Explaining Age-Differences in Working Memory:

The Role of Updating, Inhibition, and Shifting

Sascha Zuber[1,2,3]

Andreas Ihle[2, 3]

Vanessa M. Loaiza[4]

Katharina M. Schnitzspahn[5]

Christoph Stahl[6]

Louise H. Phillips[5]

Christoph P. Kaller[7]

Matthias Kliegel[1, 2, 3]

[1] Department of Psychology, University of Geneva, Switzerland.

[2] Center for the Interdisciplinary Study of Gerontology and Vulnerability, University of Geneva, Geneva, Switzerland.

[3] Swiss National Center of Competences in Research LIVES–Overcoming vulnerability: life course perspectives, Lausanne and Geneva, Switzerland.

[4] Department of Psychology, University of Essex, UK.

[5] School of Psychology, University of Aberdeen, UK

[6] Department of Psychology, University of Cologne, Germany.

[7] Department of Neurology, University Medical Center Freiburg, Germany

Correspondence:

Sascha Zuber

Department of Psychology

University of Geneva

Boulevard du Pont d'Arve 40

1211 Genève 4, Switzerland

Sascha.Zuber@unige.ch

Abstract

Working memory (WM) represents the capacity to store and process a limited amount of information. Better understanding developmental changes of WM forms a key topic in research on neuropsychology of aging. Previous studies reveal age-differences in WM and in executive functions (EFs). Although EFs are seen as essential mechanisms in WM, the specific relation between the two cognitive constructs so far remains unclear. The present study set out to investigate the unique roles of the three main facets of EFs (i.e., updating, inhibition, and shifting) in accounting for age-related variability in WM. Therefore, one-hundred seventy-five younger and 107 older adults performed a battery of cognitive tests including measures of WM, EFs, and processing speed. A set of statistical approaches including regression analyses and path models was used to examine the cognitive correlates that could explain individual and age-related variance in WM. Significant age-differences were found on WM and on EF measures. Regression analyses and path models showed that updating and inhibition but not shifting played a major role in explaining age-related variance in WM. In sum, findings suggest that updating and inhibition are most influential for age-differences in WM. They further show that age and processing speed do not significantly contribute to variability in WM performance beyond executive resource. The present findings have implications for conceptual and developmental theories of WM and may further offer an initial empirical basis for developing possible trainings to improve older adults' WM performance by strengthening the efficiency of updating and inhibitory processes.

Key Words: working memory; executive functions; aging; path model; updating; inhibition

Word count: 6796

Introduction

Working memory (WM) refers to the dynamic relationship between *passive storage* and *active processing*, manipulation or transformation of information held in memory (e.g., Baddeley, 2007, 2010, 2012). WM is involved in a wide range of complex cognitive behaviors, such as reasoning, decision making, and problem solving (e.g., Bizon, Foster, Alexander, & Glisky, 2012; Duarte, Woods, Rooney, Atkinson, & Grant, 2012; Engle, 2002). It therefore plays a major role in different core models of cognition and forms one of the main constructs of neuropsychology (e.g., Anderson & Lebiere, 2014; Cowan, 1995, 2010, 2017). Multiple studies using brain imaging have associated WM with activation of the (pre-)frontal cortex and the fronto-parietal network (see e.g., Dehn, 2017; Glisky & Kong, 2008; Kane & Engle, 2002; Nee et al., 2013; Owen, McMillan, Laird, & Bullmore, 2005; Rottschy et al., 2012; Roussel, Dujardin, Hénon, & Godefroy, 2012; Wager & Smith, 2003). As a consequence, WM further represents an essential indicator in neuropsychological assessments, as it represents a proxy of intact functioning of the cognitive processes associated to the (pre-)frontal cortex.

Most relevant to the present study, WM has been a primary topic of interest in aging research, as it consistently accounts for substantial age-related variability in a variety of other higher-order cognitive processes (e.g., Chen & Li, 2007; Kane, Bleckley, Conway, & Engle, 2001; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Verhaegen, 2012). Deficits in WM are among the first symptoms of several neuropsychological diseases related to aging, such as mild cognitive impairment or Alzheimer's disease (e.g., Belleville, Chertkow, & Gauthier, 2007; Belleville, Rouleau, Van der Linden, & Collette, 2003; Gagnon & Belleville, 2011). Further, reduced WM is associated with a decrease of older adults’ autonomy and personal well-being (e.g., Klingberg, 2010; Nissim et al., 2016; Williams & Kemper, 2010).

As a consequence, disentangling the cognitive and neuropsychological processes that underlie age-related changes in WM is a key goal in research on aging (e.g., Constantinidis & Klingberg, 2016; Craik & Salthouse, 2011; Heinzel, Lorenz, Duong, Rapp, & Deserno, 2017; Wang et al., 2011). Specifically, examining the developmental trajectory of WM has been a central interest for the last thirty years (e.g., Alloway & Alloway, 2013; Park & Payer, 2006; Swanson, 2017; Wingfield, Stine, Lahar, & Aberdeen, 1988). Taken together, the literature has so far established that WM generally declines in old age (e.g., Bopp & Verhaeghen, 2005; Borella, Carretti, & De Beni, 2008; Chai, Abd Hamid, & Abdullah, 2018; Fabiani, 2012; Rhodes & Katz, 2017; Sander, Lindenberger, & Werkle-Bergner, 2012; Verhaeghen & Salthouse, 1997). However, the question of which factors contribute to age-related decline of WM is still under heavy debate.

