08 – 0.41	.29 0.13 - 0.44	.06 -0.08 – 0.15	.06 -0.03 - 0.17	.27 0.13 -0.45	.21 0.00 -0.35	.16 -0.00 -0.28	.20 0.00 -0.33
	Task 2	.53 0.41 – 0.67	.33 0.18 - 0.47	.09 -0.03 – 0.16	.09 -0.05 - 0.19	.27 0.09 -0.45	.20 0.00 -0.31	.19 -0.00 -0.34	.24 0.00 -0.36
WM order	Task 3	.57 0.45 – 0.70	.22 0.00 – 0.33	-.01 -0.08 – 0.07	.23 -0.00 - 0.35	.32 0.16- 0.45	.19 -0.04 -0.24	.30 0.14 – 0.44	.12 -0.00 -0.31
	Task 4	.24 0.11 – 0.55	.08 -0.03 - 0.23	.11 -0.02 – 0.32	.11 -0.03 - 0.26	.06 -0.08 – 0.17	.08 -0.00 -0.14	.26 0.11 – 0.44	.01 -0.05 -0.08
WM complex	Task 5	.56 0.41 – 0.68	.31 0.14 – 0.44	.21 0.00 – 0.28	.23 0.00 - 0.33	.27 0.12 – 0.45	.16 -0.00 -0.29	.16 0 – 0.29	.17 0.00 -0.30
	Task 6	.38 0.20 – 0.51	.27 0.12 - 0.44	.21 0.00 – 0.31	.09 -0.02 - 0.21	.32 0.16 – 0.49	.13 -0.01 -0.27	.24 0.00 – 0.36	.30 0.14 -0.46

$BF_{10}>100$; $BF_{10}>10$; $BF_{10}>3$; $BF_{10}<3$; $BF_{10}<0.33$

Note. The BF_{10} values are based on a multiple regression approach and reflect the incremental evidence associated with the predictor-of-interest relative to the predictor to be partialled out. The numbers in small font show the 95% credible intervals of the regression coefficients. Task 1: nonword delayed repetition; Task 2: word immediate serial recall-item; Task 3: serial order reconstruction; Task 4: word immediate serial recall-order; Task 5: item and serial order reconstruction; Task 6: listening span; Task 7: running span; Task 8: visual array; Task 9: running span-controlled; Task 10: visual search. YA = young adult; OA = older adult; WM = working memory; BF = Bayes factor. See the online article for the color version of this figure.

order”), and four correlations were associated with moderate to decisive evidence in favor of a specific association between control of attention and simple item and order WM measures ($0.20 \leq r_p \leq 0.30$ for four of eight correlations). Accordingly, all confidence intervals for the regression coefficients of the scope of attention and control of attention predictors overlapped in the OA group for regression on the simple item and order WM measures.

These results suggest partially age-dependent associations between the simple item/order WM and control of attention measures. We therefore directly examined the role of age as a modulator variable in an additional analysis. We merged the YA and OA datasets and ran a series of Bayesian multiple regression analyses predicting the different WM measures by the different attention measures, after including an Age × Predictor interaction regressor. Figure 4 presents the BF_{10} values for the model including the interaction term relative to the same model without the interaction term as well as the credible intervals of the associated regression coefficient. As shown in Figure 4 and as expected, evidence for the absence of an interaction with age was observed for six of eight associations regarding scope of attention and simple item and serial order WM measures. For the control of attention measures, although most associations also did not show direct evidence for an interaction with age, moderate evidence in favor of such an interaction was observed for the association between the verbal control of attention measure (running span-controlled) and the serial order reconstruction measure.

Finally, as noted earlier, this study was not designed to use a latent variables approach. We, however, conducted post hoc analyses using structural equation modeling in order to confirm the theoretical associations between the tasks when considered together. For each age-group, we tested three models (see Figures A2 and A3). Model 1 reflects the expected theoretical task design of this study with a control of attention variable, a scope of attention variable, a simple item WM variable, a simple order WM variable, and a complex WM variable. Model 2 assumes that the attentional tasks do not measure any specific component beyond the attentional and memory demands already involved in the WM tasks. Model 3 assumes that the four attentional tasks measure a common general attention factor. As shown in Table A1, for the YA group, Model 1 was the most strongly supported model for all fit indices, and its fit was statistically higher relative to the two other models as reflected by $\Delta\chi^2$ tests, Model 1 > Model 3: $\Delta\chi^2(4) = 9.33$, $p = .05$; Model 3 > Model 2: $\Delta\chi^2(3) = 12.65$, $p < .001$. Model 2, considering no specific scope of attention and control of attention variables, was associated with the lowest fit. For the OA group, it was Model 3 that was associated with the best fit for the vast majority of indices (see Table A2), followed by Model 1. Model 2 was again associated with the lowest fit and was statistically different from the two other models, while Model 1 and Model 3 did not statistically differ as reflected by $\Delta\chi^2$ tests, Model 1 = Model 3: $\Delta\chi^2(4) = 2.47$, $p = .65$; Model 3 > Model 2: $\Delta\chi^2(3) = 20.87$, $p < .001$. While not allowing to directly test the associations between the different latent variables due to limited statistical power, the pattern of results of the structural equation models overall confirms the results of the preceding partial correlation and regression analyses by showing that for the YA group, specific attentional and WM variables need to be distinguished, while in the OA group, although attention and WM variables also need to be distinguished, the attention variable can be fit via a single, general attention component.

