Age-related differences in working memory updating components

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Abstract

The aim of this study was to investigate possible age-related changes throughout childhood and adolescence in different component processes of working memory updating: retrieval, transformation and substitution (Ecker, Lewandowsky, Oberauer, & Chee, 2010). A set of numerical WMU tasks was administered to four age groups (8-, 11-, 14- and 21-year-olds). In order to isolate the effect of each of the WMU components, participants performed different versions of a task that included different combinations of the WMU components. The results showed an expected overall decrease in response times and an increase in accuracy performance with age. Most importantly, specific age-related changes in the retrieval component were found, demonstrating that the effect of retrieval on accuracy was larger in children than in adolescents or young adults. These findings indicate that the availability of representations from outside the focus of attention may change with age. Thus, the retrieval component of updating could contribute to the age-related changes observed in the performance of many updating tasks.

Keywords: working memory, working memory updating, retrieval in WM, WM development

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Working memory (WM) is a cognitive system that enables us to maintain and manipulate information (Baddeley, 1983; Cowan, 1999). WM is crucial for optimal cognitive functioning and is necessary in numerous daily activities (Gathercole, 1999). Given the limited capacity of WM, an updating process is needed that quickly allows us to modify the WM content in order to accommodate new information. This updating mechanism is central to the mental architecture (Friedman et al., 2008; Schmiedek, Hildebrandt, Lövden, Wilhelm, & Lindenberger, 2009) and is involved in numerous cognitive tasks. In fact, updating is the executive function that best predicts fluid intelligence (Friedman et al., 2006) both in older adults (Chen & Li, 2007) and children (Belacchi, Carretti, & Cornoldi, 2010). Updating also plays a role in academic achievement, accounting for individual differences in key areas such as mathematics (Passolunghi & Pazzaglia, 2004; Pelegrina, Capodieci, Carretti, & Cornoldi, 2014), reading (Carretti, Cornoldi, De Beni, & Romanò, 2005; Palladino, Cornoldi, De Beni, & Pazzaglia, 2001), and professional translation (Morales, Gómez-Ariza, & Bajo, 2015).

WM develops from birth and continuously improves throughout childhood and adolescence (Brocki & Bohlin, 2004; Gathercole, Pickering, Ambridge, & Wearing, 2004; Huizinga, Dolan, & van der Molen, 2006; Luciana, Conklin, Hooper, & Yarger, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004). The ability to efficiently update information in WM also undergoes changes across childhood and adolescence (Huizinga et al., 2006; Kwon, Reiss, & Menon, 2002; Lendínez, Pelegrina, & Lechuga, 2015; Schleepen & Jonkman, 2010; Vuontela et al., 2003). This study aimed to investigate age-related changes in this mechanism focusing specifically on its underlying component processes.

Components of updating

In recent years, proposals have been made to decompose the updating process into more basic constituent components (Bledowski, Kaiser, & Rahm, 2010; Ecker et al., 2010; Zhang, Verhaeghen, & Cerella, 2012). There is consensus about the involvement of an access or retrieval process and a substitution or replacement component. On the basis of a task analysis, Ecker et al. (2010) isolated three specific processes that participate in different tasks: retrieval, transformation and substitution. These authors assumed that these processes would be combined serially. Thus, to update an element in WM, it has to be selectively retrieved, then a transformation may be applied to this representation, and finally the new information is stored making it available for future operations.

The access or retrieval process consists of accessing information outside the focus of attention in WM. Embedded models of WM (e.g., Cowan, 1995, 1999; Oberauer, 2002) assume that information may be held in different regions of WM depending on its state of activation. The focus of attention constitutes one of the levels proposed by Oberauer's concentric tripartite model (Oberauer, 2002; see also Oberauer, 2009) along with the direct-access region and the activated part of long-term memory. When a WM task is carried out, the relevant information is maintained in the direct-access region until an element is selected for processing in the focus of attention. Thus, any information that is to be updated has to be retrieved in the focus of attention. This region usually holds only a single item or chunk selected from the active elements maintained in the direct-access region. Garavan (1998) showed that there is a temporal cost when accessing one object in WM in order to perform a cognitive operation. This temporal cost is considered the time needed to retrieve the information in the focus (McElree, 2001). Since this early study, similar results have been reported across a variety of experiments (Kessler & Meiran, 2006; Lendínez et al., 2015; McElree, 2001; Oberauer, 2002, 2003; Verhaeghen & Basak, 2005; Voigt & Hagendorf, 2002).

The retrieval process involves searching for a specific representation among different competing elements maintained in the direct-access region of WM. Other information stored in the WM may cause interference and, as a consequence, may lead to incorrect representation selection. Therefore, the success of an adequate retrieval stems from a proper activation process of the target representation and the control of possible interference from other competing representations. As shown by Ecker et al. (2010), retrieval is the component that induces more commission errors and determines to a large extent the accuracy of the responses.