On a neural level, age-deficits in WM have been associated with an altered *activation modulation* in older adults: When processing a WM task, the activation of the fronto-parietal network would be broader and more rapid in older compared to younger adults (see e.g., Hakun & Johnson, 2017; Kaup, Drummond, & Eyler, 2014), which would lead to a less efficient activation of the regions that are specifically required for the particular WM task (also see Cappell, Gmeindl, & Reuter-Lorenz, 2010; Carp, Gmeindl, & Reuter-Lorenz, 2010;; Mattay et al., 2006; Nagel et al., 2011; Schneider-Garces et al., 2010).

From a cognitive perspective, one important feature of WM is the system's limited capacity, which concurrently has to be shared between *storage* and *online processing* of information. As a consequence, certain theoretical approaches have focused on the storage component of WM tasks in order to explain age-deficits. The *processing speed theory*, for example, suggests that WM deficits are caused by a general slowing of computational processes that comes with age, which would lead to difficulties in information storage (Salthouse, 1996). Specifically, items would either not be encoded and stored fast enough – or if they were temporarily stored – they would be lost before they can be rehearsed or retrieved from storage (also see Salthouse 2000a, 2000b)

In contrast, most theoretical approaches have focused on the processing component of WM tasks in order to explain age-deficits. Specifically, they suggest that with increasing age, generally less cognitive resources are available for the processing of the WM task and/or for the coordination of the two concurrent components (e.g., Bailey, Dunlosky, & Hertzog, 2009; Belleville, Rouleau, & Caza, 1998; Lustig, Hasher, & Zacks, 2007; Engle, 2002). However, these approaches disagree in that they determine different cognitive resources to be the reason for age-deficits in WM. The *inhibition-deficit theory*, for example, suggests that WM deficits arise as older adults would have fewer inhibitory resources, which would lead to more difficulties inhibiting non-pertinent information that interferes with the retrieval of task-relevant information (e.g., Hasher & Zacks, 1988; Lustig et al., 2007; Zeintl & Kliegel, 2007). The *strategy-deficit hypothesis* states that in combination with deficiencies of cognitive processing, WM deficits in older adults may increase because of difficulties in producing and using appropriate strategies to encode information (e.g., Bailey et al., 2009). Finally, the *executive attention framework* suggests that age-related variability in WM could be explained by older adults' difficulty to maintain cognitive control over task-relevant representations in challenging settings with high task-interference (e.g., Engle, 2002; Engle & Kane, 2004; Hedden & Yoon, 2006; McCabe et al., 2010).

A common feature of these theories of cognitive aging is that they associate age-deficits of WM to a decline of underlying, more specific mechanisms of controlled attention, namely *executive functions* (EFs). EFs can be defined as group of top-down attentional processes that are related to goal-directed, non-routine behavior and the control of complex cognition (e.g., Banich, 2009). They are involved in elaborating plans, adapting to novel situations, self-regulating emotional states, and in problem solving (e.g., Atkinson & Shiffrin, 1968; Diamond, 2013; Hofmann, Schmeichel & Baddeley, 2012; Norman & Shallice, 1986; Zelazo, Carlson, & Kesek, 2008).

Similar to WM, EFs have been associated to activity in the (pre-)frontal cortex by studies showing executive deficits in patients with frontal lesions (see e.g., Alvarez & Emory, 2006; Cipolotti et al., 2015; Godbout, Grenier, Braun, & Gagnon, 2005) as well as by studies using neuro-imaging (see e.g., Alvarez, & Emory, 2006; Blakemore, & Choudhury, 2006; Giedd et al., 1999; Stuss & Alexander, 2000; Stuss & Knight, 2002; Robbins & Arnsten, 2009). Further, EFs have been suggested as mediators of age-related decline in other cognitive domains (e.g., Salthouse, Atkinson & Berish, 2003).

For the present study, we focused on the conceptual framework suggested by Miyake and colleagues, which defines three distinguishable yet inter-related facets of EFs, that is, *updating*, *inhibition*, and *shifting* (see Miyake et al., 2000). *Updating* processes allow to manipulate information that is held in WM, to evaluate its relevance for the current task, and to replace it with newer, more relevant information (Passolunghi & Pazzaglia, 2005). *Inhibition* describes the ability to deliberately suppress dominant, automatic, or conflicting responses when necessary and to shield WM from distractors (Diamond, 2013). *Shifting* involves flexibly reallocating attentional resources between multiple tasks, operations, or mental sets (Altmann & Gray, 2008).

As previously outlined, executive facets have been suggested to specifically contribute to age-related decline of WM. The *inhibition-deficit theory*, for example, associated WM deficits to a decline of inhibitory control in older adults (e.g., Lustig et al., 2007). The *executive attention framework* suggests that in addition to inhibitory deficits, older adults would have more difficulties maintaining executive attention on active goals and memoranda (Engle & Kane, 2004). Further, the *strategy-deficit hypothesis* concludes that age-differences can be attributed to a decrease of executive functioning which leads to inefficient or insufficient use of strategies (Bailey et al., 2009).

Analyzing the processes that are involved in typical WM tasks in more detail further illustrates how certain EFs might be specifically deployed. In complex span tasks, for example, participants have to simultaneously process (e.g., reading a set of sentences and judging their semantical coherence) and store information (e.g., memorizing a letter presented after each sentence; Kane et al., 2004). To do so, different executive facets are required: for each new set of sentences, *updating* resources have to be deployed in order to erase and replace previously memorized items, whereas *inhibition* resources would be required in order to resist proactive interference of previously learned, now irrelevant items.