Figure 4

BF_{10} Values for the Age × Predictor Interaction Regressor for Predicting the Different WM Tasks by the Different Attention Tasks in the Merged Data Set

		Attention scope		Attention control	
		Task 7	Task 8	Task 9	Task 10
WM item	Task 1	0.50 -0.01 - 0.04	0.16 -0.00 - 0.00	0.54 -0.02 - 0.06	0.32 -0.00 - 0.00
	Task 2	0.10 -0.04 - 0.03	0.33 -0.01 - 0.00	0.23 -0.01 - 0.10	0.25 -0.00 - 0.01
WM order	Task 3	0.11 -0.07 - 0.05	0.26 -0.02 - 0.00	4.84 0.00 - 0.29	0.24 -0.01 - 0.00
	Task 4	0.16 -0.02 - 0.03	0.21 -0.02 - 0.00	0.92 -0.00 - 0.08	0.26 -0.00 - 0.00
WM complex	Task 5	0.12 -0.11 - 0.03	0.35 -0.02 - 0.00	0.11 -0.07 - 0.12	0.12 -0.01 - 0.01
	Task 6	1.63 0.00 - 0.07	0.13 -0.00 - 0.00	0.52 0.00 - 0.07	1.44 0.00 - 0.01

BF_{10}>100; BF_{10}>10; BF_{10}>3; BF_{10}< 3; BF_{10}< 0.33

Note. The numbers in small font show the 95% credible intervals of the standardized interaction regression coefficient. Task 1: nonword delayed repetition; Task 2: word immediate serial recall-item; Task 3: serial order reconstruction; Task 4: word immediate serial recall-order; Task 5: item and serial order reconstruction; Task 6: listening span; Task 7: running span; Task 8: visual array; Task 9: running span-controlled; Task 10: visual search. WM = working memory; BF = Bayes factor. See the online article for the color version of this figure.

General Discussion

This study examined the role of scope of attention versus control of attention abilities on verbal WM for item or serial order information in simple and complex WM tasks. In YA participants, the scope of attention measures was the most robustly associated with all types of WM tasks; control of attention measures were more specifically and additionally associated with performance in the complex WM tasks. OA participants presented a similar pattern of results, with however increased reliance on control of attention already for the simple WM tasks, and this particularly when involving serial order information.

While the distinction between the role of scope of attention and control of attention in WM tasks was proposed by Cowan (1988), no study so far has directly assessed the specific roles of these attentional abilities on the different aspects that define verbal WM. The present study examined this question by distinguishing two fundamental dimensions of verbal WM: the type of information to be maintained (item vs. serial order) and the type of task (simple vs. complex). A first finding is the observation that all aspects of WM examined in this study were associated with scope of attention abilities, in line with our initial predictions. Following attention-based models of WM (Barrouillet et al., 2021; Cowan, 1995; Cowan et al., 2024), even the most simple WM task should involve basic attentional focalization to encode the stimuli to be maintained and recalled. The association with scope of attention measures was slightly reduced for one specific WM measure only, the order score in the immediate serial recall task. As already noted earlier, this measure was obtained after mathematically correcting for item recall ability in the same task; this specific procedure may have removed variance explained by scope of attention ability as this ability also determines item recall—in addition to leading to lower measurement reliability. A second finding is that control of attention abilities were specifically associated with verbal WM measures mainly when task complexity increased as was the case for the complex listening span task as well as for the combined item and serial order reconstruction task involving processing of item and serial order information in the presence of distractor information. This result is compatible with previous latent-variable approaches considering that complex WM tasks strongly involved control of attention (Cowan et al., 2005; Shipstead et al., 2012). The present study goes one step further by showing a direct association between complex WM tasks and independent measures of control of attention.

