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Longitudinal Mediation of Processing Speed on Age-Related Change in Memory and Fluid Intelligence

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Age-related decline in processing speed has long been considered a key driver of cognitive aging. While the majority of empirical evidence for the processing speed hypothesis has been obtained from analyses of between-person age differences, longitudinal studies provide a direct test of within-person change. Using recent developments in longitudinal mediation analysis, we examine the speed—mediation hypothesis at both the within-and between-person levels in two longitudinal studies, Longitudinal Aging Study Amsterdam (LASA) and Origins of Variance in the Oldest-Old (OCTO-Twin). We found significant within-person indirect effects of change in age, such that increasing age was related to lower speed, which in turn relates to lower performance across repeated measures on other cognitive outcomes. Although between-person indirect effects were also significant in LASA, they were not in OCTO-Twin which is not unexpected given the age homogeneous nature of the OCTO-Twin data. A more in-depth examination through measures of effect size suggests that, for the LASA study, the within-person indirect effects were small and between-person indirect effects were consistently larger. These differing magnitudes of direct and indirect effects across levels demonstrate the importance of separating between- and within-person effects in evaluating theoretical models of age-related change.

Keywords: cognitive aging, processing speed, longitudinal analysis, multilevel structural equation modeling, mediation

Cognitive aging research has focused largely on describing age-related patterns and processes of change and on developing sound theoretical explanations for population average and individual differences in cognitive decline (Dixon, 2011; Hertzog, 1985; Hultsch, Hertzog, Dixon, & Small, 1998; Rabbitt, 1993). An important aspect of understanding the effects of age on cognition has been to identify whether particular cognitive processes drive changes observed in the broader range of cognitive functions (e.g., as seen in Hartley, 2006; Hertzog, Dixon, Hultsch, & MacDonald, 2003; Hultsch, Hertzog, Small, McDonald-Miszczak, & Dixon,

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1992; Hultsch, Hertzog, & Dixon, 1990; Hultsch et al., 1998; Salthouse, 1993; Salthouse, 1994; Sliwinski & Buschke, 1999; Sliwinski & Buschke, 2004; Tucker-Drob, 2011; Zimprich, 2002). Processing speed has long been considered to have a causal and pervasive role in cognitive aging (Birren, 1964; Birren & Fisher, 1995; Salthouse, 1996) and continues to be of high interest (Finkel, Reynolds, McArdle, & Pedersen, 2005, 2007; Lemke & Zimprich, 2005; Zimprich, 2002; Zimprich & Martin, 2002). The relationship between cognitive aging and processing speed is often referred to as the *processing speed hypothesis* and implies a mediational model such that age has an indirect effect on cognitive functioning through its direct effect on processing speed, which in turn has a direct effect on cognition.

In age-heterogeneous cross-sectional studies focusing on between-person (BP) age differences (e.g., Verhaeghen & Salthouse, 1997), cognitive performance is often ascribed to age-related changes in processing speed (Salthouse, 1996). To date, most information about age-related cognitive change and explanatory models of such change has been based on cross-sectional designs and analyses of BP differences (see reviews by Salthouse, 1996; Verhaeghen & Salthouse, 1997). Cross-sectional designs, however, are unable to address questions related to associations and determinants of within-person change and have been found to provide biased estimates of longitudinal mediational processes (Cole & Maxwell, 2003; Hofer, Flaherty, & Hoffman, 2006; Hofer & Sliwinski, 2001; Lindenberger & Pötter, 1998; Maxwell & Cole, 2007; Maxwell, Cole, & Mitchell, 2011).

The role of processing speed as a predictor and mediator of age-related change in other aspects of cognition has only been evaluated in a few longitudinal studies (Finkel et al., 2005, 2007; Hertzog, Dixon, Hultsch, & MacDonald, 2003; Hultsch, Hertzog, Small, McDonald-Miszczak, & Dixon, 1992; MacDonald, Hultsch, Strauss, & Dixon, 2003; Sliwinski & Buschke, 1999; Sliwinski & Buschke, 2004; Taylor, Miller, & Tinklenberg, 1992; Zimprich, 2002; Zimprich & Martin, 2002). These studies have generally found that while processing speed accounts for BP age differences in various cognitive outcomes, it has little, if any, mediational impact on longitudinal age-related cognitive changes (Finkel et al., 2005, 2007; Sliwinski & Buschke, 1999; Sliwinski & Buschke, 2004; Zimprich, 2002).