This is supported by empirical evidence, which indicates that specific facets of EFs are deployed by WM tasks. Studies focusing on younger adults for example demonstrate an association between WM and *inhibition* (e.g., Heitz & Engle, 2007; Kane & Engle, 2000; Kane et al., 2001; Long & Prat, 2002; Lustig, May, & Hasher, 2001; Redick & Engle, 2006; Unsworth, Schrock, & Engle, 2004; Unsworth & Spillers, 2010). Further studies on younger adults find a significant association between WM and *updating* (e.g., Miyake et al., 2000; Redick, Calvo, Gay, & Engle, 2011; Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009; Shamosh et al., 2008). There is less consensus in the literature regarding the role of shifting in WM. Some experimental studies have found a link between shifting and WM (e.g., Baddeley, Baddeley, Bucks, & Wilcock, 2001; Baddeley, Chincotta, & Adlam, 2001; Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Wongupparaj, Kumari, & Morris, 2015a). In line with these findings, the multicomponent model of Baddeley and Hitch suggests that shifting resources would be a sub-fractionation of the executive central component of WM, allowing individuals to switch between different task sets (see e.g., Baddeley, 2007). However, several other studies have failed to confirm the relation between shifting and WM (e.g., Logan, 2004; Oberauer, Süβ, Wilhelm, & Wittmann, 2008; St Clair-Thompson, 2011; St Clair-Thompson & Gathercole, 2006; Wongupparaj, Kumari, & Morris, 2015b). They conclude that besides reallocating (= shifting) attentional resources *between* different task sets, WM "reflects the ability to direct attention to multiple elements *at the same time*" (Oberauer et al., 2008, p. 650). Thus, complex WM tasks would deploy specific executive processes beyond shifting. In consideration of these opposing findings, it seems important to further explore the association between shifting and WM capacities, in particular when shifting is considered simultaneously with the other executive facets.

Taken together, one limitation of previous studies which examined the relationship between WM and EF is that they mostly examined each of the three executive facets separately. This might influence findings, on one hand because all executive tasks require shared lower-level cognitive processes (e.g., Shallice & Burgess, 1996; Stuss & Alexander, 2000), and on the other hand because the three executive facets strongly correlate and performance on executive tasks may partly depend on an underlying, more general executive factor (see e.g., Friedman & Miyake, 2017; also see e.g., Gade, Schuch, Druey, & Koch, 2014; Kiesel et al., 2010; Koch, Gade, Schuch, & Philipp, 2010).

However, given the EFs' fractionation into three correlated facets (i.e., updating, inhibition, and shifting; see Miyake et al., 2000; Friedman & Miyake, 2017), it is still unclear whether age-related decline in WM can be further attributed to particular EFs. In this context, the major focus of the present study is to clarify the most relevant EFs that account for age-related variability in WM measures, which is an important issue of neuropsychology. In order to allow for a comprehensive examination of the relation between WM and specific facets of EFs, the present study therefore set out to assess all three EFs in one group of participants.

Further, all studies referenced above examined WM performance in younger adults. In fact, only few studies addressed the relation between EFs and age-related variability in WM, with most research narrowly focusing on the role of inhibition. Salthouse and Meinz (1995), for example, showed that age-related variance in WM was substantially reduced after controlling for inhibition. Lustig et al. (2001) similarly showed that age-differences in WM were larger when the WM task required greater inhibition of proactive interference. Likewise, Van Gerven, Van Boxtel, Meijer, Willems, and Jolles (2007) demonstrated a mediating role of inhibition in age-related WM decline. Further, the role of updating and shifting in accounting for WM performance has been less explored in older adults and therefore remains an open question. As a consequence, the present study should importantly contribute to the currently available research on the specific relation of different executive facets and age-related variability in WM.

Previous theoretical approaches either focused on the storage or on the processing component of WM tasks to explain age-related decline of WM. In order to better understand the interplay of the concurrently involved components, the present study set out to disentangle the specific influence of each executive facet after controlling for processing speed.

To summarize, conceptual considerations and empirical findings indicate that updating, inhibition, and shifting may play an important role for age-related WM. However, compared to previous studies that focused on certain facets of EF separately, the present study is the first to provide a comprehensive approach including the three facets simultaneously. The present study therefore aimed at examining the relation between WM and EFs in younger and in older adults in more detail.

Method

Participants

The sample consisted of 282 participants: 175 younger adults (mean age = 23.2 years, *SD* = 3.4, range: 18-39) and 107 older adults (mean age = 66.0 years, *SD* = 3.7, range: 57-77). All younger adults were undergraduate students from the local university, who volunteered in exchange for partial course credit or a small monetary reward. All older adults volunteered in exchange for a small monetary reward. Exclusion criteria were history of or current physical and mental health problems. The two age groups did not differ with respect to gender distribution (younger adults: 52% males; older adults: 40% males; $\chi^2(df = 1) = 1.83$, $p = .177$)

and years of education (younger adults: $M = 13.3$, $SD = 2.1$; older adults: $M = 13.5$, $SD = 2.9$; $t(270) = 0.91$, $p = .364$). In terms of general cognitive abilities, the two age groups differed in both crystallized and fluid intelligence in the anticipated direction: Crystallized intelligence was assessed with a German vocabulary test (MWT; Lehrl, 1977) in which older adults ($M = 31.50$, $SD = 2.04$) attained significantly higher scores than younger adults ($M = 30.54$, $SD = 2.11$; $t(272) = 3.64$, $p < .001$). Fluid intelligence was indexed using a short version of the matrices-test (Raven, Raven, & Court, 1998), with younger adults obtaining significantly higher scores ($M = 12.10$, $SD = 1.93$) than older adults ($M = 8.28$, $SD = 2.09$; $t(279) = 15.60$, $p < .001$). The present data were part of a broader research project to examine executive control and complex cognition in younger and older adults (Schnitzspahn, Stahl, Zeintl, Kaller, & Kliegel, 2013).