It is important to note here that the verbal and visual tasks used to probe each type of attentional ability showed predominantly similar profiles of associations with the different verbal WM measures, supporting the assumption that these associations reflect links between amodal attentional abilities and not (only) task- and stimulus-domain-specific associations. While these results support the implicit or explicit assumption of amodal attentional processes assumed by most attentional frameworks of WM (Barrouillet et al., 2004; Cowan, 1988; Cowan et al., 2024; Engle et al., 1999; Kane et al., 2001), it should be noted here, however, that some studies have suggested a possible differentiation of attentional processes as a function of the auditory–verbal versus visual domain. For example, Majerus et al. (2018) showed that although attentional control is supported in the brain by neural patterns in bilateral intraparietal sulci, the neural patterns differed depending on attention to the auditory–verbal versus visual stimulus modality; this finding could, however, be explained by the fact the content of the neural attentional priority maps will necessarily differ as a function of the type of target stimuli to prioritize (Chelazzi et al., 2014; Gottlieb, 2007). C. C. Morey and Mall (2012), as well as C. C. Morey et al. (2013), also showed that variables affecting domain-general attentional control appear to have a differential impact on visual versus verbal information (see also Vergauwe et al., 2010). In any case, a nonperfect overlap between auditory-verbal and visual attentional control is also suggested by our own data, with the verbal and visual versions of each type of attentional ability showing overall relatively small correlations (in comparison to the correlations between most of the verbal WM measures) and reaching even evidence for the null for the verbal and visual control of attention tasks in the OA group.

A further novel finding of this study is the possibly age-dependent nature of the associations between the different verbal WM components and attentional abilities. While in both groups, control of attention abilities showed specific associations with the most complex WM tasks, in the OA group, control of attention abilities also showed associations with measures assessing simple recall of item or serial order information. This possible interaction with age was supported for the serial order reconstruction measure via a Bayesian regression analysis that included an Age × Attentional Predictor interaction regressor. These results suggest that verbal WM tasks, even when not requiring complex processing, may be more challenging in terms of control of attention for OA participants. This could be the result of the difficulties OA participants show in implementing fast and direct stimulus encoding and maintenance processes as a result of slowed and/or noisy stimulus identification processes (e.g., Lindenberger & Ghisletta, 2009; McCoy et al., 2005). Additional recruitment of control of attention may thus become necessary to maintain efficient task performance, even for noncomplex WM tasks in OAs, as well as in scope of attention tasks. This interpretation is also consistent with the results of the additional latent variable analyses, showing that in older participants, the different attentional variables could be fit by a single attentional component, which may reflect a common control of attention component. Stronger recruitment of attentional control in older age is made possible by the fact that attentional control ability does not appear to be significantly diminished throughout the aging process (e.g., Greene et al., 2020). At the same time, we need to remain cautious about the results here given that the differences in strength of association between control of attention and WM measures between the YA and OA groups were not particularly large, as revealed by the majority of null effects when directly comparing the associations between groups in the Age × Group interaction regression analysis. Finally, the fact that increased attentional control recruitment was most robustly observed for the serial order reconstruction measure in the OA group could be considered to support an asymmetry between attentional control requirements for serial order versus item components, as shown in a set of recent studies by Guitard et al. (2021, 2022; Guitard & Cowan, 2023a). At the same time, we could not find evidence for such an asymmetry in our younger adult participant group, control of attention measures showing very poor specific associations with both the item and serial order WM measures.