Transformation is another component of WMU that involves applying cognitive operations in order to modify a representation maintained in WM. Given that transformation is mediated by operations that may vary in difficulty, it can be assumed that the more complex the operations, the fewer the resources available to other processes such as retrieval (Garavan, 1998; but see Voigt & Hagendorf, 2002). Ecker et al. (2010) found that conditions which required transformation determined accuracy more so than other conditions that did not involve this process. This led the authors to conclude that transformation induces a higher variability in updating performance compared with other components.

Substitution could be considered the most distinctive process component of updating. It consists of replacing previous content that is no longer relevant with new information. Kessler and Meiran (2006, 2008) argued that substitution is a selective process that modifies only a subset of elements in WM while preserving the rest of the elements held in WM that must be protected from interference. They found that the more items there are from a set maintained in memory which have to be substituted, the longer it takes to replace this information. The substitution process is also mediated by the similarity between the elements involved in the process. The greater the similarity between the new and to-be-replaced information, the faster the substitution process (Lendínez, Pelegrina, & Lechuga, 2011, 2014). Both findings could be interpreted as updating entailing a selective and partial substitution of elements or representations.

Every time a substitution occurs, the new item has to be integrated with the previously maintained information. Thus, in addition to selective substitution, it is necessary to combine new information with previously maintained representations to create a complex representation (Artuso & Palladino, 2011; Kessler & Meiran, 2008; but also see Kessler & Oberauer, 2014). Ecker et al. (2010) found that substitution only had a small effect on performance, slowing down response times.

Age-related differences in WMU

Studies that have analyzed age-related changes in WMU have shown that performance in updating tasks increases linearly at least until mid-adolescence (Huizinga et al., 2006; Kwon et al., 2002; Pelegrina et al., 2015; Schleepen & Jonkman, 2009; Vuontela et al., 2003). These studies use a variety of tasks that may require to a different extent the involvement of different component processes of WMU.

One of the most widely known updating tasks is the n-back task, in which sequences of items are presented and participants are asked to judge whether the current item matches the one shown *n* steps back. To do this, they have to continuously access items maintained outside of the focus of attention, and then they have to substitute the oldest item for the most recently presented. Thus, this task involves both retrieval and substitution component processes. Mature levels in the 1-back task are reached at the end of childhood (10-12 years), whereas at more demanding levels (e.g., 2-back) performance continues to improve well into adolescence (Brahmbhatt, White, & Barch, 2010; Pelegrina et. al., 2015; Schleepen & Jonkman, 2010; Vuontela et al., 2003). It is important to note that at 1-back the information to be compared with the new item is still in the focus of attention, whereas at higher levels this information is outside of the focus and consequently retrieval is necessary. Therefore, it could be possible that the different developmental patterns for 1-back and higher task levels may be related, among other factors, to the ability to retrieve information from outside the focus of attention.

Similar to the n-back task, running memory requires both retrieval and substitution components. In this task, the last n elements of a list of unpredictable length have to be recalled. To do so, it is necessary to maintain a string of items that have to be continuously updated by deleting the oldest item and adding the new one. Although the substitution component is inherent to the definition of an updating task, there is some controversy surrounding the fact that it is possible to use passive strategies that do not involve the active substitution of information (Botto, Basso, Ferrari, & Palladino, 2014; Bunting, Cowan, & Saults, 2006; Ruiz, Elosúa, & Lechuga, 2005). Be that as it may, clear age-related differences have also been informed. Lee, Bull, and Ho (2013) used a cohort-sequential design to follow different groups of children from kindergarten through 6th grade over four years on different executive tasks. Improvements in updating performance assessed using a pictorial running memory task were found at all time points. Analogous findings were reported by Tamnes et al. (2010), who administered a version of the running task (letter memory task) to children and adolescents from 8 through 20 years of age. Their results showed a linear increase in performance with age which indicates a late development of the processes necessary to perform the task.

Other WMU tasks include, in addition to substitution and retrieval processes, the transformation of information. For example, in the mental counter task, participants have to keep track of the values of a variable number of counters, increasing or decreasing each counter after certain specific cues (Larson, Merritt, & Williams, 1998). This task requires access to a previously stored number, to apply a transformation to the representation maintained in the memory and to substitute the number for the new result. According to the results obtained by Huizinga et al. (2006), adult levels of performance are not reached until mid-adolescence.