Procedure

In two sessions of approximately 2h each, participants were individually administered a battery of cognitive tasks which were partly computerized and partly paper-pencil based and presented in the same pseudo-randomized order for all participants. Each session included a short break. After informed consent was obtained, a sociodemographic questionnaire was given to the participants. They were asked to fill it out at home and return it at the second testing session. Thereafter, the tests followed, which are described in detail below. The first session included two inhibition and two shifting tasks and one updating task as well as the measures of fluid and crystallized intelligence. The second session included the second updating task, two measures of speed, and the WM measures. The two tasks measuring the same construct were intermixed with measures of other constructs and never administered directly one after the other.

Materials

WM measures

To assess WM, we used two established WM span tasks: reading span (Daneman & Carpenter, 1980) and counting span (Engle, Tuholski, Laughlin, & Conway, 1999). In the reading span task, participants had to read and evaluate the semantic coherence of simple sentences one at a time and to memorize the last word of each sentence in the order of the presentation. In the counting span task, a series of displays were presented, and participants had to count and memorize the number of dark blue circles among light blue circles and dark blue squares in the order of presentation. The number of targets per display varied from three to nine. The number of color distractors (light blue circles) and the number of shape distractors (dark blue squares) was also varied.

For both tasks, three practice trials and eight critical trials were administered, with list lengths that pseudo-randomly varied between 2 to 5 items to be remembered per trial. The dependent variables were partial-credit unit scores (PCU; see Conway et al., 2005), which were chosen due to their high internal consistency. PCU express the mean proportion of items within a trial that were recalled correctly.

EF measures

Updating. To assess updating, we used the keep-track and letter-memory tasks (see Miyake et al., 2000). The keep-track task consisted of 5 series of 15 words. Each word represented one of six possible semantic categories and was randomly presented for 1500 ms on the computer screen. Participants were instructed to remember the last exemplar from different target categories (e.g., “fruit”). The number of target categories increased over trials from 2 to 4. For each series, 2-3 exemplars from each target category were presented (requiring participants to replace the memorized words in WM with newly memorized words). The dependent variable was the mean proportion of correctly recalled words across the 5 series.

For the letter-memory task, 12 letter-series were presented for 1500 ms per letter, one letter at a time. Each series consisted of 5 to 9 letters and participants’ task was to recall the last three letters of each list (for a total of 36 letters). The dependent variable was the mean proportion of correctly recalled letters across 12 series.

Inhibition. To measure inhibition, we used an antisaccade task (see Miyake et al., 2000), and a Simon task (see Simon & Berbaum, 1990). On the antisaccade task, for each trial participants had to fixate a fixation point presented at the center of the screen for 1000 to 3000 ms. As soon as a cue appeared on one side of the screen, participants were instructed to shift their gaze to the opposite side, where, shortly (225 ms) after the cue, an arrow was briefly presented (100 ms) and then masked. Participants were instructed to indicate the direction in which the arrow pointed (left, up, or right) by pressing one of three response buttons. Correct identification was only possible when the gaze was immediately shifted in the direction opposite to the cue. A total of 92 trials were presented. The dependent variable was the proportion of correct responses.

On the Simon task, for each trial, the central fixation point was followed by a left or right pointing arrow which was presented on the left, center or right of the screen. Participants were asked to indicate the direction of the arrow (independent from its screen position) by pressing a right or left response key. Inter-trial interval was 500 ms; a total of 120 trials were presented. The dependent variable was the difference in mean reaction times (RTs) between correct responses on congruent trials (e.g., left-pointing arrows presented on the right side of the screen) and congruent trials (e.g., left-pointing arrows presented on the left side of the screen). Note that proportion scores were calculated (see below).

Shifting. To assess shifting, we used the category-switch (Friedman et al., 2006; Mayr & Kliegl, 2000) and the color-shape task (Friedman et al., 2006). In the category-switch task, words representing objects or animals were presented on the screen. In task A, participants had to categorize them as “small” (e.g., a coin) versus “large” (e.g., a lion), whereas in task B, they had to categorize them as “living” (e.g., a lion) versus “non-living” (e.g., a coin). Participants first performed a block of task A and a block of task B in randomized order, both of which consisted of 28 trials. They then performed a mixed block of 80 trials, for which participants had to switch between task A and task B at random intervals (the current classification task was indicated with stimulus presentation).

In the color-shape task, circles and triangles that were either blue or red were presented on the screen and participants had to indicate their color (task A), or their shape (task B). The procedure was similar to the category-switch task, with the difference that the pure blocks consisted of 26 trials and the mixed block consisted of 82 trials. The dependent variable for both switching tasks was the difference in mean RT between the mixed block and the two task-pure blocks (see Miyake et al., 2000).

Processing Speed measures

To assess participants' processing speed, we used the identical-pictures and number-comparison tasks (Ekstrom, French, & Harman, 1976). In the identical-pictures task, participants had to compare simple line drawings. For each trial, a target line drawing was presented on the left of the screen, along with different visually similar drawings on the right that served as the response options. Participants were instructed to indicate which drawing was identical to the target, by pushing an associated button.

