# Unraveling the Aging Skein: Disentangling Sensory and Cognitive Predictors of Age-related Differences in Decision Making

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ABSTRACT

Age-related differences in sensory functioning, processing speed, and working memory have been identified as three significant predictors of the age-related performance decline observed in complex cognitive tasks. Yet, the assessment of their relative predictive capacity and interrelations is still an open issue in decision making and cognitive aging research. Indeed, no previous investigation has examined the relationships of all these three predictors with decision making. In an individual-differences study, we therefore disentangled the relative contribution of sensory functioning, processing speed, and working memory to the prediction of the age-related decline in cognitively demanding judgment and decision-making tasks. Structural equation modeling showed that the age-related decline in working memory plays an important predictive role, even when controlling for sensory functioning, processing speed, and education. Implications for research on decision making and cognitive aging are discussed

KEY WORDS judgment and decision making; cognitive aging; working memory; processing speed; sensory functioning

In the field of judgment and decision making, the investigation of predictors of age-related differences is still relatively new (e.g., Peters & Bruine de Bruin, 2012; Peters, Hess, Västfjäll & Auman, 2007; Strough, Parker & Bruine de Bruin, 2015). Moreover, cognitively oriented individual-differences studies have focused mainly on general measures of cognitive ability and numeracy, while mostly excluding measures of more specific skills (like working memory and processing speed) and entirely neglecting the potential role of sensory functioning (see the next section for a focused review).

The first goal of the individual-differences study presented in this paper is to provide a contribution to our understanding of the predictive role of sensory and basic cognitive measures to the age-related decline in cognitively demanding decision-making tasks (e.g., Bruine de Bruin, Parker & Fischhoff, 2007; Finucane & Gullion, 2010).[1] Indeed, we investigated, for the first time in a single study the relative contribution of sensory functioning, processing speed, and working memory to the prediction of performance in three cognitively demanding decision-making tasks of the Adult Decision-Making Competence (A-DMC) battery (Bruine de Bruin et al., 2007). Beyond filling a major gap in decision-making research, our study has broader implications for the investigation of predictors of age-related declines in complex cognition (e.g., Salthouse, 2012, 2014a).

In the next section, we will present the theoretical background of our study, focusing first on relevant cognitive aging research and then considering decision-making investigations. Next, we will introduce our hypotheses. The subsequent section will present the individual-differences study, which was carried out on a population-based sample of 563 adults from 30 to 85 years of age in the context of the Betula project on aging memory and dementia (Nilsson et al., 1997, 2004; Rönnlund & Nilsson, 2006; http://www.org.umu.se/betula/betula/), recently extended to include assessments of decision-making competence (Del Missier et al., 2013). Then, we will explain the rationale for the data analysis, carried out via comparative structural equation modeling. Next, the findings will be presented, and we will discuss their theoretical and applied implications. Finally, we will acknowledge the limitations of our investigation and show how they could be addressed in future research.

## THEORETICAL BACKGROUND

### Predictors of age-related performance decline in complex cognitive tasks

Three prominent predictors of age-related decline in complex cognitive performance are sensory functioning, processing speed, and working memory (e.g., Park, 2000; Salthouse, 1991a). Early studies reported that a large part of the age-related variance in tasks involving speed, verbal fluency, memory, and reasoning was mediated by sensory

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[1]Following Salthouse (2012) and for clarity of expression, results based on contrasts of cross-sectional data are referred to here as declines.

functioning, as assessed by tests of visual and auditory acuity (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Sensory functioning was proposed as a more basic construct than processing speed, reflecting neural/brain integrity (Baltes & Lindenberger, 1997). However, subsequent findings showed that sensory functioning plays only a minor role (e.g., Lindenberger & Ghisletta, 2009; Salthouse, 2014a), even when compared with processing speed (Park et al., 2002). Moreover, some studies failed to identify a single common sensory factor (e.g., Park et al., 2002, also Lindenberger & Baltes, 1994), thus casting doubts on the hypothesis that age-related declines in different sensory domains reflect a common cause or a single neural substrate.

More recently, research on functional biomarkers promoted a resurgence of interest in sensory indicators, extending the investigation to the predictive capacity of motor measures (e.g., Anstey, 2012). However, the predictive capacity of biological indicators and sensory functioning measures still needs to be convincingly demonstrated for complex cognition (e.g., Lindenberger & Ghisletta, 2009; MacDonald et al., 2011; Salthouse, 2014a; Sternäng, Jonsson, Wahlin, Nyberg & Nilsson, 2010—for neural predictors, see Salthouse, 2011a). Current views mainly assume that age-related reductions in sensory functioning lead to less effective encoding of information (e.g., Craik & Rose, 2012; Grady & Craik, 2000; Wingfield, Tun & McCoy, 2005) or still posit that sensory functioning measures can be considered as proxies reflecting age-related neural or biochemical changes, which also affect cognitive functioning (e.g., Anstey, 2012, MacDonald et al., 2011; Salthouse, 2011a). Declines in both vision and hearing[2] can undermine the richness or specificity of the information encoded, either because the greater effort spent on perception and comprehension may impair memory formation or because the reduced accuracy of the perceptual record affects further processing (Craik & Rose, 2012).[3]

It has also been proposed that age differences in complex cognitive performance can be explained by declines in processing speed (Salthouse, 1996). Studies have found that processing speed plays a significant role in tasks involving working memory and long-term memory (e.g., Park et al., 2002; Salthouse, 1996). Salthouse (1996) proposed that slower processing may negatively affect performance in two ways. First, slower execution of earlier operations can greatly reduce the time available to perform later operations, with negative consequences under time constraints (limited time mechanism). Second, the products of earlier processing may be lost by the time later processing is completed, resulting in performance declines even when there is no time pressure (simultaneity mechanisms). More recent research conceived processing speed not as a fundamental explanatory construct of age-related cognitive decline but as a sensitive marker of cognitive aging (Anstey, 2012), possibly with a distinct neural substrate (Habeck et al., 2015).

Working memory seems to be especially important for complex cognition (Baddeley, 2003, 2007; Cowan, 2005; Engle & Kane, 2004; Engle, Tuholski, Laughlin & Conway, 1999, Miyake & Shah, 1999). Indeed, working memory processes play important functional roles in complex cognitive tasks, actively maintaining information during execution, updating task-relevant information, and inhibiting or filtering irrelevant or no longer relevant information (Park, 2000; Hasher & Zacks, 1988). Age-related differences in working memory are well documented (Bopp & Verhaeghen, 2005; Jenkins, Myerson, Joerding, & Hale, 2000; Park et al., 2002; Verhaeghen, Marcoen, & Goosens, 1993; Verhaeghen & Salthouse, 1997), and these differences have been related to performance declines in complex cognitive tasks involving long-term memory, reasoning, and fluid intelligence (e.g., Craik & Jennings, 1992; Park et al., 1996; Salthouse, 1991b). As a consequence, working memory is regarded as one of the core constructs of cognitive aging (e.g., Park et al., 1996; Park, 2000; Verhaeghen, 2012). Recent studies suggest that working memory also plays a significant role in explaining age differences in more cognitively demanding judgment and decision-making tasks (see Del Missier et al., 2013, Del Missier, Mäntylä & Nilsson, 2015, and the next section).

An important aspect to be considered in the discussion of age differences in cognition is the nature and the complexity of the criterion tasks. For more complex tasks, working memory can play a greater functional role, owing to the increased need to actively maintain and update task-relevant information. In line with this reasoning, a number of studies have suggested that that working memory contributes uniquely to age-related differences in more complex tasks beyond processing speed (e.g., Mayr & Kliegl, 1993; Kliegl, Mayr & Krampe, 1994, Nettelbeck & Rabbitt, 1992; Park et al., 1996; Verhaeghen & Salthouse, 1997, see also Park, 2000, Verhaeghen, 2012).

## Predictors of age-related performance decline in decision making

Decision making has traditionally received limited attention from researchers of cognitive aging, despite its obvious relevance for successful aging. However, recent research studies have shown that some decision-making abilities decline with age, while others are preserved or improve (for reviews, see

[2]Some age-related declines in sensory functioning are well documented in normal aging, even if individual differences are apparent in each sensory domain. In particular, visual acuity can decrease (Attebo, Mitchell & Smith, 1996) as well as the capacity to focus and to adapt to the light (owing to changes in the eye lens, eye muscles, and pupil size, and alterations in the integrity of the macular pigment and neural pathways). Hearing acuity can decrease as well (e.g., Cruickshanks et al., 1998) owing to conductive or sensorineural losses, especially in relation to high-frequency sounds. Also olfactory sensitivity can be reduced in older adults (e.g., Larsson, Nilsson, Olofsson & Nordin, 2004). These age-related declines may reduce the ability to read and understand, perceive the environment and notice important signals, drive, conduct a social life, and eat properly (owing to taste loss), and, in some cases, they may be associated with a significant reduction in the individual's functioning (e.g., Dalton et al., 2003).