Other updating tasks require applying some types of operations using the information maintained in WM; this does not, however, entail their transformation. For instance, in the semantic updating task, participants are asked to recall the smallest elements (e.g., objects or animals) in a list. To this end, with each new item, participants have to retrieve the stored items in order to perform a size comparison with the new one; they then need to substitute an object when the new element is smaller. Belacchi et al. (2010) administered this task to children between 5 and 11 years of age and found a linear increase in performance across childhood. Using a similar task, Lechuga, Moreno, Pelegrina, Gómez-Ariza, and Bajo (2006) found no differences in performance between 11-year-old children and adults. On the other hand, Lendínez et al. (2015), employing a task with numerical content that required recalling the smallest numbers at the end of a list, observed age-related changes until mid-adolescence and, more importantly, they were able to identify some differences in the time needed for focus switching. Specifically, young 8- and 11-year-old children took longer to access an element outside the focus than adolescents and young adults.

In sum, a variety of studies using different WMU tasks have shown age-related changes in updating performance. The asymptotic level of performance seems to be reached at different ages from mid to late adolescence depending on the task and the study. It should be pointed out that the previously described tasks were not specifically designed to separate the effect of each of the different components involved in updating. Therefore, the extent to which the underlying processes undergo specific age-related changes that may ultimately impact on general performance remains to be determined.

The present study

The purpose of this study was to assess possible age-related changes in different updating components. To do this, we adopted a strategy similar to that proposed by Ecker et al. (2010), employing a variety of tasks involving different components. Between-task comparisons including (or not) a particular updating component would reveal the effect of this specific component on performance. Possible interactions of these effects with age would inform about age-related changes in the different components. The advantage of this approach is that it can give a more precise account of the specific processes involved in age differences in updating when compared with the use of conventional updating tasks in which the different components participate to different extents.

To simplify the task proposed by Ecker et al. (2010) and to make it more accessible to children, instead of an alphabetic-numeric operation, we used simple arithmetic operations of addition and subtraction that are practiced extensively during the first years of school. This task is similar to that described by Oberauer, Wendland, and Kliegl (2003) and Salthouse, Babcock, and Shaw (1991). Variations of this general task were designed to include different combinations of updating processes: retrieval (R), transformation (T) and substitution (S). In the RTS task, for each item, participants had to retrieve a number (e.g., 5), apply a simple arithmetic operation to that number (e.g., +1), and substitute the previous number for the result of the operation (e.g., 6).

The other versions of the task (RT, TS, T, S) resulted from omitting one or two of the components (see Figure 1). For example, in the RT task, participants had to retrieve one of the memorized numbers and apply an operation (i.e., transform). In the TS task, participants were asked to solve arithmetic operations (e.g., 4+2) and memorize the results. Thus, transformation and substitution were required. In the T task, participants simply had to work out the result of an arithmetic operation (e.g., 4+2) and type it in. Hence, only transformation was needed. Finally, in the S task, participants had to memorize numbers (e.g., 2) as they were presented; therefore, only the substitution component was required (see Figure 1 for an example of each task).

Response times and accuracy for each item making up the different tasks would be recorded. We would expect response times to increase and accuracy to decrease as more updating components are added to the task. Comparisons regarding performance on tasks involving different components would allow us to determine the relative contribution of each particular component. In addition, we would expect to possibly see more pronounced age differences for some of the components. More specifically, given that Ecker et al. (2010) found retrieval to be more prone to capturing individual differences, we would expect age-related differences to more likely appear in tasks involving this component. We would, however, offer no specific predictions about age-related differences in the substitution and transformation components.

Method

Participants

A total of 96 participants belonging to four age groups (n=24 per group) were included in the present study. The first group was composed of 14 boys and 10 girls aged between 8 and 9 years (mean age: 8 years and 6 months). The second group comprised 13 boys and 11 girls aged between 11 and 12 years (mean age: 11 years and

6 months). The third group was composed of adolescents (9 boys and 15 girls) aged between 14 and 15 years (mean age: 14 years and 7 months); and the fourth group was made up of university students (11 men and 13 women) (mean age: 23 years and 6 months). All children and adolescents were recruited from two different local schools. Written informed consent was obtained from university students and parents of the children and adolescents. Children and adolescents assented to participate after being given a description of the tasks. University students were given awarded course credit for their participation.

Material and procedure

Stimuli were presented on a computer with a 15.6 inch color monitor. The presentation of stimuli and the recording of response latencies and responses were controlled using the E-Prime program (Schneider, Eschman, & Zuccolotto, 2002).

Six tasks were presented as different games. The two initial items in each list were numbers (ranging from 1 to 6), which were displayed on the screen in two rectangular frames or boxes (one on the right and the other on the left, both at the same height). The boxes measured approximately 3.5 x 2.5 cm and were 1.3 cm apart. After the two initial numbers, eight items appeared which varied depending on the task. They could be mathematical operations (+1, -1, +2 and -2), numbers, question marks, or a combination, which were also displayed inside one of the two rectangular frames. These mathematical operations were chosen to ensure that all participants were familiar with them and that they could perform them efficiently. Each item had a 50% probability of being associated with one of the frames. At the end of the list, two empty boxes appeared in which participants had to type the first or last numbers or last results (depending on the task). Once the first number had been entered into the first box and after pressing the ENTER key, the second number had to be typed into the other box.