Previous studies have used a variety of different statistical approaches that have been instrumental in evaluating the role of processing speed in other cognitive outcomes (e.g., memory or reasoning). We therefore examine eight of these studies in more detail to demonstrate how the current study, applying recent developments for testing longitudinal mediation, expands previous work.

Longitudinal Studies of the Processing Speed Hypothesis

Hultsch, Hertzog, Small, McDonald-Miszczak, and Dixon (1992)

Hultsch et al.'s (1992) study is one of the first studies to our knowledge to distinguish the longitudinal (over a 3-year period) and cross-sectional mediation effects of processing speed on other cognitive outcomes. Using a two-step approach, they found that cross-sectional effects for previously significant cognitive variables became nonsignificant with the inclusion of basic processing speed measures, the only exception being reading comprehension. On the other hand, longitudinal decline in working memory, verbal fluency, and working knowledge did not become nonsignificant with the inclusion of processing speed, highlighting the discrepancy between cross-sectional and longitudinal findings related to speed mediation.

Hertzog, Dixon, Hultsch, and MacDonald (2003)

Hertzog et al., (2003) used data from the Victoria Longitudinal Study to examine the relationship between processing speed and episodic memory using a latent change model over a 6-year period. They found that change in episodic memory was associated with changes in processing speed.

Sliwinski and Buschke (1999)

In their 1999 paper, data from the Einstein Aging Study were used to model the effect of age on numerous cognitive outcomes and to examine the extent to which processing speed predicted and mediated cross-sectional and within-person longitudinal change in these outcomes. A repeated measures multilevel model (Laird & Ware, 1982) was used with a level-1 model representing within-person change and a level-2 model describing individual differences in within-person level and change. The model was intended to distinguish between the cross-sectional (Time 1 BP) and longitudinal (within-person after Time 1) effect of processing speed on the other cognitive outcomes.

In the first step, only the effect of age on the cognitive outcomes was modeled. In the second step, the mediator (processing speed) was modeled as a time-varying covariate. To explore cross-sectional mediation, BP age effects at Time 1 on initial status of the outcome variables was used as the baseline for comparison with the subsequent models including speed (the mediator) as a time-varying and time-invariant covariate. To explore longitudinal mediation, they compared rate of change in the age only model with that of the model with processing speed. This approach to testing mediation focused on the percentage of the cross-sectional and longitudinal associations that were explained by accounting for processing speed at the within- and BP level (Raudenbush & Bryk, 2002; Singer & Willett, 2003).

Sliwinski and Buschke (1999) found that the cross-sectional age effects mediated via processing speed were substantially larger than the mediated longitudinal effects. They also found that speed at baseline was significantly related with each of their 11 cognitive outcomes and that within-person change in processing speed predicted changes in all cognitive outcomes, with the exception of Letter fluency, Vocabulary, and Similarities.

Sliwinski and Buschke (2004)

Using additional data from the longitudinal Einstein Aging Study, Sliwinski and Buschke (2004) replicated and extended their previous work on modeling within-person cognitive change. This new analysis accounted for variability in the slope of memory and fluency as a function of baseline age and baseline speed. Although age is treated as a time-varying covariate in level-1 of the model, age also encompasses BP properties given that individuals differ in age at baseline. Accordingly, it is recommended that baseline age should be included as a covariate of both the intercept and the slope to differentiate BP and within-person results (Mehta & West, 2000; Mendes de Leon, 2007; Singer & Willett, 2003; Sliwinski, Hoffman, & Hofer, 2010; Ware, 1985).

Their reasoning was that, as with age, individual differences in speed at baseline must be included as a predictor of the age slope rather than only for the intercept to disentangle between- and within-person effects of age. They found, at level 1, that time-specific changes in processing speed predicted time-specific variation in memory and fluency. However, after accounting for changes because of age, changes in speed accounted for only 15% and 21% of the within-person fixed effect of age on memory and fluency, respectively. Despite the revised model, these findings were in alignment with the Sliwinski and Buschke (1999) results.