[3]Although the decision-making tasks we investigated in the present study require mainly visual processing at encoding, with no apparent contribution from other sensory channels, collecting data on the other sensory processes was well justified from the viewpoint of the common cause or biological aging views, which assume that multiple indicators, collected across multiple sensory channels, may reflect an unique construct affected by the age-related decline.

Del Missier et al., 2015; Peters & Bruine de Bruin, 2012; Peters et al., 2007; Strough et al., 2015). In particular, older adults show worse performance in cognitively demanding tasks involving multi-attribute choice and multiple-cue judgments (e.g., Besedeš, Deck, Sarangi & Shor, 2012; Bruine de Bruin, Parker & Fischhoff, 2012; Chasseigne, Mullet & Stewart, 1997; Del Missier et al., 2013; Finucane & Gullion, 2010; Finucane, Mertz, Slovic, & Schmidt, 2005). Older adults' reduced performance on complex decision tasks has been explained by age-related declines of fluid cognitive abilities (e.g., Bruine de Bruin et al., 2012; Del Missier et al., 2013), possibly related to older adults' frontal deterioration (MacPherson, Phillips, & Della Sala, 2002; Mather, 2006).

In contrast, older adults perform similarly to young adults or even better when the task is cognitively less demanding (e.g., Bruine de Bruin et al., 2012; Queen & Hess, 2010) or relies more on knowledge and experience (e.g., Del Missier et al., 2013; Li, Baldassi, Johnson, & Weber, 2013; Li et al., 2015; Meyer, Russo & Talbot, 1995; Meyer & Pollard, 2004). Finally, older adults may show better decisions than young adults in some tasks requiring social skills (e.g., Hess, Osowski & Leclerc, 2005) or emotion regulation (MacPherson et al., 2002; Strough, Mehta, McFall & Schuller, 2008; Scheibe, Mata, & Carstensen, 2011), possibly owing to their motivation to optimize emotional experiences and maintain relationships (e.g., Carstensen, 2006; Hess et al., 2005). However, older adults' greater focus on positive emotions may also promote less effective decisions due to greater self-serving memory distortion (Mather, 2006; Mather & Johnson, 2000).

Only a few studies have considered the potential predictors underlying the age-related decline observed in the more cognitively demanding judgment and decision-making tasks. Recent studies have shown that older adults performed especially poorly on the cognitively demanding decision tasks of the A-DMC battery, which require more executive control and high-level cognitive abilities (Bruine de Bruin et al., 2007, Del Missier et al., 2010, 2012; Parker & Fischhoff, 2005—see the Supporting Information for example items). The negative relationship between age and performance on those decision-making competence tasks was found to be mediated by age-related declines in fluid intelligence (Bruine de Bruin et al., 2012) and working memory (Del Missier et al., 2013). The latter finding held even after taking into account individual differences in episodic and semantic memory.

Studies on aging and decision making have largely ignored the role of sensory functioning and processing speed. Three exceptions can be noted. First, Finucane et al. (2005) found that older age and task complexity are related to more comprehension errors and inconsistency in decision making. Cognitive measures, including two indicators of processing speed and short-term memory, were significant predictors of comprehension and, to a lesser extent, of consistency. However, the respective role of each predictor was not specifically appraised. Second, Finucane and Gullion (2010) observed that decision-making performance was moderately related to measures of short-term memory and processing speed. However, as in the previous study, the specific roles of memory and processing speed were not disentangled. Third, Henninger, Madden and Huettel (2010) found that age differences in the Cambridge Gambling Task and in the Balloon Analogue Risk Task were mediated by processing speed. However, their model included only a speed factor and a long-term memory factor (a short-term memory measure, Digit Span, was excluded from the analysis).

Hence, to the best of our knowledge, no study has considered at the same time the relative contribution of sensory functioning, processing speed, and working memory to performance in cognitively demanding judgment and decision tasks across the adult lifespan. The study presented here aims to fill this gap.

## AN INDIVIDUAL-DIFFERENCES INVESTIGATION ON AGE-RELATED PREDICTORS OF DECISION MAKING

### Hypotheses

Our study focuses on the contribution of sensory functioning, processing speed, and working memory to age differences in decision-making performance. Our main hypothesis is that working memory will play a unique and prominent role in predicting age-related differences in complex decision-making tasks, beyond sensory functioning and processing speed. This hypothesis derives from investigations showing that the specific contribution of working memory is apparent in more complex tasks with specific cognitive demands (e.g., Mayr & Kliegl, 1993; Kliegl, Mayr & Krampe, 1994, Nettelbeck & Rabbitt, 1992; Park et al., 1996; Verhaeghen & Salthouse, 1997, also Park, 2000, Verhaeghen, 2012).

Each of the three decision-making tasks that we employed in our study, measuring resistance to framing, applying decision rules, and under/overconfidence, capture important aspects of decision-making competence (Bruine de Bruin et al., 2007; Parker & Fischhoff, 2005). Performance on each of these tasks appears to rely on working memory, requiring elaborative encoding, active updating of relevant information, and/or suppression of irrelevant or no longer relevant stimuli or memories (for supporting evidence, see Del Missier et al., 2010, 2012, 2013; for a detailed description of the tasks, see the Method section).

Indeed, in the Resistance to Framing task, working memory maintenance and updating processes are needed when participants encode the problem, process the relevant information, suppress irrelevant and superficial emotion-laden appraisals, construct a thoughtful representation of the problem, and generate a preference judgment (De Martino, Kumaran, Seymour, & Dolan, 2006; Del Missier et al., 2012, 2013; Kahneman & Frederick, 2007; McElroy & Seta, 2003). In the Applying Decision Rules tasks, working memory processes support the execution of a complex sequence of cognitive operations to choose between options (i.e., encoding, comparing, and aggregating attribute values, keeping active running evaluations or counts), while ignoring or suppressing irrelevant or no longer relevant stimuli (Del Missier et al., 2010, 2012, 2013; Payne et al., 1993). In the Under/Overconfidence task, working memory processes are required to consider the pros and cons of answers to knowledge questions, searching memory for relevant evidence and summarizing the quality of that evidence in a confidence judgment (Del Missier et al., 2013; Dougherty & Hunter, 2003; Koriat, Lichtenstein, & Fischhoff, 1980; Sprenger & Dougherty, 2006; Stanovich, 2009).

## Method

### *Participants and procedure*

Individuals recruited for two sessions in the fifth wave (T5) of the Betula Prospective Cohort Study took part in the present study. A stratified random sampling scheme was used, with high-evidence of population validity (Nilsson et al., 1997, 2004). Participants were recruited from the inhabitants of the middle-size northern Swedish city of Umeå. At the recruitment stage, participants were screened for dementia, severe sensory impairments, mental retardation, and a native tongue other than Swedish (for further details concerning sampling, recruitment and inclusion criteria, see Nilsson et al., 1997).

At the first session, participants underwent a health assessment including sensory measures. One week later, participants returned and completed cognitive measures, including processing speed and working memory. Each session lasted about 2 hours. Additionally, the 1047 participants received the Swedish-language version of the A-DMC battery to complete at home and return it by postal mail.[4] Five hundred and seventy-eight participants (55%) returned the questionnaire with at least 80% of all items completed. The remaining participants were considered to have dropped out (45%).[5] The final sample was composed of 563 adults (51% females)[6] between 30 and 85 years of age (with 136 participants in the 30–55 age range, 182 participants in the 56–65 age range, and 245 participants in the 66–85 age range).

### *Measures*

*Decision-making measures.* Participants received three cognitively demanding measures of decision-making competence taken from the A-DMC battery (Bruine de Bruin et al., 2007).[7] We used a Swedish-language version that has psychometric properties similar to the original battery (Mäntylä et al., 2012). Overall performance on each A-DMC task was computed such that higher scores reflect better performance.