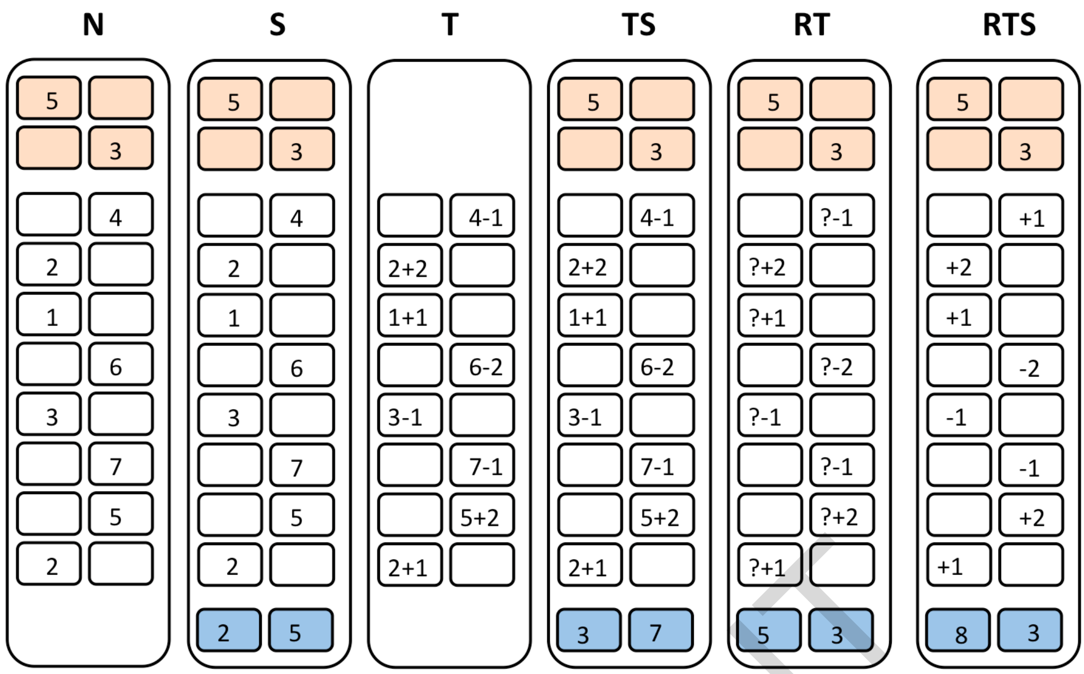

Figure 1. Representation of a list of the different tasks and a description of what the participants had to do on each task in the present study. Each rectangle corresponds to a different task whose label is shown at the top. For each task, each row of boxes represents an item and each column of boxes represents a different object or element. The first two rows, colored in orange, represent the initial numbers. The next eight rows, left in white, show study items. The last row, colored in blue, indicates recall items.

Each task was labeled with the first letter of the corresponding process name. Thus, *R* represented the retrieval component; *S* referred to substitution, and finally, *T* represented transformation. One task, labeled *N*, was used for training purposes and did not involve any of the aforementioned updating components. The six tasks were as follows: N, S, T, TS, RT and RTS. Each task had a different background screen, consisting of a picture that framed the boxes. This was intended to help children to better differentiate between the different tasks. Figure 1 gives an example of each of these tasks.

The N task was included to familiarize children with the sequence of events and responses in the task and did not involve any updating components. The two initial numbers and eight additional numbers were presented consecutively inside one of the boxes (e.g., 5, 3, ...). The participants had to type the numbers in using the keyboard. This task was associated with a picture of a treasure chest.

In the S task, the lists comprised two initial and eight additional numbers (e.g., 3, 4, ...). Participants had to memorize the initial numbers, one for each box. Then, when a new number was presented inside a box, they had to replace the old number related to that box with the new one. In order to move onto the next item, they had to type the number that appeared inside the box. At the end of the trial, participants were asked to write down the last two numbers for each box. This task was associated with a picture of a fishbowl.

In the T task, no initial numbers were given. Each of the eight items indicated mathematical operations inside the boxes (e.g., 3+2, 4-1, ...). Participants had to enter the result after each operation. No empty boxes came at the end as this task did not require information retrieval. This task was associated with a picture of a gift box.

In the TS task, after the two initial numbers were presented, eight items corresponding to mathematical operations appeared inside each of the boxes (e.g., 4+2, 3-1, ...). Participants had to perform mental arithmetic operations and type in the results that had to be memorized. At the end of the list, participants had to recall the last number memorized for each box. This task was associated with a picture of a television.