The present results refine our understanding of the links between attention and verbal WM by confirming not only that scope of attention and control of attention need to be distinguished, but also by showing that different aspects of WM recruit these two aspects of attention to various degrees. Models like the embedded processes framework by Cowan (1999; Cowan et al., 2024) are the most compatible with the results of this study, as they explicitly distinguish between these two components of attention in WM as opposed to other models. The present data, however, further indicate that models of WM also need to consider the interactions between these attentional aspects and the different dimensions of WM. We propose below an outline of a functional architecture that considers these interactions (see Figure 5). The architecture is an extension of the framework presented in Majerus (2009) and in Majerus and D'Argembeau by integrating the scope of attention and the control of attention components as proposed by Cowan (1988, 1999). The architecture also includes a more precise definition of the concept of scope of attention and, particularly, of its association with memory. In our partial correlation analyses, we controlled for memory load associated with the attentional tasks by assuming that the memory-related shared variance between an attentional task and a WM task will be canceled out when adding a second attentional task sharing a similar memory load. Also, the latent variable analyses showed that for both age groups, distinct components define attention and WM measures. However, by allowing us to be aware of a limited set of information at one time and to be able to report it, the scope of attention also serves a memory function, even if it is a very basic and nonstrategic one. For this reason, we construed the scope of attention component as a sliding window that reads out currently active representations in both item and serial order components (Figure 5, Panel a) or in one of the components, depending on whether the task involves both components, as in standard immediate serial recall tasks, or involves only one component, as in the single nonword repetition task used in this study (Figure 5, Panel b). Capacity limits of the scope of attention will be more quickly reached when this readout process needs to cover both the item and serial order components. Capacity limits of the scope of attention may also be more quickly reached when information needs to be read out selectively in the serial order component versus the item component, as serial order readout will inevitably also involve the connections that link the serial order representations to corresponding items. As already noted, the results of our study provide, however, only partial evidence for this assumption by showing enhanced intervention of the control of attention component (indicating that capacity limits of the scope of attention have been reached; see below) for serial order WM measures only in OA participants and for one of the two serial order measures. The control of attention component will intervene when passive readout of information within the scope of attention is not sufficient for task performance. In that case, the control component can selectively cue specific types of items or specific serial positions, if the task involves maintaining and/or processing only a subset of items or positions that are activated (as in the listening span task and in the item-order serial order reconstruction task of the present study; Figure 5, Panels c and d). The control of attention component can also orient top-down attentional resources more broadly to the item or serial order processing components, when information in these components is more difficult to activate (due to noisy input, hearing impairment, slowed access) in order to optimize activation levels and their readout by the scope of attention (Figure 5, Panel e). This situation could reflect the stronger recruitment of control of attention for simple item and serial order recall in OA participants in the present study. Finally, in line with Cowan (1988, 1999; Cowan et al., 2024), the control of attention component can also directly influence information readout by the focus of attention, by prioritizing specific representations and inhibiting others within the scope of attention, or by implementing attentional refreshing or elaboration over target activations (Ricker & Vergauwe, 2022; Figure 5, Panel f). The flexible nature of control of attention allows for adaptation and change of information being present in the scope of attention as a function of task requirements. Future behavioral and modeling studies will need to empirically test different predictions, such as the intervention of the control of attention component only when scope of attention readout is not sufficient versus a minimal involvement of control of attention in any WM situation that may be needed just to inform the scope of attention that some information should be attended to and read out.