*Resistance to framing.* This task is composed of seven risky-choice problems and seven attribute-framing problems. Each risky-choice problem includes a gain frame and a loss frame. The seven gain frames are presented together and are separated from the seven loss frames by other A-DMC tasks. The item order of the gain frames and the loss frames is varied (Bruine de Bruin et al., 2007). In each frame, participants have to state their preference between a sure option and a risky option. For example, one item asked participants to consider that a pesticide is threatening the lives of 1200 endangered animals (after Schneider, 1992). The positively framed version offers a choice between saving 600 animals for sure and a gamble with a 75% chance that 800 animals will be saved and a 25% chance that no animals will be saved. The negatively framed version offers a choice between 600 animals lost for sure and a gamble with a 75% chance that 400 animals will be lost and a 25% chance that 1200 animals will be lost. Participants then state their relative preference for the two options on a 6-point scale ranging from 1 (*definitely would choose A*) and 6 (*definitely would choose B*). Similarly, each attribute-framing problem involves a positive description and a negative description of a decision attribute. For example, one item pair asks participants to evaluate the quality of ground beef (after Levin & Gaeth, 1988), with the positive version labeling it as 80% lean and the negative version labeling it as 20% fat. Participants express their judgment on a 6-point scale ranging from *very low* to *very high*. Overall, performance on the Resistance to Framing task is reflected as the mean of the absolute differences in ratings between the two versions of the same problems. This score is reversed, such that higher values indicate a better resistance to framing.

*Applying decision rules.* This task includes 10 multi-attribute decision problems. Each asks participants to use a specified decision rule to choose between five DVD players with numeric ratings presented for five features (like sound quality and image quality). Decision rules include satisficing and elimination by aspects (Payne et al., 1993). Each rule is presented with a written description of the procedure to be applied to the specific problem. The task final score is the percentage of problems in which participants made choices reflecting the correct application of the decision rules.

*Under/overconfidence.* This task presents 34 true/false statements about everyday knowledge (e.g., "You can take wrinkles out of your clothes by putting them in the dryer with a damp towel."). For each statement, participants indicate if it is true or false and express their confidence in their answer by ticking a graduated ruler ranging from 50% (just guessing) to 100% (absolutely sure). The final performance score equals one minus the absolute difference between the mean confidence judgments over the 34 items and the percentage of correct responses across items. Higher scores indicate a better performance.

*Measures of sensory functioning, processing speed, and working memory.* The sensory functioning, processing speed, and working memory measures were part of the test battery of the Betula project. The presentation order of sensory

[4]Participants were allowed to use corrective devices during all the cognitive and decision-making tests, to assure a fair assessment of their performance in their normal living condition.

[5]No significant attrition effect was observed for years of education ($t(1013) = 1.41$, $p = .16$). The dropouts were 43% male and 57% female, percentages that were only slightly different from the returnees' ones (albeit the difference was marginally significant: $p = .053$). A slight difference was observed also for age: returnees were, on average, 2 years older than dropouts ($t(1045) = 2.5$, $p = .01$; 63 vs. 61 years).

[6]Fourteen cases were further discarded being outside the 30–85 age range and one owing to more than 80% of missing items in the tests of our specific interest. The calculation of age in note 5 includes these discarded cases.

[7]The full set of A-DMC tasks in English is available on line: http://www.sjdm.org/dmidi/Adult_-_Decision_Making_Competence.html and example items are presented in the Supporting Information of this paper.

measures was as follows: Scandinavian Odor Identification Test (SOIT), Five-Minute Hearing Test (FMHT), pure-tone audiometric measurement, and visual tests from 3 and 5 m (with other tests interspaced). The presentation order of cognitive tests was as follows: Block design, Letter-digit substitution, Letter comparison, Pattern comparison, *N*-back, and Reading span (with other tests interspaced).

*Sensory functioning measures.* Olfactory measure. We used an odor identification test designed for Swedish participants, which has good sensitivity and specificity (the modified SOIT, Nordin et al., 1998). SOIT performance strongly correlates with the University of Pennsylvania Smell Identification Test (Doty, Shaman & Dann, 1984) and the CCCRC Threshold Test (Cain, 1989). The modified SOIT has shown age-related differences in odor identification that could not be accounted for by demographic and cognitive variables (Larsson, Nilsson, Olofsson & Nordin, 2004). The test comprises 13 olfactory stimuli presented as a cotton pad injected with liquid odorant and placed in an opaque 80-ml glass jar. Each stimulus was presented 1–2 cm under the participant's nose for as long as requested. To limit adaptation effects, there was a 30-second inter-stimulus interval between odor items. For each stimulus, participants identified which out of four response alternatives represented the correct description. All participants received the same 13 stimuli, but in 10 different random orders. Performance was evaluated as the number of odors correctly identified.

Auditory measures. Two auditory functioning measures were used. First, we used the FMHT, based on the Revised American Academy of Otolaryngology-Head & Neck Surgery test (Koike, Hurst & Wetmore, 1994). Participants self-reported potential signs of hearing problems by rating their agreement with 15 statements (like "I have problems hearing what is said on the phone" on a 4-point frequency scale (0 = *never*; 3 = *almost always*)). A summative score was computed, with higher scores indicating higher auditory problems. Koike et al. (1994) showed that the test is positively correlated with objective measures of hearing loss. The second auditory measure was derived from a standard pure-tone audiometric measurement (International Organization for Standardization 8253-1). Following Rönnberg et al. (2011), we averaged hearing losses at four frequencies (500, 1000, 2000, and 4000 Hz). We present the results for both ears, with higher scores representing greater hearing loss.

Visual measures. Visual acuity measures were obtained using standard vision tests with Snellen charts without corrections from 3 and 5 m (i.e., no eyeglasses). Scores are expressed in decimal scale.

*Processing speed measures.* Letter-digit substitution. This task was a revised version of the digit-symbol substitution test (Salthouse & Babcock, 1991; Wechsler, 1981). Participants received a reference table with nine letter-digit pairs. Then, they were presented with a randomized series of letters for which they had to indicate the corresponding digits. After a practice trial, participants had 60 seconds to find as many letter-digit correspondences as possible. Performance was assessed with the number of pairs correctly completed.

Letter comparison task. Participants were asked to decide whether pairs of letter strings are equal or different (Salthouse & Babcock, 1991; Salthouse, Berish, & Siedlecki, 2004). Length of strings varied across items. Performance was assessed with the number of correct responses given in 30 seconds.

Pattern comparison task. In this task (Salthouse & Babcock, 1991; Salthouse et al., 2004), participants decided whether pairs of line drawings were equal or different. The performance score was the number of correct responses in 30 seconds.

*Working memory measures.* Reading span. Participants received a computerized verbal span task, jointly tapping working memory storage and processing functions (Daneman & Carpenter, 1980). In each trial, the participant had to decide whether or not a sentence displayed on a computer screen was semantically meaningful or not and to memorize a sequence of single words presented in between sentences (see also Engle, Tuholski, Laughlin & Conway, 1999). In our study, participants performed three trials, at each of four different levels of cognitive load, corresponding to a successive increase in storage demands from two to five items (i.e., number of words to be memorized in a trial). Working memory capacity was evaluated as the proportion of words recalled in correct serial order across the different trials and load levels.

N-back. A computerized version of the 2-back task assessed the ability to update working memory contents (e.g., Owen, McMillan, Laird & Bullmore, 2005). Forty words were displayed sequentially on a computer screen. Participants were required to maintain the two most recent words and their temporal order in working memory, and to indicate whether or not the current word was the same as the one presented two items earlier or not. If the current word matched the "2-back" word actively held in working memory the participants had to respond by pressing a "yes" key, otherwise a "no" key. The task included two rounds of 15 practice items, and the performance score was the proportion of correct responses.

Block design. The WAIS-R Block Design test involved the manipulation of cubes to match a series of target patterns provided on pictures and presented in ascending order of difficulty. The task was administered in accordance with the WAIS-R-manual, and raw scores were used as performance measure (Wechsler, 1981). Performance in Block Design is selectively associated with working memory updating (Friedman et al., 2006), a finding consistent with several studies reporting a strong relation between working memory capacity and fluid intelligence (e.g., Carpenter, Just, & Shell, 1990; Kane, Hambrick & Conway, 2005; Engle et al., 1999). In the current investigation, it has been used as an additional indicator of working memory functioning.

*Data analysis plan*

We first carried out correlational analysis and confirmatory structural equation modeling (henceforth SEM) to appraise the empirical support for the specification of distinct latent variables for sensory functioning, processing speed, working memory, and decision making.[8] As we will show in the next section, this specification was supported for all predictors except sensory functioning. Thus, we selected the SOIT as the best indicator of sensory functioning in the following analyses, in the light of its more consistent and stronger relations with age and decision making (cf. Table 2), and we employed three latent variables, built from manifest indicators of processing speed, working memory, and decision making (e.g., Friedman & Miyake, 2004; Miyake et al., 2000). We also checked the robustness of our findings to changes in the sensory functioning indicator (Supporting Information).