In the RT task, after the two initial numbers, eight items were presented; these were numerical operations that included a question mark (e.g., ?+2, ?-1, ...). Participants had to retrieve the number associated with the box, apply the operation and enter the result. At the end of each list, two empty boxes were presented so that participants could type in the two numbers memorized initially. It should be noted that, because there was no substitution, the numbers maintained in memory did not change over the course of the trials. This task was associated with a picture of a wicker basket.

Finally, in the RTS task, two initial numbers also had to be memorized. After these initial numbers, eight items consisting of arithmetic operations were presented in one of the two boxes (e.g., +2, -1). Participants had to retrieve the number associated with the current box, apply the operation, enter the result and memorize the new result in order to use it in subsequent items. Finally, two empty boxes appeared in which the participants had to type in the end results for each box. This task was associated with a picture of a bag of money.

Tasks were organized into two blocks. The complexity of the tasks increased throughout the first block and decreased in the second block. Specifically, the six experimental tasks in the first block were arranged as follows: N, S, T, TS, RT and RTS; in the second block, the opposite order was used: RTS, RT, TS, T, and S. Presenting the simplest tasks at the start of the first session would make it easier for the younger children to understand the procedures. Reversing the order in the second block equates the average serial position in which the tasks are presented. A total of eight lists were constructed for each of the different tasks. Each task included four lists in the first block and the remaining four in the second block. In total, there were 48 experimental and 24 practice trials.

Detailed instructions were given before each task. When the experimenter was confident that the participants had understood the task, and following two practice trials, the experimental task was administered. To prevent fatigue among the younger participants (8 through 12 years), the tasks were administered in two sessions a few days apart. In each session a block was administered that did not exceed 30 minutes. For the remaining two groups (14–15 years and adults), the tasks were administered in a single session lasting approximately 50 minutes.

Results

Two sets of analyses were performed to determine the effect of the different updating components on accuracy and response times. It was not possible to perform a complete factorial design because not all combinations of components were used to devise a task. For instance, the combination RS (retrieval and substitution) did not make practical sense, given that it would require retrieving a number and immediately (without transformation) memorizing the same number. Nonetheless, the two sets of analyses allowed us to determine the effects of each component on response times and accuracy. The first set examined the effects of retrieval and substitution, whereas the second set was carried out to assess the effect of transformation. Descriptive statistics for each dependent variable in each task are shown in Tables 1 and 2. In order to analyze response times, a log transformation was applied to convert proportional differences in response time due to general slowing with age into additive differences (Cerella, 1990).

Retrieval and substitution

Accuracy

A mixed analysis of variance 4 x (2 x 2) ANOVA was performed on accuracy, with age group (8-, 11-, 14-years and adults) as the between-subject factor and retrieval (retrieval vs. no retrieval) and substitution (substitution vs. no substitution) as within-subject factors. Thus, the following tasks (with their corresponding conditions in parentheses) were included in the analysis: T (no retrieval and no substitution); TS (no retrieval and substitution); RT (retrieval and no substitution); and RTS (retrieval and substitution). It should be noted that all these tasks involved the transformation component but varied on whether or not the retrieval component was involved (RT&RTS vs. T&TS) and whether or not the substitution component was involved (TS&RTS vs. T&RT). Table 1 shows accuracy percentage for items on each task[1].

Table 1

Mean and standard deviations for accuracy percentage for items on each task as a function of age group.

	S		T		TS		RT		RTS	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
8-year-olds	96.42	5.35	96.50	5.39	96.00	5.41	65.96	25.38	59.87	24.33
11-year-olds	99.25	1.11	97.29	2.54	97.42	2.60	78.25	25.01	74.29	24.66
14-year-olds	99.33	1.31	97.08	2.52	96.54	2.47	85.67	10.61	73.00	15.02
Adults	99.67	0.76	97.88	2.31	98.54	1.89	94.25	5.83	86.21	15.88

The main effects of retrieval, $F(1, 92) = 148.61$, $p < .001$, $\eta_p^2 = .62$, substitution, $F(1, 92) = 13.47$, $p < .001$, $\eta_p^2 = .13$, and age group, $F(3, 92) = 10.72$, $p < .001$, $\eta_p^2 = .26$, were significant. The interaction between retrieval and substitution was also significant, $F(1, 92) = 12.80$, $p = .001$, $\eta_p^2 = .12$. Further unifactorial ANOVAs showed that when retrieval was not required, the effect of substitution did not reach significance, $F(1, 92) = .02$, $p = .895$, $\eta_p^2 = .00$. However, the substitution effect was significant when the information had to be retrieved, $F(1, 92) = 13.81$, $p < .001$, $\eta_p^2 = .13$, indicating that accuracy was higher in the RT (81%) than in the RTS task (73%).