In the number-comparison task, participants had to compare number-pairs. For each trial, a pair of two numbers (with number of digits varying between trials) were presented at the center of the screen, and participants had to indicate whether they were identical.

In both tasks, a time limit of 90 s was imposed, and participants were instructed to solve as many problems correctly as possible out of a maximum of 90 problems. The dependent variable was the number of correctly solved problems within the given time.

Data preprocessing and analysis

To account for general age-related slowing, we computed proportional scores for all dependent variables relying on reaction times (i.e., performance in the Simon task measuring inhibition as well as in the category-switch and the color-shape task measuring shifting).

Proportion scores were computed by dividing the dependent variable (i.e., the difference in RT between both conditions, e.g., incongruent and congruent conditions in the Simon task, mixed and pure blocks in the shifting tasks) by the mean RT. The resulting proportion score expresses the magnitude of an individual's RT difference score as a percentage of his/her average response latency. The goal of this procedure is to control for general slowing effects - the underlying idea is that such general slowing effects are not of interest. Instead, interactions of slowing with conditions are the variables of interest (e.g., a disproportionate slowing in mixed as opposed to pure blocks).

Before analyses, we performed the following corrections and transformations: First, RT measures were computed on correct trials only. Of the correct trials, we excluded those that had RTs more than two interquartile ranges above the third quartile or below the first quartile of each individual's RT distribution in a given task.[1] Second, variables measuring the proportion of correct responses were arcsine-transformed to assure that they were approximately distributed normally; RT difference scores were computed and multiplied by -1 so that higher values represented better performance. Individuals that were univariate outliers (i.e., values more than three interquartile ranges above the third quartile or below the first quartile) or multivariate outliers (i.e., extreme Mahalanobis distance with $p < .001$) were excluded.[2] Across the 12 tasks and 282 participants, 4.4% (4.0% for the younger and 4.9% for the older group) of the data were missing. Listwise deletion was conducted in terms of the particular analysis (i.e., only cases with full information in the respective analysis investigated variables were included)[3]. For all analyses, the R environment was used (version 2.14.2; R Development Core Team, 2011) and the R package lavaan (Rosseel, 2012) for the path model analyses.

Results

In a first step, we investigated whether there were age-differences in the cognitive measures using *t*-tests. In a second step, regression analyses were conducted for an initial exploration of the relation between EF facets and WM but also to identify the cognitive measures that would serve as predictors for WM in general and age-related WM in particular. In a third step, path models were used to evaluate the individual role of updating, inhibition, and shifting in mediating age-differences on WM.

Descriptive Statistics and Age-Differences

Results revealed reliable age-differences in the expected direction (i.e., age decline) on all cognitive variables, (all *ps* < .003) except for performance in the color-shape task measuring shifting (see Table 1). Cohen's *d* (Cohen, 1988; defined effect sizes of 0.2 as small, 0.5 as medium, and 0.8 as large) varied between -0.03 (color shape task) and 2.04 (identical-pictures task); the largest age-differences were obtained in updating, processing speed, and the Simon task measuring inhibition. To build constructs, all cognitive measures were converted into standardized (z)-scores and then, the two relevant construct measures were combined. Reliable age-detriments were found for all constructs (for WM, updating, inhibition, and speed: *p*s < .001; for shifting: one-tailed *p*-value = .040).

Insert Table 1 about here

Correlation analyses. To describe relations between all cognitive constructs, pairwise correlations were computed (see Table 2). In these analyses, all constructs were represented as the means of their two respective individual indicator variables. WM significantly correlated with all other cognitive constructs except for shifting. Regarding the intercorrelation of the executive facets, updating and inhibition correlated significantly (r = .42), while shifting showed no relation with the other EF facets or WM.

Insert Table 2 about here

Explaining the Age-Differences on WM

Regression analyses. Next, we computed regression analyses to investigate age-differences on WM. In these analyses, the constructs of WM, speed, updating, inhibition, and shifting were again represented as the means of their two respective individual indicator variables. WM served as the dependent measure. In order to examine whether non-executive and/or executive measures could account for age-variability in WM, a set of hierarchical regression analyses was conducted (cf. Baron & Kenny, 1986; Judd & Kenny, 1981). First, age was included as (continuous) predictor of WM, yielding a clear effect (which represents the above reported age difference). All following steps addressed the question of whether this age-difference could be better accounted for by cognitive measures. Thus, in order to test whether the age-difference could be better accounted for by lower level cognitive resources, in a second step, processing speed was included as an additional predictor. Analogously, in order to test whether the age-difference could be better accounted for by higher order cognitive processes, in a third step, the three EF measures were included as additional predictors. The results are summarized in Table 3. In addition to identifying cognitive measures that could serve as predictors of WM in general, this analysis was a first exploration of which measures account for variance in WM when all cognitive measures are considered concurrently. This approach was followed by subsequent analyses using a path model approach to evaluate separate mediational mechanisms for the EF measures.