Then, we adopted a comparative modeling approach (e.g., Del Missier et al., 2013; Friedman & Miyake, 2004; Miyake et al., 2000) to appraise the role of sensory functioning, processing speed, and working memory in predicting decision-making performance. We compared three alternative models, centered on the mediational role of each main predictor, assuming that the candidate predictor (but not the other two) mediates the effects of age on decision making. For each of these models, we specified two variants, the former assuming total mediation of age effects on decision making and the latter partial mediation (for a diagrammatic representation, see Figure 1, panel A). As references of comparison for evaluating the fit of these mediation models, we employed both a full-path model, in which we included the effects of all the three predictors on decision making, and a no-path model, in which none of the predictors were included (Figure 1, panel B).

All of our models share a common kernel (Figure 1, panel B, the solid lines in the no-path model), representing the interrelations between the three predictors (and age), with a variable ordering that goes from sensory functioning, to processing speed, to working memory. This ordering is consistent with previous work with similar aims (e.g., Park et al., 1996, 2002; Salthouse, 1991b; Verhaeghen & Salthouse, 1997), thus being compatible with existing theoretical accounts, and it establishes a very conservative test of our working-memory mediation hypothesis. Indeed, the ordering implies that the relationship between age, working memory, and decision making is appraised while controlling for all the other effects of age, including the indirect ones via sensory functioning and processing speed. We also included education as a control variable for cohort effects in all the models tested (Figure 1, panel C), because this proved to be a very effective form of control on the Betula memory data, making education-corrected cross-sectional results fully comparable with longitudinal ones after correction for practice effects (Rönnlund, Nyberg, Bäckman, & Nilsson, 2005).

All models were estimated by using the maximum likelihood method in AMOS 22 (Arbuckle, 2013).[9] Following common SEM practice, the evaluation of the models was carried out by using multiple standard measures of fit: the $\chi^2/df$ ratio,[10] Bentler's comparative fit index (CFI), the root-mean-square error of approximation (RMSEA), and Akaike's information criterion (AIC).[11] We also employed the $\chi^2$ difference test to compare the fit of nested models. The significance of each structural coefficient was also examined, together with the predictive power of the model ($R^2$).

After comparative modeling, we carried out a further data analysis step on the best-fitting model, estimating each indirect effect (and computing its 95% bootstrap confidence intervals—Preacher & Hayes, 2008; Shrout & Bolger, 2002) in order to fully characterize the specific contribution of the different predictors (Figure 3) as deployed through different paths (e.g., Taylor, MacKinnon & Tein, 2008). This analysis was carried out with MPLUS 7.2 (Muthén & Muthén, 2012).

To further appraise the robustness of our conclusions, we carried out several additional analyses, which are all reported in the Supporting Information. In particular, we estimated the loss in predictive capacity in lesion versions of the models, obtained by selectively removing a predictor (i.e., sensory functioning, processing speed, and working memory) from the full-path model or by deleting single links from age to the target mediator in the partial-mediation models (e.g., age➔working memory). Other control analyses included the use of measures of sensory functioning other than the SOIT and the use of single decision-making manifest variables as criterion tasks. Finally, we checked the robustness of the results when applying an alternative method to assess mediation (Schmiedek & Li, 2004).

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[8]The choice of SEM for data analysis was motivated by several reasons. First, predictors of decision making are interrelated, in some cases with rather strong correlations between variables, and as a consequence, an approach based on ordinary regression would not be fully justified. A second important reason is that the use of latent variables (vs. manifest indicators) allows a more reliable and purer assessment of a construct, which is less affected by task-specific features and requirements (e.g., Miyake et al., 2000). This is useful when the reliability of the measures is not very high and performance measurement can reflect also task-specific skills (as can happen in complex tasks measuring executive control and decision making). A more conceptual point is that SEM requires (and allows) the researcher to make explicit the potential network of relationships between variables and to test it (even comparatively), thus shedding light on a more complex set of relationships than multiple regression. Finally, with SEM, it is possible to quantify multi-path indirect effects (in our case, multi-path indirect effects of aging on decision making), something that is not feasible with regression methods.

[9]We used regression imputation of missing data, but no appreciable changes in the results were obtained by using non-imputed data or alternative estimation methods, like the asymptotically distribution-free method (Browne, 1984).

[10]The probability of the $\chi^2$ statistic is not reported, given that with big sample sizes even good fitting models can show a significant $\chi^2$ (e.g., Hair, Black, Babin & Anderson, 2009; Kline, 1998). Thus, the significance of this statistics is not useful in discriminating good and bad models in studies like the present one. Instead, the $\chi^2/df$ ratio is reported, which is less sensitive to sample size.

[11]Reference thresholds for good fitting models are as follows: $\chi^2$/df ratio $< 3$, but the lower the better; CFI $> 0.95$, but the higher the better; RMSEA $< 0.06$, but the lower the better; AIC the lower the better.

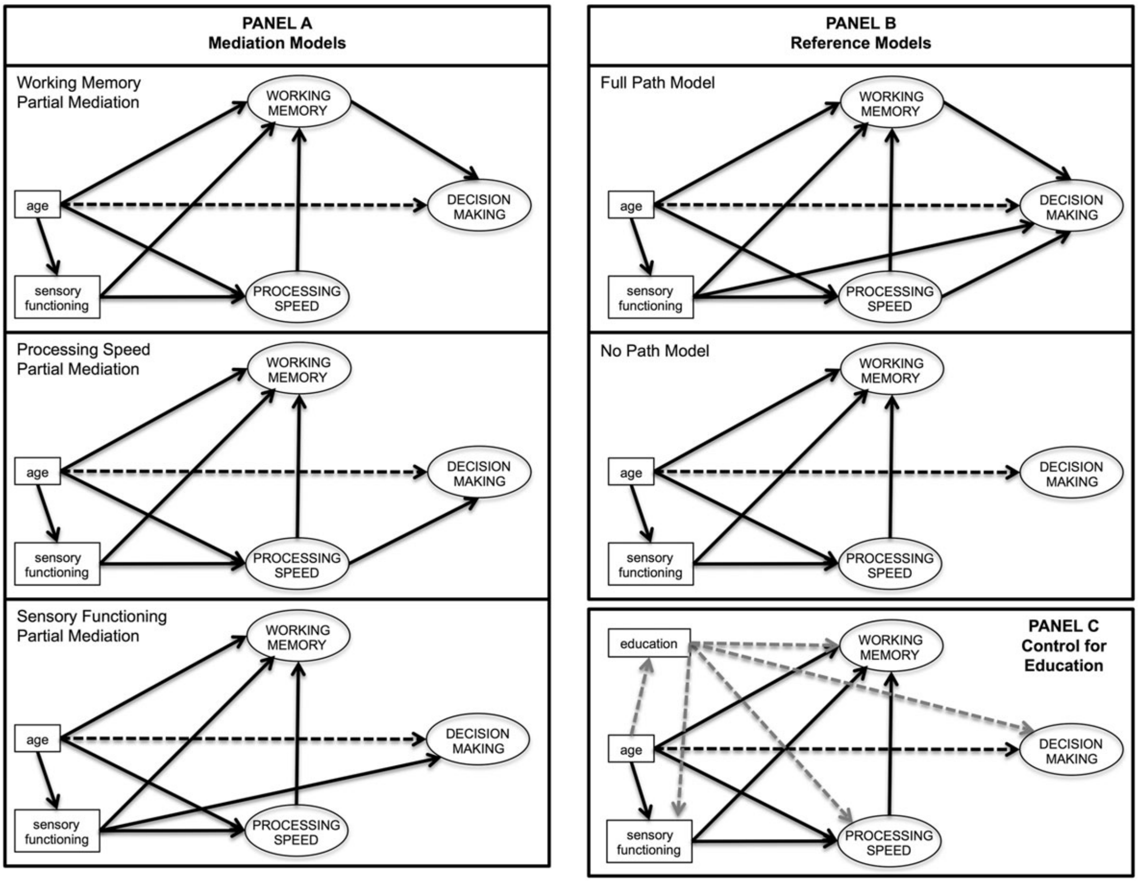


Figure 1. Panel A (left) presents alternative mediation models centered on single predictors (working memory, processing speed, and sensory functioning). Partial-mediation models are displayed; removing the direct relation between age and decision making (dotted line) leads to the full mediation versions of the same models. Panel B (upper right) presents the two reference models (full path, no path). The solid lines in the no-path model represent the common kernel of all the models, specifying the relations between predictors of decision making. Panel C illustrates how the control for education was applied to all the tested models (dotted gray lines)

**Results**

*Descriptive statistics, correlational analysis, and confirmatory measurement SEM*

Table 1 presents descriptive statistics for all measures, which are in line with previous investigations (e.g., Bruine de Bruin et al., 2007, 2012; Del Missier et al., 2012, 2013).