More importantly, a significant interaction between retrieval and age group was also found. In addition, the crucial interaction between the linear trend for age group and retrieval was significant, $F(1, 92) = 28.09$, $p < .001$, $\eta_p^2 = .23$. To analyze this interaction, the T and TS tasks were combined to determine the effect of age when retrieval was not required and the RT and RTS tasks when it was. An age-trend analysis for each retrieval level indicated a small but significant increase in performance with age when retrieval was not required (*Meandiff* = 2%), $F(1, 92) = 6.15$, $p = .015$, $\eta_p^2 = .06$. There was a more pronounced linear trend with age when retrieval was involved, $F(1, 92) = 29.33$, $p < .001$, $\eta_p^2 = .24$, (*Meandiff* = 27%). Post hoc analyses showed that when retrieval was not required the only significant difference was between the extreme age groups: 8-year-olds and adults (p = .048). In contrast, when retrieval was necessary there were differences between 8-year-olds and all groups (11-year-olds, $p = .044$; 14-year-olds, $p = .007$; and adults, $p < .001$) and between 11-year-olds and adults ($p = .031$).

Response times

Similarly, a mixed analysis of variance 4 x (2 x 2) ANOVA was performed on log-transformed times, with age group (8-, 11-, 14-years and adults) as the between-subject factor and retrieval (retrieval vs. no retrieval) and substitution (substitution vs. no substitution) as the within-subject factors. Data pertaining to five children in the 8-year-old group, five in the 11-year-old group, three in the 14-year-old group and two in the adult group were eliminated from this analysis, because after excluding incorrect lists, there were not enough observations for some conditions. Participants were included in the time analyses if they produced at least one correct list for each task. This criterion would therefore involve a minimum of 8 observations per condition per participant. The mean number of observations per condition varied from 42 (8 year-olds) to 56 (younger adults). In this analysis, response times from practice lists and those from incorrectly recalled lists were excluded (20% incorrect lists). Table 2 shows response times for items from each task.

The analysis showed the main effects of retrieval, $F(1, 77) = 114.42$, $p < .001$, $\eta_p^2 = .60$, and substitution $F(1, 77) = 25.66$, $p < .001$, $\eta_p^2 = .25$. These effects were qualified by the interaction between retrieval and substitution, $F(1, 77) = 146.97$, $p < .001$, $\eta_p^2 = .66$. To analyze this interaction, two unifactorial ANOVAs with substitution as the within-subject factor were run for each retrieval condition. Substitution did not reach significance when retrieval was not required (T vs. TS), $F(1, 91) = 2.99$, $p = .087$, $\eta_p^2 = .03$, but it was significant when the information had to be retrieved (RT vs. RTS), $F(1, 77) = 15.06$, $p < .001$, $\eta_p^2 = .16$. Unexpectedly, response times were longer in the RT condition (*M* = 2925), where there was no need to substitute the information, than in the RTS condition (*M* = 2623) where substitution was required.

Table 2

Mean and standard deviations for response times (ms) for items on the different tasks as a function of age group

	S		T		TS		RT		RTS	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
8-year-olds	2042	547	2744	767	3595	1034	4439	1513	3601	1518
11-year-olds	1360	326	1635	456	2046	454	2753	764	2600	1133
14-year-olds	1223	263	1457	230	1973	454	2551	504	2476	551
Adults	1052	253	1260	258	1621	427	2055	534	1895	521

The main effect of age group was also significant. A trend analysis revealed a significant linear component for age, $F(1, 77) = 83.43$, $p < .001$, $\eta_p^2 = .52$, which explained 81.42% of the variance. The quadratic component, $F(1, 77) = 13.25$, $p < .001$, $\eta_p^2 = .15$, and cubic component, $F(1, 77) = 5.78$, $p = .019$, $\eta_p^2 = .07$, also reached the significance level, accounting for 12.84% and 5.74% of the variance, respectively. An examination of response times indicated that 11-year-olds and 14-year-olds showed similar response times ($p = 1$), while 8-year-olds and adults differed from all groups ($p < .001$ for all comparisons, except for those between adults and 11-year-olds, $p = .002$, and between adults and 14-year-olds, $p = .014$).

In sum, both retrieval and substitution influenced response times and accuracy. As expected, faster response times and more accurate responses were obtained as the age of the participants increased. Particularly important was the finding that the effect of retrieval on accuracy showed age-related differences, demonstrating that the retrieval requirements had a large effect at younger ages, whereas substitution did not.

Transformation

Accuracy

To determine a possible age-related effect on the transformation component, an analysis with the S and TS tasks as within-participant factors and age as a between factor was performed on accuracy scores. In this analysis, the main effect of transformation was found to be significant, which indicated that when transformation was required, the percentage of correct answers was slightly lower (97%) than when transformation was not necessary (99%). The main effect of age group turned out to be significant. A trend analysis revealed a significant linear component, $F(1, 92) = 15.57$, p

$< .001$, $\eta_p^2 = .14$, explaining 71.26% of the total variance, and a cubic component for age, $F(1, 92) = 4.03$, $p = .048$, $\eta_p^2 = .04$, which accounted for 18.43% of the variance.