Insert Table 3 about here

In the first step, age accounted for approximately 8% of variability in WM, $F(1, 251) = 21.59$, $p < .001$. In the second step, including processing speed as an additional predictor increased the explained variability to 11%, $F(2, 250) = 15.85$, $p < .001$. In this two-level regression, only processing speed (but not age) was a significant predictor of WM. Including the three EF facets as additional predictors in a third step increased the explained variability to 22%, $F(5, 247) = 13.80$, $p < .001$. In this three-level regression, age, processing speed, and shifting were non-significant predictors of WM; the variability in WM was accounted for by updating and inhibition, with the latter emerging as the strongest predictor. A set of model comparisons revealed the role of updating and inhibition as predictors of WM: Removing the three EF measures from the model resulted in a significant reduction of explained variance, $\Delta R^2 = .11$, $p < .001$. In contrast, removing age from the model did not result in a significant reduction of explained variance, $\Delta R^2 < .01$, $p = .390$. The same pattern emerged when removing processing speed, $\Delta R^2 = .01$, $p = .119$, removing age and processing speed together, $\Delta R^2 = .01$, $p = .294$, and removing age, processing speed, and shifting together from the model, $\Delta R^2 = .01$, $p = .474$. Thus, the most economical model contained only updating ($\beta = .19$, $p = .002$) and inhibition ($\beta = .33$, $p < .001$) as predictors for WM, $R^2 = .21$, $F(2, 250) = 33.32$, $p < .001$.

Mediation analyses. The previous regression analyses indicated that there was no remaining variance in WM accounted for by age, once variability in EF (particularly updating and inhibition) was entered in the model. To further evaluate the individual role of each EF in mediating age-differences in WM, path models were used to simultaneously estimate indirect and direct effects. For all models, age was entered as a continuous variable. In a first step, for each executive facet a separate model was created, examining whether the respective facet would mediate age-differences in WM. These indirect effects were significant both for updating (standardized $\beta = -.15$; p < .001) as well as for inhibition (standardized $\beta = -.20$; $p <$

.001), where this was not the case for shifting (standardized $\beta < .01$; $p = .751$). The direct effect of age on WM was not significant for the updating-model (standardized $\beta = -.13$; $p = .054$) nor for the inhibition-model (standardized $\beta = -.08$; $p = .263$), but was significant for the shifting-model (standardized $\beta = -.28$; $p < .001$).

As one of the shifting measures (i.e., the color-shape task) failed to detect age-differences, the shifting model was repeated with the category-switch task as single indicator to evaluate whether results were caused by the low shifting-age relation. This analysis revealed the same pattern of results: The indirect effect via shifting was still non-significant (standardized $\beta = .01$; $p = .377$) and the direct effect of age on WM remained significant (standardized $\beta = -.29$; $p < .001$).

The full model

In a final step answering the developmental question of whether specific facets of EF predicted age-differences in WM, a comprehensive model was evaluated. In this approach, previously revealed mechanisms were arranged in a global path model to allow for a simultaneous evaluation of the individual role of each executive facet in predicting age-related WM. The derived model contained mediational paths for each EF to constitute indirect effects of age on WM via the EF measures (see Figure 1). As shifting did not show any pairwise correlation with the two other EF, only the correlation between updating and inhibition was included in the model. All constructs were again represented as the means of their two respective individual indicator variables. Age was entered as a continuous variable. The resulting model showed a nearly perfect fit, $\chi^2(df = 3) = 1.02$, $p = .797$, $CFI > .99$, $RMSEA < .01$.

Insert Figure 1 about here

For updating and inhibition, the respective indirect effect was significant (via updating: standardized β = -.09; p = .006; via inhibition: standardized β = -.19; p < .001), where this was not the case for shifting (standardized β < .01; p = .609). The direct effect of age on WM was not significant (standardized β = .01; p = .890).

Repeating the full model with the category-switch task as single indicator for shifting revealed the same results: The indirect effect via shifting was still non-significant (standardized β = .01; p = .369). The indirect effects via updating (standardized β = -.09; p = .006) and via inhibition (standardized β = -.19; p < .001) remained significant. The direct effect of age on WM was still non-significant (standardized β < .01; p = .988).

Discussion

The present study investigated the specific role of the three major facets of EF in age-related changes of WM performance. Using multiple indicators per variable and different statistical approaches, several major results were revealed: First, age-differences in WM were confirmed (supporting previous literature, see e.g., Bopp & Verhaeghen, 2005; Chai et al., 2018; Rhodes & Katz, 2017; Sander et al., 2012). Second, age-differences were also found in all three EF facets (also replicating previous results, e.g., Bélanger et al., 2010; Mayr & Liebscher, 2001; Verhaeghen & Basak, 2005). Third, and most importantly, a set of statistical approaches suggests that executive facets differently account for age-related variability in WM. Specifically, updating and inhibition seem most influential.

The main question of the current project was whether EF predicts WM beyond basic cognitive processes (i.e., processing speed), and if so, whether certain executive facets would specifically underlie age-differences in WM performance. A set of hierarchical regression analyses showed that the inclusion of EF measures as predictors in addition to age and processing speed led to a greater amount of explained variance in WM. More specifically, updating and inhibition (but not shifting) significantly predicted WM. Importantly, when all factors were considered together in one model, age and processing speed did not contribute to variability in WM performance beyond executive resources. Moreover, when executive predictors were considered, age and processing speed no longer significantly predicted WM.

A set of model comparisons suggests that age, speed, and shifting were redundant predictors in the presence of the other executive measures. Congruently, mediation analyses using path models showed that the WM age-differences were mediated by updating and inhibition, whereas this was not the case for shifting. This supports the notion that inhibition and updating are the most relevant EF facets underlying age-differences in WM. These results are congruent with predictions of the *executive attention framework* (Engle, 2002; Engle & Kane, 2004), such that maintaining and refreshing goals or memoranda in memory (which deploys updating resources) while suppressing interfering, non-pertinent information (which deploys inhibition resources) are the most important factors underlying individual (age-) differences in WM.