Table 2 presents pairwise correlations between our measures. Age shows a significant negative correlation with performance on all the decision-making tasks. Significant correlations with decision-making performance are also observed in the case of the SOIT (odor identification) and, to a lesser extent, of hearing loss, while there are no significant correlations between FMHT (self-reported hearing) or visual tests and decision making. Processing speed and working memory are positively associated with decision-making performance, with slightly stronger correlations in the case of working memory. Table 2 (last column) also shows the expected negative relations between age and all the predictors, which are stronger for some sensory measure (i.e., SOIT and hearing loss) and in the case of processing speed and working memory.

The analysis of intercorrelations between sensory functioning measures showed strong correlations between the two visual tests ($r = .84$; $p < .001$), between assessments of hearing loss in the two ears ($r = .89$; $p < .001$), and between FMHT and hearing losses (left: $r = .53$, $p < .001$; right: $r = .51$, $p < .001$). However, the visual tests were not significantly correlated with any of the other sensory measures, and the SOIT correlated weakly with the auditory measures (FMHT: $r = -.14$, $p < .01$; hearing loss left: $r = -.15$, $p < .001$; hearing loss right: $r = -.17$, $p < .001$). Thus, the correlations seem strong within sensory domains but much weaker across domains. For this reason, as in previous studies (e.g., Lindenberger & Baltes, 1994; Park et al., 2002), it was not possible to build a single sensory functioning latent variable from our indicators. Such an attempt, made via SEM confirmatory analysis, failed in identifying a valid model, with the identification failing even when assuming a hierarchical model of sensory functioning, built on the three different sensory domains. Thus, in the present study, we focused on the SOIT as our primary indicator of sensory functioning, given its more consistent and stronger correlations with decision making and age.

The three processing speed measures were strongly intercorrelated ($r_{\text{letter-digitletter-comp}} = .65$, $p < .001$; $r_{\text{letter-digitpattern-comp}} = .66$, $p < .001$; $r_{\text{letter-comppattern-comp}} = .62$, $p < .001$). A similar pattern, with lower correlations, emerged for working memory measures ($r_{\text{reading-span2-back}} = .26$, $p < .001$; $r_{\text{reading-spanblock-des}} = .29$, $p < .001$; $r_{\text{2-back-block-des}} = .43$, $p < .001$). Also decision-making variables

Table 1. Descriptive statistics

| | *N* | Mean | Min | Max | *SD* | Skewness | Kurtosis | Reliability |
|---|---|---|---|---|---|---|---|---|
| Age | 563 | 64.33 | 30.00 | 85.00 | 11.16 | −.81 | .72 | — |
| Education (years) | 553 | 12.80 | 6.00 | 26.00 | 4.02 | .25 | −.38 | — |
| Sensory functioning tests | | | | | | | | |
| SOIT | 545 | 6.77 | .00 | 12.00 | 2.24 | −.18 | −.21 | .79 |
| FMHT | 556 | 7.97 | .00 | 42.00 | 7.63 | 1.41 | 1.93 | .95 |
| Hearing loss left | 518 | 17.12 | −2.50 | 66.25 | 13.36 | .95 | .77 | .84 |
| Hearing loss right | 518 | 17.52 | −1.25 | 77.50 | 14.58 | .96 | .61 | .84 |
| Vision test 3 m | 515 | .56 | .00 | 1.00 | .31 | .08 | −1.31 | .89 |
| Vision test 5 m | 512 | .60 | .00 | 2.00 | .35 | .30 | −.34 | .89 |
| Processing speed tests | | | | | | | | |
| Letter-digit substitution | 559 | 29.75 | .00 | 49.00 | 7.27 | −.18 | .47 | NA |
| Letter comparison | 562 | 8.24 | 1.00 | 18.00 | 2.70 | .36 | .17 | .71 |
| Pattern comparison | 561 | 15.05 | 1.00 | 27.00 | 3.82 | .32 | .20 | .73 |
| Working memory tests | | | | | | | | |
| Reading span | 511 | .35 | .00 | 1.00 | .19 | .73 | .02 | NA |
| 2-Back | 516 | .56 | .00 | 1.00 | .18 | .12 | .63 | .76 |
| Block design | 562 | 28.67 | 2.00 | 51.00 | 9.73 | .03 | −.59 | .81 |
| Decision-making tests | | | | | | | | |
| Framing | 563 | 3.90 | 2.36 | 4.93 | .52 | −.40 | −.18 | .59 |
| Applying decision rules | 559 | .73 | .27 | 1.00 | .16 | −.28 | −.62 | .83 |
| Under/overconfidence | 563 | .89 | .41 | 1.00 | .08 | −1.03 | 1.64 | .62 |

*Note*: Reliabilities refer to Cronbach's alpha, unless otherwise specified. Reliability was literature-derived for the following measures: FMHT (Kochkin & Bentler, 2010), SOIT (Nordin et al., 1998—test–retest), Letter and Pattern comparison (Salthouse & Babcock, 1991—split-half correlations corrected with Spearman–Brown formula), Block design (Rönnlund, & Nilsson, 2006—5-year stability). Reliabilities for the Reading span and the Letter-digit substitution tests used in our study were not available (NA), but working memory span tests reliabilities are typically in the .70–.90 range (Conway, Kane, Bunting, Hambrick, Wilhelm and Engle, 2005), and Wechsler (1981) reported that test–retest reliability for the digit-symbol is .82. Reliability for vision tests refers to the pairwise correlation between the 3- and the 5-m tests, while reliability for hearing refers to the correlation between the left and right ear tests. The 2-Back scores were cube-transformed to reduce kurtosis.
FMHT, Five-Minute Hearing Test; SOIT, Scandinavian Odor Identification Test.

Table 2. Correlations between predictors, decision-making measures, and age

| | Decision-making tasks | | | |
|---|---|---|---|---|
| | Framing | Applying decision rules | Under/overconfidence | Age |
| Age | −.11** | −.35*** | −.17*** | – |
| Sensory functioning tests | | | | |
| SOIT | .12** | .28*** | .12** | −.40*** |
| FMHT | −.04 | −.08 | −.03 | .26***,[a] |
| Hearing loss left | −.07 | −.16** | −.11* | .41***,[a] |
| Hearing loss right | −.11* | −.14** | −.15** | .38***,[a] |
| Vision test 3 m | .02 | .08 | .03 | −.17*** |
| Vision test 5 m | .02 | .05 | .03 | −.18*** |
| Processing speed tests | | | | |
| Letter−digit substitution | .12** | .33*** | .12** | −.60*** |
| Letter comparison | .12** | .29*** | .08 | −.50*** |
| Pattern comparison | .06 | .25*** | .12** | −.58*** |
| Working memory tests | | | | |
| Reading span | .15** | .21*** | .14** | −.22*** |
| 2-Back | .21*** | .33*** | .20*** | −.43*** |
| Block design | .17*** | .40*** | .17*** | −.56*** |

*Note*: Pairwise correlations.
FMHT, Five-Minute Hearing Test; SOIT, Scandinavian Odor Identification Test.
[a]Higher scores in FMHT and Hearing loss denote worse sensory functioning.
$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

were all consistently intercorrelated, even if correlations were smaller ($r_{framingapplying} = .22$, $p < .001$; $r_{framingUO/confidence} = .11$ $p < .05$; $r_{applying\text{-}UO/confidence} = .19$, $p < .001$). This pattern of correlations, together with theoretical arguments (the introduction), supports the aggregation into three latent variables of indicators of processing speed, working memory, and decision making. Therefore a structural equation measurement model was built on these three predictors, conceived as separate but related. The fit of the model was very good ($\chi^2 = 23.708$, $df = 24$, $\chi^2/df = .478$, CFI = 1.000, RMSEA = .000) and all its structural coefficients significant.