Response times

An analogous analysis including the S and TS tasks as within-participant factors and age as a between factor was run on log-transformed times. In this analysis, the main effect of transformation was found to be significant, which indicated that when transformation was necessary, response times were longer (*M* = 2327) than when there was no transformation (*M* = 1417). The main effect of age group was also significant. A trend analysis revealed a significant linear component, $F(1, 91) = 20.38$, $p < .001$, $\eta_p^2 = .18$, explaining 55.34% of the variance; a quadratic component, $F(1, 91) = 9.10$, $p = .003$, $\eta_p^2 = .09$, accounting for 24.81% of the variance; and a cubic component for age, $F(1, 91) = 7.31$, $p = .008$, $\eta_p^2 = .07$, explaining 19.85% of the variance.

In short, transformation produced an increase in response times and a decrease in accuracy. The analyses revealed a main age effect, although no interaction with age was found.

Discussion

This study sought to determine possible age-related trends in different WMU component processes. To achieve this, a set of tasks was devised to assess possible age-related differences in each of the WMU components. In line with Ecker et al. (2010), all WMU components had effects on response times and accuracy. As expected, a decrease in response times and an increase in accuracy performance were found with age. More importantly, only the retrieval component had an effect on performance that was related to age.

Retrieval

Results confirmed that retrieval has a considerable effect both on WMU accuracy and response times, consistent with that reported by Ecker et al. (2010). In the present study, retrieval was needed to access the information stored outside the focus in order to apply a numerical operation. Importantly, age-related differences were observed in the retrieval process. Eight-year-old children showed lower accuracy than the other groups and there were also differences between the 11-year-old and adult groups. McElree (2001) drew a distinction between the effects of accessing information outside the focus on accuracy and response times. Retrieval accuracy would tap the availability of an item outside the focus, whereas response times would be an index of accessibility reflecting how fast the item is accessed. The reported finding suggests that some changes related to the retrieval process take place after childhood. More specifically, when items must be retrieved from outside the focus, they become more available adolescents or young adults than to children.

There are some, not mutually exclusive, possible reasons underlying the observed age-related trend in availability. One possibility is that young children are less able to select items accurately from outside the focus. Access to an element outside the focus involves activating both its content (e.g., a numerical value) and its context. The context may consist of diverse cues related to an element, such as the spatial location in which the information appeared. Thus, each time a new item is presented, its content as well as its context must be bound so that they are both accessed at the time of retrieval (Oberauer & Bialkova, 2009, Oberauer, 2013). In the task used in this study, children had to bind a numerical value to a frame located in a specific position. It is possible that young children are less able to retrieve this integrated representation using the context. There is evidence to support that the binding mechanism necessary for the formation and retrieval of complex representations in short-term memory undergoes developmental changes up to adulthood. For instance, Cowan, Saults, and Morey (2006) found that young children (e.g., 8-year-olds) showed less accuracy than adults in a STM task that required binding names and location. Similarly, Fandakova, Sanders, Werkle-Bergner, and Shing (2014) reported that young children were less able to learn and retrieve associations between letters and positions in comparison with adolescents and younger adults.

The age-related trends shown for availability could also be due to differences when it comes to maintaining information outside the focus. Information suffers from interference when it leaves the focus of attention. Thus, it is possible that young children are more susceptible to certain types of interference in WM. Recently, Göthe, Esser, Gendt, and Kliegl (2012) and Rodriguez-Villagra, Göthe, Oberauer, and Kliegl (2013) tested an interference model to account for developmental trends in WM performance that included parameters for two types of interference in WM: 1) overwriting between simultaneously held elements, and 2) confusion among items at retrieval. Both studies found that only the latter type of interference showed age-related differences. Thus, developmental differences in susceptibility to interference due to confusion among items may contribute to age-related differences in availability observed in the present study.

The present results can be added to those obtained with older adults to provide a broader picture of the age-related changes in accessing information in WM. Previous studies have shown that the availability of information may be particularly affected in older adults. They seem to be less accurate when accessing representations that are not active (Basak & Verhaeghen, 2011; Dorbath, Hasselhorn, & Titz, 2011; Dorbath & Titz, 2011; Oberauer et al., 2003; Vaughan, Basak, Hartman, & Verhaeghen, 2008;

Verhaeghen & Basak, 2005; Verhaeghen & Hoyer, 2007). Overall, it could be suggested that representations tend to be less available to both children and older adults in comparison to younger adults.