Limitations and Constraints on Generality

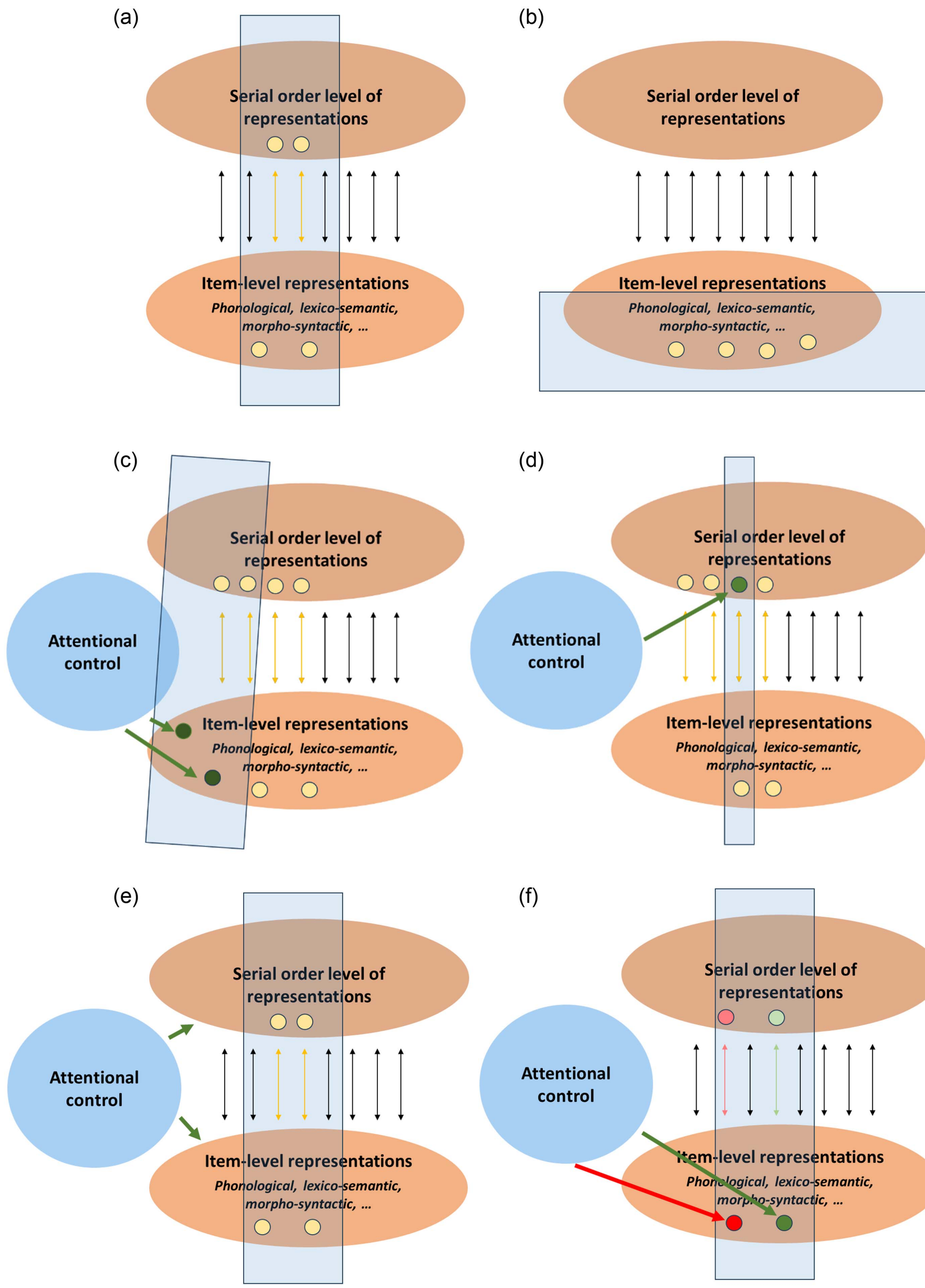
This study has one limitation that needs to be mentioned. As already noted, this study was not designed for a latent variable approach given that its aim was to examine the role of theoretically defined types of attention in different types of WM tasks based on a multicomponent approach of verbal WM, by explicitly assuming that no single WM task will involve the different WM components and types of attention to the same extent. The question examined in this study is foremost a pragmatic one: For a given WM task and a given age-group, what are the attentional processes that intervene, based on two types of attention as defined by WM models and examined so far mainly in the context of complex WM tasks? Although we provide a post hoc latent variable analysis confirming the overall separability of the different theoretical constructs used, this study did not have sufficient statistical power nor a sufficient number of indicators per construct for full structural equation modeling examining the pattern of associations between the constructs and their differences between age groups. While this study provides novel insights into the heterogeneity of commonly used WM tasks in terms of attentional processes involved and age groups being tested, full latent variable approaches will allow for drawing stronger theoretical conclusions about the degree of overlap between the concepts of attention and WM.

In addition, this study targeted specifically YAs aged 18–30 years and older healthy adults aged 65–77 years. These participants groups were chosen to examine the associations between different types of attention and WM tasks in a sample considered to represent the general population of young and OAs of the French-speaking Belgian population. However, the pattern of results reported here may be different for age groups not examined in this study. More particularly, the partially age-dependent associations between control of attention and WM tasks may become stronger, if participants older than 77 years are examined. Results may also differ, if the same study is conducted in children.

To conclude, the present study furthers our understanding of the task-dependent association of verbal WM with different types of attention, an association that varies as a function of the WM component involved and, to some extent, as a function of age. The data call for dynamic theoretical frameworks of WM that take into account the variable nature and complexity of WM environments in terms of attentional process requirements.

Figure 5

Theoretical Outline of the Intervention of Scope of Attention (Transparent Rectangle) and Control of Attention in Different WM Task Contexts



Note. (a and b) Readout by the scope of attention of currently active information, at the serial order and/or item level, as a function of task requirements. (c and d) Additional activation (green dots) of item (c) or of serial order representations (d) by the control of attention component, as needed in complex WM tasks and/or when the scope of attention is narrowed (represented by the narrower rectangle in Figure d). (e) Broader orientation of control of attention resources to the item and serial order components to facilitate activation of information in these components (e.g., in case of noisy input due to hearing impairment) and associated readout by the scope of attention. (f) Both activation and inhibition (red dot) functions of the control of attention, for example, when distracting information enters the scope of attention. WM = working memory. See the online article for the color version of this figure.