Engle and Kane (2004) argue that active memory maintenance and inhibitory control are the two interdependent factors that form executive attention, which consists the central core of WM. The present results confirm that updating and inhibition are two related, yet separable constructs that contribute to WM performance. As a consequence, the current findings speak against the alternative frameworks which predict that age-related variance in WM is exclusively accounted for by inhibitory control (e.g., Lustig et al., 2007) or by processing-related resources such as updating (e.g., Belleville et al., 2003). Instead, the current data support the view that a combination of inhibition and updating resources are essential in explaining age-related decline in WM, which is consistent with the two-factor view of cognitive control (see e.g., Engle, 2002; Engle & Kane, 2004).

Further, the present data suggests that age-related variance in shifting does not contribute to age-detriments in WM. This is in line with previous meta-analytic results (see Verhaeghen, 2011), which showed that task-shifting did not explain any age-related variance in complex cognition over and beyond the effects explained by processing speed. Similarly, Oberauer and colleagues (2008) have also shown that shifting was unrelated to WM, whereas Miyake and colleagues (2000) showed a negative relation between shifting and WM.

Given that only one of the two shifting tasks used in the present study showed age-differences (i.e. category-switch task), one could argue that these missing age-differences are the reason why shifting was not related to age-related WM in the present study. However, path model analyses using the category-switch task as single indicator for shifting revealed the same pattern of results in all cases. Thus, even when focusing on a task which showed a substantial age decline, shifting did not play any role in explaining age-related WM. This result supports the conclusion drawn above that shifting is not as essential as the other EF facets for explaining age-differences in WM.

In addition to supporting previous research exhibiting age-related decline in EF (e.g., Crawford et al., 2000; Salthouse et al., 2003), our results are novel in that they address the specific role of the different executive facets in age-related decline in WM more comprehensively. Thus, our data supports previous research that has highlighted the individual roles of inhibition (e.g., Lustig et al., 2001; Salthouse & Meinz, 1995; Van Gerven et al., 2007) and updating (Pelegrina, Borella, Carretti, & Lechuga, 2012; Schmiedek, Li, & Lindenberger, 2009) on age-differences in WM separately. However, our results extend the current literature by examining how these executive facets in combination account for independent age-related variance in WM.

Finally, and of more practical relevance, previous studies show that decreases of older adults' WM not only are among the first symptoms of neuropsychological diseases, such as mild cognitive impairment and Alzheimer's disease (e.g., Belleville et al., 2003, 2007; Gagnon & Belleville, 2011), but that they can also lead to less autonomy and lower quality of life (e.g., Klingberg, 2010; Nissim et al., 2016). As a consequence, the current findings may provide crucial novel insight into the specific facets of EFs that could be particularly relevant when aiming to improve older adults' WM. Past literature demonstrates the plasticity of higher-order cognitive functions such as WM (e.g., Williams & Kemper, 2010). It further illustrates how cognitive training interventions can lead to increased activity in the (pre-)frontal cortex and the fronto-parietal network that underlies WM functioning (e.g., Constantinidis & Klingberg, 2016). As a consequence, the present findings seem of particular interest, as they illustrate that in order to increase WM performance, cognitive trainings targeting pre-frontally mediated updating resources and inhibitory control may be particularly efficient. Thus, repeated enhancement of updating and inhibition resources may lead to increased WM capacity, which may prolong older adults' independence and increase their personal well-being.

Limitations of the present study concern the following issues: First, the specificity of the selected cognitive tasks may limit the generalizability of the results. However, to reduce distortions due to a specific single task, multiple indicators for the cognitive constructs were used. In addition, all tasks represent established indicators of WM, updating, inhibition, and shifting. Second, age-differences were not obtained in one of the two shifting measures. Thus, further research has to examine whether the role of shifting in explaining age-related WM remains comparably negligible when more sensitive shifting tasks are used which may show clearer age-differences. Note, however, the findings by Verhaeghen (2011) suggest that shifting may be an exception among the EF facets: It seems to be less influenced by age, and may therefore not be underlying the age decline in other cognitive functions such as WM. Third, we acknowledge that the present results might be biased due to missing data. Yet, the amount of missing data was comparably small in both age groups (and the pattern of results was identical for three different missing data techniques). Fourth, although a relatively large sample was tested, the younger age group consisted mainly of university students, which might limit the generalizability of the present findings: Different correlational patterns between the EF facets and WM might be found in clinical samples or participants with a lower level of education.

To review, the present study shows that updating and inhibition are key aspects of EF involved in age-related WM performance. This empirical finding supports the theoretical assumption that memory manipulation and maintenance as well as inhibitory control are the most essential underpinnings of WM (e.g., Engle & Kane, 2004). By identifying which executive facets specifically underlie WM in aging, the present study further offers an empirical basis for developing possible interventions and trainings to improve older adults' WM performance by strengthening their updating and inhibition performance.

Footnotes

[1] The proportions of excluded trials were, for the younger and older sample, respectively, 1.3% and 2.6% in the Simon task, 3.7% and 2.2% in the category-switch task, and 2.0% and 1.4% in the color-shape task.

[2] There were univariate outliers in the switching tasks (2 younger and 2 older adults) and the letter-memory task (1 older adult). Furthermore, there were three multivariate outliers from the group of older adults. When these outliers were included, analyses yielded a highly similar pattern of results.