*Comparative structural equation modeling*

Comparative modeling was carried out to test our hypotheses (with the correlation matrix between the measures being presented in the Supporting Information). Table 3 presents the absolute fit of each alternative mediation model, in both its partial and total mediation versions. The same table presents the comparison of each alternative model with the respective no-path and full-path reference models, carried out with the $\chi^2$ difference test, and the standardized coefficients of the path linking, in each model, the target mediator with decision making.

The findings in Table 3 show that the three alternative partial-mediation models for sensory functioning, processing speed, and working memory have at least an acceptable level of fit. However, the working memory partial-mediation model has better values on all the indices, reaching a level of fit that is almost as good as for the full-path model. Indeed, although all the alternative models have a significantly better fit than the corresponding no-path model, the $\chi^2$ differences tests show that only the working-memory partial-mediation model achieves a fit that is not significantly different from that for the full-path model. In addition, the examination of standardized coefficients in Table 3 shows that only working memory is significantly related to decision making in the full-path model, while sensory functioning and processing speed are not.

The analysis of total mediation models offers a very similar pattern of findings, with the working memory model showing a better fit than the two models centered on the alternative predictors. However, the total mediation models present a systematically lower fit than the corresponding partial-mediation models, and the $\chi^2$ differences tests show significant differences favoring the partial-mediation models versus the total mediation ones in all the cases but processing speed (full path: $\chi^2_{diff}(1) = 4.562$, $p < .05$; working memory: $\chi^2_{diff}(1) = 6.203$, $p < .05$; processing speed: $\chi^2_{diff}(1) = 2.383$, $p = .12$; sensory functioning: $\chi^2_{diff}(1) = 16.863$, $p < .001$; no path: $\chi^2_{diff}(1) = 30.310$, $p < .001$).

Overall, the comparative modeling findings indicate that partial mediation of age effects in decision making through working memory is the best account of our data. The working memory partial-mediation model (Figure 2) displays the expected negative relations between age and the three different predictors of decision making (e.g., Park et al., 1996, 2002; Salthouse, 1996), together with a positive relation between working memory and decision making, which is also consistent with previous investigations (Del Missier et al., 2012, 2013). All the coefficients of the model are significant, and the model is able to explain a large part of the variance in decision making (77%). Interestingly, when the negative effects of age mediated by working memory are controlled for, a positive direct relation between age and decision making is apparent (i.e., a suppression effect). We will comment on these findings in the General Discussion.

*Estimation of indirect effects*

The third step of data analysis was carried out with the aim of understanding better the specific role of the different

Table 3. Fit of the structural equation models

| Model ($N = 563$) | $\chi^2$, $df$ | $\chi^2/df$ | CFI | RMSEA | AIC | $\chi^2$ diff. vs. full path | $\chi^2$ diff. vs. no path | Standardized coefficients | | | | $R^2$ DM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | WM→DM | Speed→DM | SOIT→DM | Age→DM | |
| Full path | | | | | | | | | | | | |
| Partial mediation | 63.788, 42 | 1.519 | .989 | .030 | 135.79 | — | $\chi^2_{diff}(3) = 65.852$, $p < .001$ | .963* | −.154 *ns* | .082 *ns* | .210 *ns* | .805 |
| Total mediation | 68.350, 43 | 1.590 | .987 | .032 | 138.35 | — | $\chi^2_{diff}(3) = 91.600$, $p < .001$ | .793** | −.191 *ns* | .083 *ns* | — | .735 |
| Working memory | | | | | | | | | | | | |
| Partial mediation | 67.581, 44 | 1.536 | .988 | .031 | 135.58 | $\chi^2_{diff}(2) = 3.793$, $p = .150$ | $\chi^2_{diff}(1) = 62.059$, $p < .001$ | .889** | — | — | .235^ | .772 |
| Total mediation | 73.784, 45 | 1.640 | .986 | .034 | 139.78 | $\chi^2_{diff}(2) = 5.434$, $p = .066$ | $\chi^2_{diff}(1) = 86.166$, $p < .001$ | .658*** | — | — | — | .679 |
| Processing speed | | | | | | | | | | | | |
| Partial mediation | 118.477, 44 | 2.693 | .963 | .055 | 186.48 | $\chi^2_{diff}(2) = 54.689$, $p < .001$ | $\chi^2_{diff}(1) = 11.163$, $p < .001$ | — | .286** | — | −.123 *ns* | .466 |
| Total mediation | 120.860, 45 | 2.686 | .962 | .055 | 186.86 | $\chi^2_{diff}(2) = 52.510$, $p < .001$ | $\chi^2_{diff}(1) = 39.090$, $p < .001$ | — | .381*** | — | — | .468 |
| Sensory functioning | | | | | | | | | | | | |
| Partial mediation | 117.635, 44 | 2.674 | .963 | .055 | 185.63 | $\chi^2_{diff}(2) = 53.847$, $p < .001$ | $\chi^2_{diff}(1) = 12.005$, $p < .001$ | — | — | .195** | −.224*** | .462 |
| Total mediation | 134.498, 45 | 2.989 | .955 | .059 | 200.50 | $\chi^2_{diff}(2) = 66.148$, $p < .001$ | $\chi^2_{diff}(1) = 25.452$, $p < .001$ | — | — | .276*** | — | .424 |
| No path | | | | | | | | | | | | |
| Partial mediation | 129.640, 45 | 2.881 | .958 | .058 | 195.64 | — | — | — | — | — | −.314*** | .434 |
| Total mediation | 159.950, 46 | 3.477 | .943 | .066 | 223.95 | — | — | — | — | — | — | .362 |

*Note*: WM, working memory; DM, decision making; Speed, processing speed; SOIT, Scandinavian Odor Identification Test; CFI, comparative fit index; RMSEA, root-mean-square error of approximation; AIC, Akaike's information criterion.

^$p < .10$; *$p < .05$; **$p < .01$; ***$p < .001$.

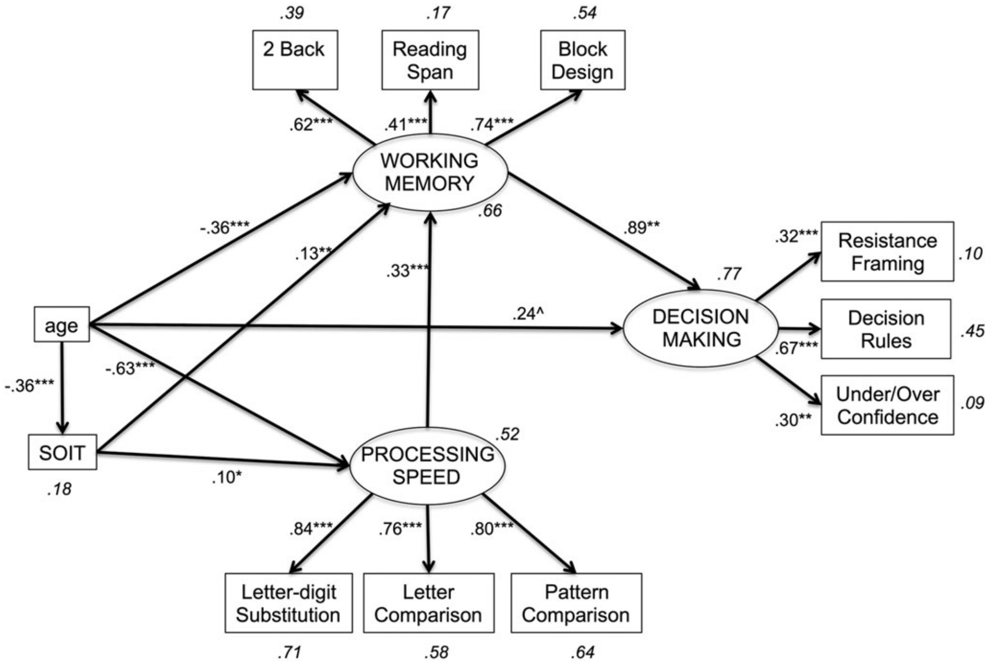


Figure 2. The best-fitting partial-mediation working memory model. Standardized coefficients are on the respective arrows, while explained variance ($R^2$) is displayed in italics close to each variable. For clarity, the representation does not present the education indicator and its relations with the other variables (Figure 1, Panel C), which are as follows: age➔education ($-.40$, $p < .001$, $R^2 = .16$), education➔SOIT (.13, $p < .01$), education➔processing speed (.11, $p < .01$), education➔working memory (.21, $p < .001$), education➔decision making (.24, $p < .01$). Significance levels are as follows: ^$p < .10$,*$p < .05$, **$p < .01$, ***$p < .001$. SOIT, Scandinavian Odor Identification Test

predictors within the working memory partial-mediation model. The structure of the working memory partial-mediation model (Figure 2) shows that there are four different indirect paths connecting age and decision making (Figure 3). Indeed, working memory seems to act both as a direct mediator of the effects of age on decision making and as an indirect mediator of age-related effects via sensory functioning and processing speed. Thus, we estimated each indirect effect of age on decision making and computed their 95% bootstrap confidence intervals (Preacher & Hayes, 2008; Shrout & Bolger, 2002; Taylor et al., 2008) on 2000 runs with the percentile method (no or only negligible differences emerged when using the bias-corrected percentile method). The results of this analysis, carried out with MPLUS 7.2 (Muthén & Muthén, 2012), are presented in Figure 3.