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(*Appendix follows*)

Appendix

Additional Tables and Figures Reporting Corrected Reliability Coefficients and SEM Results

Figure A1

Comparison of Raw Correlation and Attenuation-Corrected Correlations (in Italics) for the YA Group (Upper Panel) and the OA Group (Lower Panel)

Group YA		Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10
WM item	Task 1	0.45	0.37	0.13	0.40	0.34	0.29	0.31	0.14	0.13
		0.58	*0.47*	*0.20*	*0.49*	*0.43*	*0.35*	*0.39*	*0.17*	*0.16*
	Task 2	1	0.44	0.16	0.55	0.46	0.56	0.36	0.24	0.18
			0.54	*0.23*	*0.64*	*0.55*	*0.65*	*0.43*	*0.28*	*0.22*
WM order	Task 3		1	0.34	0.72	0.52	0.59	0.27	0.16	0.28
				0.49	*0.84*	*0.62*	*0.68*	*0.32*	*0.19*	*0.34*
	Task 4			1	0.43	0.30	0.28	0.11	0.18	*0.13*
					0.59	*0.42*	*0.38*	*0.15*	*0.25*	*0.18*
WM complex	Task 5				1	0.49	0.60	0.36	0.34	0.29
						0.56	*0.66*	*0.41*	*0.38*	*0.33*
	Task 6					1	0.43	0.30	0.30	0.16
							0.49	*0.35*	*0.35*	*0.18*
Attention scope	Task 7						1	0.32	0.29	0.10
								0.36	*0.32*	*0.11*
	Task 8							1	0.32	0.25
									0.37	*0.29*
Attention conttrol	Task 9								1	0.05
										0.06

(*figure continues*)

(*Appendix continues*)

Figure A1 (*continued*)

Group OA		Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10
WM item	Task 1	0.50	0.30	0.03	0.41	0.38	0.35	0.27	0.28	0.26
		0.64	*0.39*	*0.05*	*0.50*	*0.48*	*0.43*	*0.34*	*0.35*	*0.33*
	Task 2	1	0.33	-0.07	0.41	0.47	0.36	0.27	0.31	0.30
			0.40	*-0.10*	*0.48*	*0.56*	*0.42*	*0.32*	*0.35*	*0.37*
WM order	Task 3		1	0.41	0.56	0.43	0.44	0.23	0.43	0.18
				0.59	*0.65*	*0.51*	*0.51*	*0.27*	*0.51*	*0.22*
	Task 4			1	0.26	0.25	0.18	0.09	0.31	0.03
					0.36	*0.35*	*0.25*	*0.13*	*0.43*	*0.04*
WM complex	Task 5				1	0.48	0.35	0.21	0.27	0.22
						0.55	*0.39*	*0.24*	*0.30*	*0.25*
	Task 6					1	0.42	0.22	0.37	0.34
							0.47	*0.25*	*0.43*	*0.40*
Attention scope	Task 7						1	0.17	0.41	0.27
								0.19	*0.46*	*0.31*
	Task 8							1	0.19	0.29
									0.22	*0.34*
Attention conttrol	Task 9								1	0.28
										0.32

Note. The attenuation correction formula provided by Spearman (1910) was used, based on the split-half reliability estimates provided in Table 1. These correlations are provided for informational purposes only. See Winne and Belfry (1982) for a critical discussion of the limits of the use of this correction. Task 1: nonword delayed repetition; Task 2: word immediate serial recall-item; Task 3: serial order reconstruction; Task 4: word immediate serial recall-order; Task 5: item and serial order reconstruction; Task 6: listening span; Task 7: running span; Task 8: visual array; Task 9: running span-controlled; Task 10: visual search. YA = young adult; WM = working memory; OA = older adult. See the online article for the color version of this figure.

(*Appendix continues*)

Table A1
Fit Indices for SEMs for the YA Group

Fit index	Model 1[a]	Model 2[b]	Model 3[c]
χ^2 test	**38.50, *p* = .04, *dl* = 25**	60.47, *p* < .01, *dl* = 32	47.82, *p* = .02, *dl* = 29
AIC	**8,407.57**	8,415.21	8,408.57
SSABIC	**8,401.86**	8,410.77	8,403.72
CFI	**0.971**	0.939	0.959
NNFI	**0.948**	0.914	0.937
IFI	**0.972**	0.940	0.961
RMSEA	**0.059**	0.076	0.065
SRMR	**0.046**	0.050	**0.046**

Note. Highest fit marked in bold. Criteria for fit: $\chi^2 = p > .05$ (p), AIC and SSABIC: the lowest score; CFI, NNFI, and IFI: >.90; RMSEA and SRMR: <.08 (Awang, 2012; Byrne, 1994; West et al., 2023); for highest precision, three decimals are provided for fit indices. SEM = structural equation model; YA = young adult; AIC = Akaike; SSABIC = sample size–adjusted Bayesian; CFI = comparative fit Index; NNFi = Bentler–Bonett Normed Fit Index; IFI = Bollen's Incremental Fit Index; RMSEA = root-mean-square error of approximation; SRMR = standardized root-mean-square residual.
[a] Model 1: variable (indicators): scope of attention (running span; visual array), control of attention (running span-controlled; visual search), item working memory (WM; nonword delayed repetition; word immediate serial recall-item), order WM (serial order reconstruction; word immediate serial recall-order), complex WM (item and serial order reconstruction; listening span). [b] Model 2: variable (indicators): item WM (nonword delayed repetition; word immediate serial recall-item, running span), order WM (serial order reconstruction; word immediate serial recall-order, visual array), complex WM (item and serial order reconstruction; listening span; running span-controlled; visual search). [c] Model 3: variable (indicators): general attention (running span; visual array; running span-controlled; visual search), item WM, order WM, and complex WM.