[3] Because of the small proportion of missing data in general and the comparable fraction for both age groups, the applied listwise deletion technique was considered justifiable and results are reported for this method. Additionally, for a more conservative investigation, all analyses were repeated using mean imputation (i.e., all missing values were replaced with the mean of the respective variable). Furthermore, the path model analyses were repeated using the full-information maximum likelihood algorithm to estimate missing values allowing the inclusion of all 282 participants. Note that the pattern of results was the same for all three missing data techniques.

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Table 1

Participants' mean scores and standard deviations in the neuropsychological tests as a function of age group (younger versus older adults)

Neuropsychological tests	Younger adults				Older adults					
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*	*t* value	Cohen's *d*
Working Memory										
Reading span task [a]	0.94	0.25	0.37	1.57	0.83	0.27	0.25	1.57	3.15**	0.41
Counting span task [a]	0.96	0.24	0.25	1.57	0.85	0.20	0.34	1.32	4.12***	0.51
Updating										
Keep-track task [a]	0.78	0.18	0.41	1.25	0.65	0.15	0.22	1.02	5.80***	0.73
Letter-memory task [a]	1.11	0.28	0.43	1.57	0.82	0.24	0.11	1.33	8.45***	1.05
Inhibition										
Antisaccade task [a]	1.05	0.22	0.45	1.57	0.94	0.20	0.34	1.57	4.05***	0.51
Simon task [b]	-0.05	0.07	-0.24	0.12	-0.16	0.07	-0.35	-0.01	12.84***	1.62
Shifting										
Category-switch task [b]	-0.41	0.18	-0.76	0.15	-0.47	0.13	-0.80	0.02	3.05**	0.38
Color-shape task [b]	-0.70	0.13	-0.97	-0.09	-0.70	0.13	-0.98	-0.34	0.27	-0.03
Processing Speed										
Identical-pictures task	36.03	5.21	22	49	25.95	4.44	16	41	16.27***	2.04
Number-comparison task	22.60	4.78	13	35	18.17	4.01	11	30	7.85***	0.98

Note. [a] Accuracy scores were arcsine-transformed. [b] The sign of the response latency difference scores has been reversed; as a consequence, negative values represent costs and positive benefits, i.e. higher values represent better performance across all variables; proportion scores were used for the respective measures.

** $p < .01$; *** $p < .001$ (after applying a Bonferroni correction, controlling for multiple testing per construct).

Table 2

Pairwise correlations between performances in all cognitive constructs

Construct	*1*	*2*	*3*	*4*	*5*
1. WM	1	---	---	---	---
2. Updating	.35***	1	---	---	---
3. Inhibition	.41***	.42***	1	---	---
4. Shifting	-.04	.08	.004	1	---
5. Speed	.29***	.44***	.52***	.13	1

Note. All constructs are represented as the combined standardized means of their two respective individual indicator variables. Higher values represent better performance across all variables. Proportion scores were used for inhibition and shifting.
*** $p < .001$ (after applying a Bonferroni correction, controlling for multiple testing).

Table 3

Hierarchical regression predicting WM

Predictors	β	R^2	ΔR^2	F	$df1$	$df2$
Step 1		.08	.08***	21.59***	1	251
Age	-.27***			21.59***	1	251
Step 2		.11	.03**	15.85**	2	250
Age	-.11			2.08	1	250
Speed	.23**			9.39**	1	250
Step 3		.22	.11***	13.80***	5	247
Age	.07			0.74	1	247
Speed	.12			2.45	1	247
Updating	.18**			7.18**	1	247
Inhibition	.32***			20.86***	1	247
Shifting	-.02			0.13	1	247

Note. All constructs are represented as the combined means of their two respective individual indicator variables. Higher values represent better performance across all variables. Age was entered as a continuous variable. β coefficients are standardized. *df1* = degree of freedom in the numerator; *df2* = degree of freedom in the denominator.
** $p < .01$; *** $p < .001$.

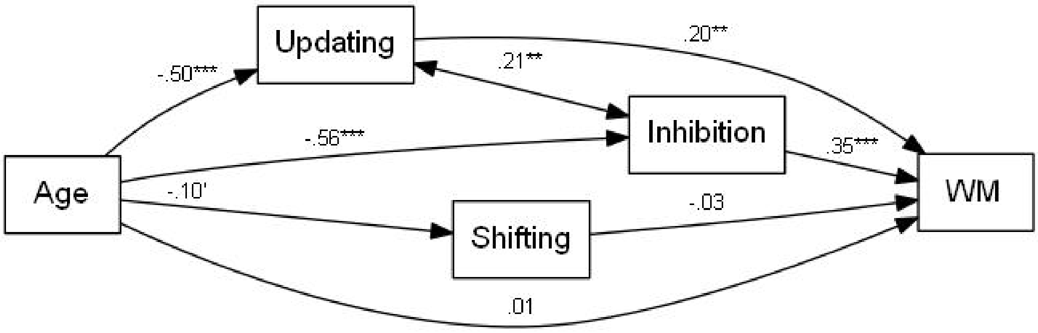

Figure 1. The full model. All constructs are represented as the combined means of their two respective individual indicator variables. Age was entered as a continuous variable. Note that as shifting did not show any pairwise correlation with the two other EF, only the correlation between updating and inhibition was included in the model. Values on uni-directional arrows represent standardized β-weights, whereas values on double arrows represent correlation coefficients (' $p < .10$, significance at one-tailed level; ** $p < .01$; *** $p < .001$).