The results show stronger negative effects of age on decision making through the paths age➔working memory➔decision making (Figure 3, panel A) and age➔processing speed ➔working memory➔decision making (Figure 3, panel C) than through the paths including sensory functioning (Figure 3, panels B and D). Bootstrap confidence intervals show that all indirect effects are reliable except for the one associated with the path age➔SOIT➔processing speed➔working memory➔decision making. These findings confirm the sizable indirect negative effect of age on decision making, showing that it is both directly mediated by working memory (age➔working memory➔decision making) and indirectly deployed through working memory via longer chains including processing speed and sensory functioning (age➔processing speed➔working memory➔decision making, and age➔SOIT➔working memory➔decision making).

## GENERAL DISCUSSION

### Summary of findings and control analyses

The main aim of our study was to disentangle the relative role of sensory and basic cognitive predictors on age-related differences in decision making, starting from research on cognitive aging and decision making. Using a large population-based sample, we found that working memory plays a prominent role in predicting the age-related decline in cognitively demanding decision tasks beyond sensory functioning and processing speed. The findings of comparative modeling provided strong evidence in support of a partial-mediation model centered on working memory. Alternative models, centered on processing speed or sensory functioning, presented a much lower fit and a reduced predictive capacity. Moreover, the findings supported a partial-mediation account, in that differences in working memory partially mediated the effects of age on decision making, leaving room for a marginally significant direct and positive relation between age and decision making. The estimation of specific age-related effects on decision making identified three different paths in order of effect strength: (i) age➔working memory➔ decision making; (ii) age➔speed➔working memory➔decision making; and (iii) age➔sensory functioning➔working memory➔decision making. This made clear that the effects of age on decision making involve working memory as a direct mediator and, indirectly, via a longer chain of paths including sensory functioning and processing speed.

Several control analyses supported the findings of comparative modeling (cf. Supporting Information). Model lesion, carried out both by removing entire predictors and

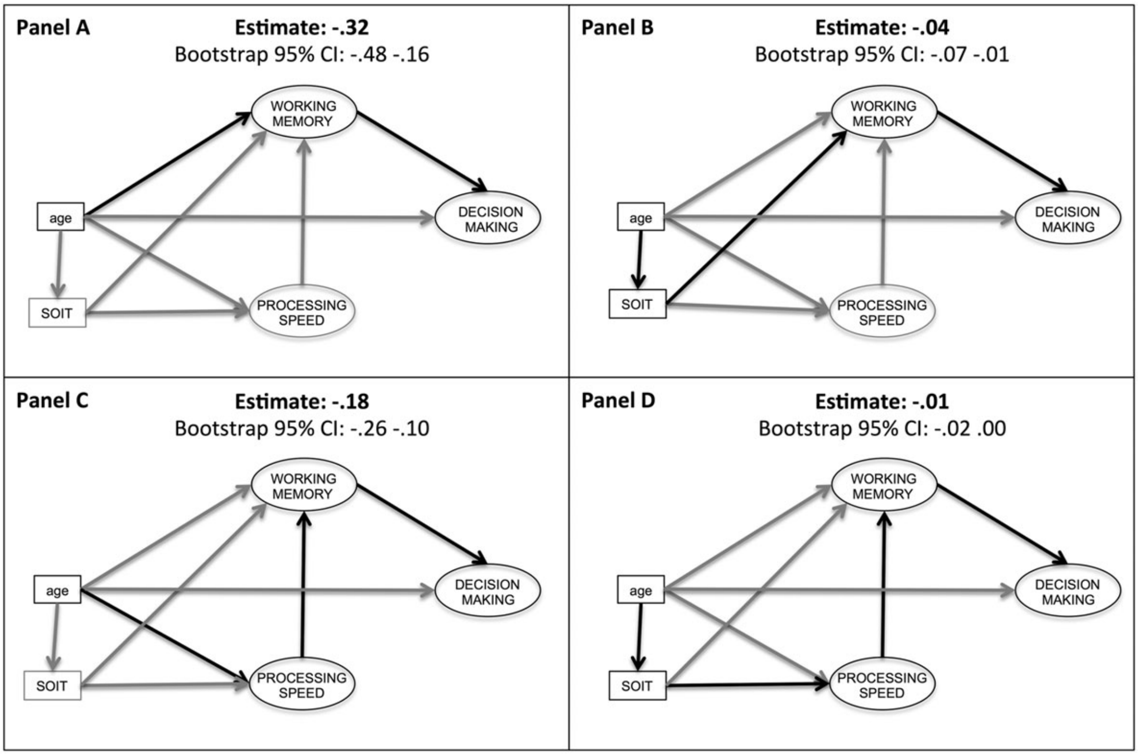


Figure 3. Estimation of indirect effects of age on decision making. Each panel presents a specific indirect effect (in black) within the working memory partial-mediation model, its estimated standardized effect, and the respective 95% confidence interval as computed from 2000 bootstrap cycles with the percentile method

their indicators and by removing the specific links between age and the core mediators, confirmed the prominent influence of working memory. Moreover, the results proved to be robust to variation in the sensory functioning indicators (albeit the sensory-related effects on decision making disappeared when using measures other than the SOIT). Furthermore, analyses carried out on single A-DMC tasks confirmed the ones obtained with the decision-making latent variable, with a single qualification (i.e., total mediation of age effects for Under/Overconfidence). Finally, converging results were obtained by using an alternative approach to assess mediation of age-related effects (Schmiedek & Li, 2004).

### Theoretical implications

According to our findings, working memory appears to play a prominent role in predicting age-related differences in cognitively demanding decision-making task, in line with a stream of studies in cognitive aging (Kliegl et al., 1994; Mayr and Kliegl, 1993; Park et al., 1996; also Park, 2000; Verhaeghen & Salthouse, 1997; also Engle & Kane, 2004; Engle et al., 1999; Verhaeghen, 2012). Based on our findings, the aforementioned studies, and related aging research (e.g., Finucane et al., 2005; Mata, Schooler, & Rieskamp, 2007; Mata, von Helversen, & Rieskamp, 2010), we hypothesize that the role of working memory is greater as the execution of tasks requires more active maintenance, updating, and inhibition of task-irrelevant information (also Del Missier et al., 2012, 2013, 2015).

Our results also showed that working memory is both a direct mediator of age-related influences on decision making and an indirect mediator of age-related effects involving sensory functioning and processing speed. This suggests the possibility of a specific age-related decline in core working memory functions (e.g., maintenance, updating, and inhibition) together with a reduced efficiency of different processes contributing to working memory functioning. In our case, the age-related decline in processing speed may have negatively harmed working memory functioning, possibly owing to the products of earlier processing being lost by the time later processing is completed (Salthouse, 1996). For what concerns sensory functioning, less effective encoding (e.g., Craik & Rose, 2012; Grady & Craik, 2000; Wingfield et al., 2005) is not a viable explanation of our findings, because A-DMC tasks require visual encoding and the visual measures were not related to decision making (unlike the olfactory one). Thus, in our case, sensory functioning indicators may be better considered as lower level markers of processing effectiveness, possibly reflecting neural or biological changes in the aging brain (e.g., Anstey, 2012).[12] However, only further studies could shed more light on the processes underlying the interesting dual mediational role of working memory and elucidate the specific mechanisms underlying its less effective age-related functioning.

[12]The smaller effects of sensory functioning on decision making we observed may also reflect the more distal nature of sensory effects when compared with processing speed or working memory. However, the stronger effects of age through working memory and processing speed appear to be independent from sensory paths. Moreover, the generally low correlations between sensory measures and decision making and the absence of direct sensory effects on decision making in SEM (despite the indicator used) both speak against a strong contribution of sensory functioning in our study.