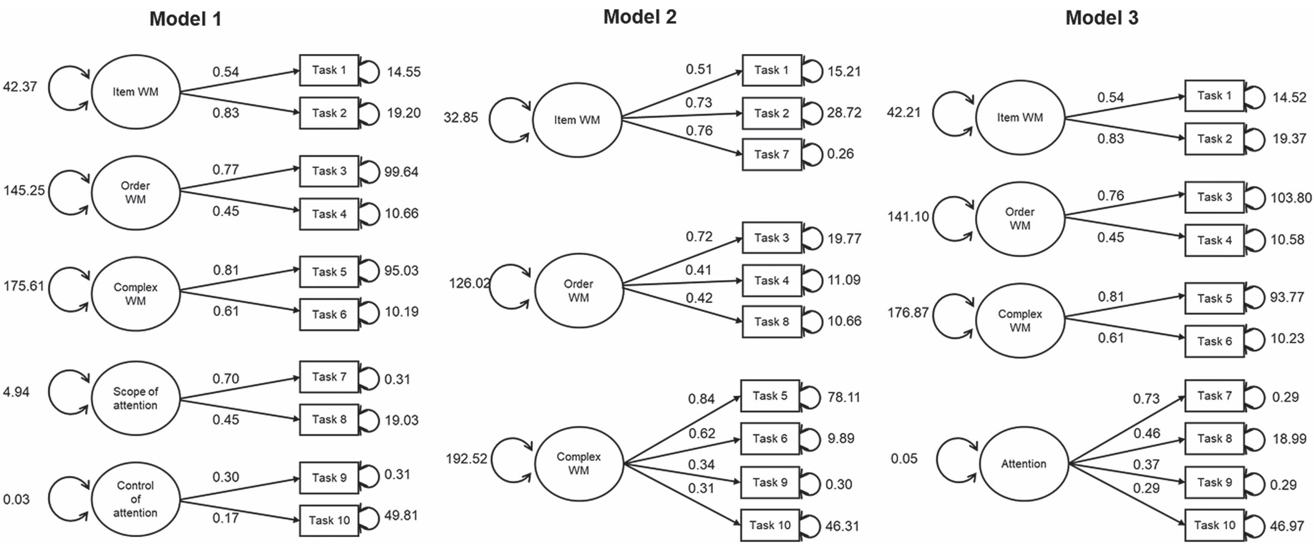
Table A2
Fit Indices for SEMs for the OA Group

Fit index	Model 1[a]	Model 2[b]	Model 3[c]
χ^2 test	43.34, *p* = .01, *dl* = 25	66.69, *p* < .01, *dl* = 32	**45.82, *p* = .02, *dl* = 29**
AIC	8,842.24	8,851.59	**8,836.71**
SSABIC	8,836.34	8,846.71	**8,831.40**
CFI	0.950	0.905	**0.954**
NNFI	0.910	0.866	**0.929**
IFI	0.952	0.908	**0.956**
RMSEA	0.070	0.085	**0.062**
SRMR	**0.052**	0.068	0.053

Note. Highest fit marked in bold. Criteria for fit: $\chi^2 = p > .05$ (p), AIC and SSABIC: the lowest score; CFI, NNFI, and IFI: >.90; RMSEA and SRMR: <.08 (Awang, 2012; Byrne, 1994; West et al., 2023); for highest precision, three decimals are provided for fit indices. SEM = structural equation model; OA = older adult; AIC = Akaike; SSABIC = Sample size–adjusted Bayesian; CFI = comparative fit index; NNFI = Bentler–Bonett Normed Fit Index; IFI = Bollen's Incremental Fit Index; RMSEA = root-mean-square error of approximation; SRMR = standardized root-mean-square residual.
[a] Model 1: variable (indicators): scope of attention (running span; visual array), control of attention (running span-controlled; visual search), item working memory (WM; nonword delayed repetition; word immediate serial recall-item), order WM (serial order reconstruction; word immediate serial recall-order), complex WM (item and serial order reconstruction; listening span). [b] Model 2: variable (indicators): item WM (nonword delayed repetition; word immediate serial recall-item, running span), Order WM (serial order reconstruction; word immediate serial recall-order, visual array), complex WM (item and serial order reconstruction; listening span; running span-controlled; visual search). [c] Model 3: variable (indicators): general attention (running span; visual array; running span-controlled; visual search), item WM, order WM, and complex WM.