In contrast to the age-related differences seen in availability, analogous differences in accessibility were not present. Such a possibility, however, should not be excluded. Lendínez et al. (2015) reported that younger children spent comparatively more time than adolescents and younger adults in accessing information maintained outside the focus of attention. Differences between the two studies may reside in the type of task used. The aforementioned authors used a numerical comparison-updating task more than appropriate for obtaining differences in the time domain, although it did not allow for collecting data on accuracy. In contrast, the set of tasks selected for the present study has the reciprocal advantage of enabling us to obtain precise information about accuracy.

Substitution

The substitution component had only a modest effect on both response times and accuracy. In the tasks used in this study, substitution was required each time a number had to be replaced because it had become obsolete. When a number has to be substituted, a selective replacement must be carried out in which part of the information (i.e., a number) has to be replaced, while the rest (i.e., the other number) remain unmodified. The new number must also be bound to the other elements (Artuso & Palladino, 2011, 2014; Kessler & Meiran, 2008; but see Kessler & Oberauer, 2014).

Substitution had a different effect on response times and accuracy depending on whether the retrieval component was involved. On the one hand, in those tasks that did not require retrieval of information (TS and T), substitution did not affect performance. On the other hand, when retrieval was required, substitution contributed to the decrease in accuracy, but unexpectedly more time was spent on the RT than on the RTS task. It is possible that in the RT task, after performing each operation, participants engaged in attentional refreshing or rehearsal to reactivate the initial numbers that had to remain unchanged. It is also possible that both the initial number and the result of the operation (that once typed becomes no longer relevant) would interfere. Thus, in the RTS task, reactivation of the number would not be required because it is in the focus, and given that this is the number to store there would be no interference. Although further research is needed to clarify this pattern, it seems clear that the substitution component imposes, at the very most, only modest cognitive demands (see also Ecker et al., 2010).

Children's performance on these tasks was affected by substitution requirements to the same extent as that of younger adults. Lendínez et al. (2015) compared response times in two conditions which differed on whether information should or should not be substituted. Much like the result obtained in the present study, they did not find differences among eight-year-olds and young adults. Therefore, evidence from different tasks suggests that the substitution process performed either alongside retrieval or separately does not undergo changes within the age ranges considered.

Transformation

As for the transformation component, the results of this study indicate that this process seems to be the most time-consuming component, in line with the results obtained by Ecker et al. (2010). Performing a transformation involves a dual process, given that it requires manipulating and maintaining some information. The transformation effect on accuracy was, however, rather modest. This indicates that the young children in this study were proficient in the simple arithmetic operations used in this task. The age pattern obtained may be explained by domain-general developmental processes (e.g., increase in processing speed with age, Kail, 1991).

Conclusions

Accessing information outside the focus is a critical process necessary to perform numerous WMU or WM tasks. For example, in the reading span and operation span tasks, the last words or numbers of a variable number of trials have to be retrieved in the same order of presentation. Similarly, the majority of updating tasks such as the n-back, running task, and keeping track require one to constantly access information outside the focus. Then, age differences in the ability to retrieve information might be a source of the age trends reported in numerous studies that have assessed children's performance on updating tasks (Brahmbhatt, White, & Barch, 2010; Huizinga et al., 2006; Pelegrina et al., 2015; Schleepen & Jonkman, 2009; Vuontela et al., 2003).

The obtained age-related trend fits well with current evidence that individual differences in WM capacity are also related to retrieval efficiency. Unsworth and Engle (2008) found individual differences both in the speed and accuracy of accessing information from outside the focus. However, only retrieval accuracy and not speed of retrieval was related to both WM span and fluid intelligence. The aforementioned authors argued that the low recall accuracy showed by low-ability individuals may lie in the difficulty of differentiating target and non-target representations. Along the same lines, Ecker et al. (2010) reported that individuals with low WM capacity were less able to correctly retrieve the information. They suggested that these people might experience more interference between representations maintained in WM.

Access to the to-be-replaced information is critical in complex cognitive tasks where information has to be constantly updated. For instance, retrieval is required to solve multi-digit operations; to select and modify relevant information during reading; and to understand driving directions. Thus, the developmental trends observed in complex tasks across many different areas (e.g., reading comprehension, numerical cognition, problem solving) may be related to the ability to accurately retrieve information during updating.

In conclusion, remarkable age-related differences in WMU have been observed in this study on accessing information outside the focus. This pattern suggests that retrieval accuracy underlies not only individual differences in WM, but also age-related differences. We did not find age differences in the substitution and transformation processes. Given that we only tested children over eight years of age, it would be interesting to investigate how younger children perform tasks involving this process. This could provide us with relevant information about the possible earlier development of these components.

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Footnotes

[1] To rule out the possibility that part of the results were due to ceiling effects in some conditions, we tested the accuracy of each group on each task against ceiling (100) using a set of one-sample t tests. For all tasks, accuracy was below perfect performance, all *p*s $< .05$.