Our working memory findings may also have implications for learning in decision making. Indeed, age-related declines in working memory and fluid abilities are more likely to affect tasks requiring explicit learning of complex rules or intensive monitoring and effortful learning of many options as compared with tasks relying more on implicit or low-effort learning processes (Del Missier et al., 2015; Frey, Mata, & Hertwig, 2015; Mata, Josef, Samanez-Larkin & Hertwig, 2011).

It should be noted, however, that working memory may not be as relevant for decision tasks that rely less on fluid abilities and more on consolidated knowledge (Del Missier et al., 2013; Li et al., 2013, 2015), more on episodic memory (Del Missier et al., 2013; Hoffmann, von Helversen, & Rieskamp, 2014) or emotion-related processes (Bruine de Bruin, Strough & Parker, 2014; MacPherson et al., 2002). Indeed, decision-making tasks may vary in the extent to which they rely on different processes, some of which may decline with age, while others stay the same or even improve (Strough Parker & Bruine de Bruin, 2015).

In our study, in line with this multi-processes view of the aging decision maker, a positive relationship emerged between age and decision performance after controlling for working memory declines (i.e., a suppression effect). It is possible that older adults' greater investment in emotion regulation or their increased knowledge helped them in making decisions and partly buffered the observed age-related decline in working memory (e.g., De Martino et al., 2006; Peters et al., 2007; Del Missier et al., 2013; Finucane & Gullion, 2010; Finucane et al., 2005; Li et al., 2013, 2015). However, these interpretations need to be empirically supported by further studies.

**Applied implications**

The findings of our study also have potential implications for the design of interventions to support decision making. If declines in working memory may undermine older adults' performance on the more demanding decision-making tasks, then it might seem promising to provide older adults with working memory training. However, the effectiveness of working memory training has been disputed owing to inconclusive results on far transfer and to various methodological problems of training studies (e.g., Redick et al., 2013; Shipstead, Redick & Engle, 2012; also Karbach and Verhaeghen, 2014). A more promising intervention may therefore involve training decision-making strategies that reduce reliance on working memory. Indeed, it has been argued that experts rely less on fluid cognition and working memory, because they have learned how to tackle the relevant decisions in their domain (Ericsson, Prietula, & Cokely, 2007). Similarly, despite the age-related cognitive decline, older adults' financial knowledge may help them to make better financial decisions, as well as to obtain better credit scores (Li et al., 2013, 2015). Promising but still limited evidence exists about the effectiveness of interventions aiming to teach better decision-making competence (Fischhoff, 1982; Larrick, 2004), and more research is thus needed.

A second promising approach is to provide environmental support for working memory via task and interaction design (Craik & Jennings 1992; Wickens, Hollands, Banbury & Parasuraman, 2013). For example, working memory load may be reduced by designing decision tasks that do not require keeping in mind complex intermediate results, simplify, and make clear the sequence of operations to be performed, provide the right information at the right time, and indicate the progress (and the actual position) in task completion (e.g., Del Missier, 2014). This general approach is thought to hold both in electronic and in more traditional environments (e.g., filling in a complex tax form or choosing a pension plan from among a set of possibilities). However, empirical work on these topics is surprisingly scarce, and further theory-driven research would be helpful.

**Limitations and future directions**

We would like to acknowledge some limitations of our study, which could be addressed in further research. First, despite already covering many constructs with multiple measures, the inclusion of additional predictors and decision-making tasks would strengthen our findings. A promising extension would be to add measures of inhibition, which has been linked to age-related declines (e.g., Hasher & Zacks, 1988; Hasher, Stoltzfus, Zacks & Rypma, 1991). However, this may turn out to be a very problematic enterprise, considering the still-debated theoretical status of the inhibition construct (e.g., Friedman et al., 2008; Friedman & Miyake, 2004) and the known problems in measuring individual differences in inhibition (e.g., Del Missier et al., 2012; Friedman et al., 2008; Huizinga, Dolan & van der Molen, 2006; van der Sluis et al., 2007). It would also be worthwhile to use decision-making tasks varying systematically in their complexity (also Frey et al. 2015).

Another potential limitation is related to measurement issues. Although the sensory measures we used seem to be reliable and sensitive, as reported by papers investigating their psychometric properties (see the Method section) and as seen in their strong within-modality correlations and predicted correlations with age, the Snellen chart is not without limitations (e.g., Lovie-Kitchin, 1988). However, it is the universally accepted method in clinical practice to assess visual acuity as in most retrospective case series and medico-legal decisions, and thus, it was the method of choice in the Betula data collection. It should also be noted that the use of Block Design as an indicator of working memory may have resulted in our working memory latent variable encompassing also more general fluid aspects. However, previous investigations showed that Block Design is selectively related to working memory updating (Friedman et al., 2006), and, for this reason, we used it as an additional indicator of working memory functioning in addition to Reading Span and 2-back. Future studies could consider both employing alternative methods to assess visual acuity (and, more generally, different sensory indicators) and varying the working memory indicators to appraise the robustness of our findings.

All three of decision-making tasks were assessed based on self-administered and untimed measures, and this may not be representative of different decision-making contexts (e.g., decision making under time pressure). However, considering the general slowing of older adults, using time-pressured task would have probably placed them into a very unfair situation and possibly improperly boosted the role of processing speed and working memory limitations. Moreover, real-world conditions in which older adults have to decide and judge under strict time pressure are not very frequent, and older adults can cope with these too demanding situations by avoiding them or by relying on the help of others (Salthouse, 2012). Additionally, we found it informative that the role of age-related differences in processing speed and (especially) working memory on decision making was apparent also in conditions of no time pressure and no stress, thus in conditions that are thought to be less conducive to these effects. Finally, although very minor (or no) attrition effects have been observed in our study, it is worth reminding that returnees were, on average, 2 years older than dropouts. We deem as very unlikely the possibility that this small difference may have affected strongly the results and their generalizability, also considering the overall returnees' sample composition and size.

A third, more general, limitation of our study resides in its correlational nature, which suggests great caution in the evaluation of the observed relationships, although our models were derived from existing theories and we operated within a SEM context (Bollen & Pearl, 2013). Indeed, we consider the present study as an investigation providing novel evidence on potential predictors of age-related decline in decision making, but the relations observed should be further elucidated by investigations using complementary methods (e.g., experimental, neuroimaging, and neuroscience studies).

A fourth limitation of the present study may concern its cross-sectional research design. Longitudinal and cross-sectional designs can lead to results that can be partly different, with (practice uncorrected) longitudinal studies usually showing a less negative picture of age-related changes than (cohort uncorrected) cross-sectional ones (e.g., Rönnlund et al., 2005).[13] In our study, we addressed this potential concern in two ways. First, we included education as a control variable, by relying on previous studies that showed that this is a very effective form of control in the Betula data, making the findings comparable with the ones obtained with practice-corrected longitudinal designs (Rönnlund et al., 2005). Second, we tested our models also by using an alternative method to assess mediation, which some researchers deem as more appropriate for cross-sectional mediation analysis (Schmiedek & Li, 2004—for detailed results, see the Supporting Information). Finally, we strive toward obtaining converging results with different research designs, by comparing the results described in the present paper with those obtained from longitudinal data that will be collected in the Betula project.

[13]Recently, the ability of cross-sectional designs to provide valid conclusions on age-related changes has been questioned by relying on formal analysis (Lindenberger et al., 2011; Maxwell & Cole, 2007), although these arguments are still controversial (Salthouse, 2011b). It is important to underline that both longitudinal and cross-sectional designs have relative strengths and weaknesses (e.g., Salthouse, 2010, 2011b; Rönnlund et al., 2005), with longitudinal studies being even more problematic in some important respects (Salthouse, in press, 2014b, see also Salthouse 2014c).

### Conclusion

The present study advances our understanding of the relative role of main predictors of age-related decline in cognitively demanding decision tasks. In particular, it shows that working memory can play an important role in predicting age-related differences in these tasks, beyond education, sensory functioning, and processing speed. This fills a significant gap in the decision-making literature, in which the investigation of age-related differences has not included sensory and basic cognitive predictors in a single study and hopefully contributes to unravel the intricate skein of multiple predictors on decision making.

## ACKNOWLEDGEMENTS

This research was supported by a research grant awarded to Timo Mäntylä by Riksbankens Jubileumsfond for the project *Aging and decision-making competence*. It was also supported by a Wenner Gren grant awarded to Fabio Del Missier for the project *Decision-making abilities across the adult life span*: *A psychological*, *genetic*, *and neuroscientific investigation* and a grant from the European Union to Wändi Bruine de Bruin (FP7-People-2013-CIG-618522).

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