(*Appendix continues*)

Figure A2
Path Coefficients for the SEMs in the YA Group



Covariances	Item WM	Order WM	Complex WM	Scope of attention
Order WM	53.20			
Complex WM	74.09	184.20		
Scope of attention	13.83	26.66	30.70	
Control of attention	1.15	2.29	3.67	0.60

Covariances	Item WM	Order WM
Order WM	61.92	
Complex WM	73.44	181.93

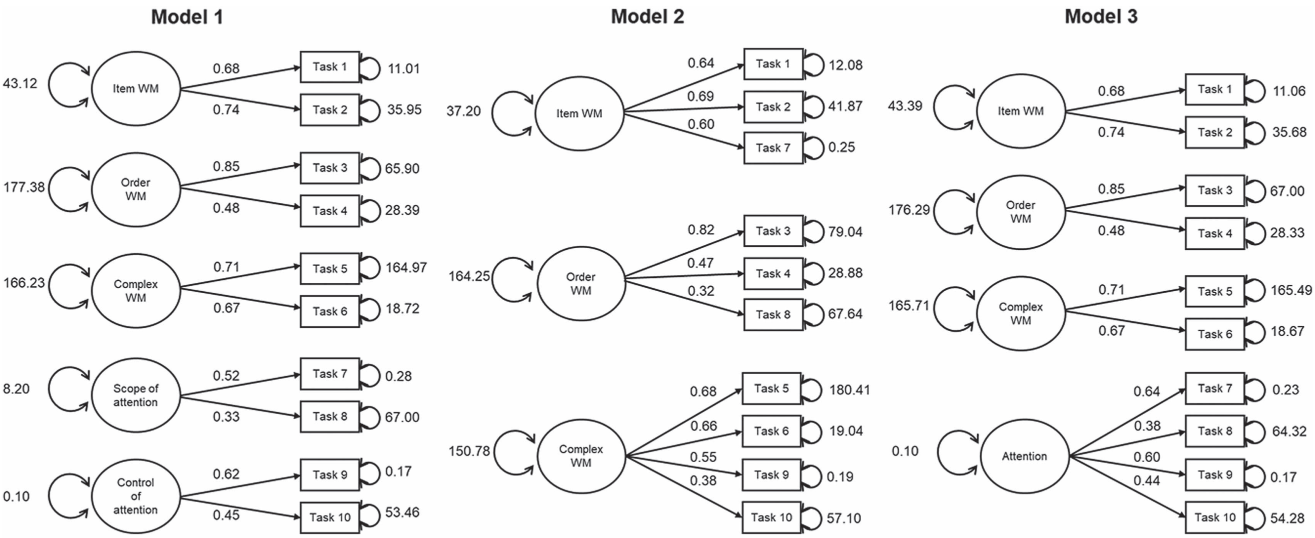
Covariances	Item WM	Order WM	Complex WM
Order WM	52.74		
Complex WM	74.15	183.76	
Attention	1.25	2.44	2.95

Note. Task 1: nonword delayed repetition; Task 2: word immediate serial recall-item; Task 3: serial order reconstruction; Task 4: word immediate serial recall-order; Task 5: item and serial order reconstruction; Task 6: listening span; Task 7: running span; Task 8: visual array; Task 9: running span-controlled; Task 10: visual search. WM = working memory; YA = young adult; SEM = structural equation model.

(*Appendix continues*)

Figure A3

Path Coefficients for the SEMs in the OA Group



Covariances	Item WM	Order WM	Complex WM	Scope of attention
Order WM	40.09			
Complex WM	72.21	144.47		
Scope of attention	18.76	34.79	37.84	
Control of attention	1.55	3.07	3.25	1.13

Covariances	Item WM	Order WM
Order WM	48.57	
Complex WM	71.78	140.70

Covariances	Item WM	Order WM	Complex WM
Order WM	40.03		
Complex WM	72.32	144.10	
Attention	1.63	3.12	3.35

Note. Task 1: nonword delayed repetition; Task 2: word immediate serial recall-item; Task 3: serial order reconstruction; Task 4: word immediate serial recall-order; Task 5: item and serial order reconstruction; Task 6: listening span; Task 7: running span; Task 8: visual array; Task 9: running span-controlled; Task 10: visual search. WM = working memory; OA = older adult; SEM = structural equation model.

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