Zimprich (2002)

Using the Bonn Longitudinal Study on Aging (Lehr & Thomae, 1987), Zimprich (2002) also examined the processing speed hypothesis using longitudinal hierarchical linear models for a series of cognitive outcomes. Cross-sectional mediation models included baseline processing speed similarly to Sliwinski and Buschke (2004) and estimated the extent to which the direct age association was reduced after including processing speed in the model. Accounting for BP differences in speed at baseline rendered previously significant cross-sectional age effects nonsignificant. In contrast to Sliwinski and Buschke (1999, 2004), longitudinal mediation was explored using a multivariate longitudinal hierarchical linear model. Covariances between BP differences in change in speed and change in cognitive outcomes were significant for Similarities, Block Design, and Object Assembly, but not for Information, Comprehension, Picture Completion, Picture Arrangement, Arithmetic, and Digit Span. Furthermore, changes in processing speed only accounted for between 0% and 17% of BP differences of change. Similarly to Sliwinski and Buschke (1999, 2004), the findings suggest a more substantial effect of processing speed on the cross-sectional age differences than on within-person age changes.

Zimprich and Martin (2002)

Using data from the Interdisciplinary Study on Adult Development (Martin, Grünendahl, & Martin, 2001), Zimprich and Martin (2002) applied a latent change factor model (McArdle & Nesselroade, 1994) between two occasions over a 4-year period to examine the relationship between change in speed and change in fluid intelligence. To test mediation, they examined the covariance between change in speed and change in fluid intelligence, and found that changes in speed were correlated with changes in fluid intelligence (r = .53). These findings further illustrate how the longitudinal shared variance between speed and other cognitive outcomes is lower than cross-sectional reports (Verhaeghen & Salthouse, 1997).

Finkel, Reynolds, McArdle, and Pedersen (2005)

Using SATSA data (Pedersen et al., 1991), Finkel et al. (2005) utilized bivariate latent growth curve models to examine the correlations between intercepts, linear slopes, and quadratic slopes for change over time. Intercept–intercept correlations (cross-sectional relationship) between processing speed and cognitive functioning were consistently larger than the linear slope–slope correlations (longitudinal relationship), further supporting the importance in differentiating between cross-sectional and longitudinal findings (Finkel et al., 2005). However, the longitudinal and cross-sectional effects were at the BP level. They also found that speed at baseline was related to the quadratic trend, with higher speed scores associated with less accelerated decline for spatial abilities and memory (Finkel et al., 2005).

Finkel, Reynolds, McArdle, and Pedersen (2007)

In their 2007 paper, Finkel and colleagues continued to use SATSA data (Pedersen et al., 1991) to further explore the role of processing speed by employing a dual change score model (DCSM). The DCSM is a variation of the LGM (McArdle, 2001; McArdle & Hamagami, 2001). The DCSM provides information about whether changes in cognitive performance can be attributable to level of processing speed at previous occasions and whether changes in speed can be explained by previous levels of cognitive functioning. The model is evaluated by examining the significance of proportional change estimates and improvement in model fit. This model also provides information about the slope–slope and intercept–intercept covariance. The authors found that changes in processing speed predicted changes in memory and spatial abilities but not in verbal knowledge (Finkel et al., 2007).

The Need for Statistical Tests of Mediation

The goal of the present study is to provide a novel examination of the processing speed hypothesis by explicitly testing indirect effects between age and cognition through processing speed at multiple levels of analysis. Although studies that examine the extent to which processing speed is related to other cognitive variables are useful for other aims (e.g., Finkel et al., 2005; Zimprich, 2002), they do not directly assess mediation. Furthermore, the current study differs from previous work in how it distinguishes levels of analysis. For instance, Sliwinski and Buschke (1999, 2004) previously distinguished cross-sectional from longitudinal effects based on the first occasion, but an alternative approach of estimating BP and within-person effects—both of which make use of all occasions—may provide a clearer decomposition. In addition, Sliwinski and Buschke (1999, 2004) and Zimprich (2002) used a two-step approach in testing mediation, whereas advances in software and model developments now allow decomposition of BP and within-person mediation simultaneously, including direct and indirect BP and within-person effects.

Furthermore, recent MLM advances allow examination of multiple indirect effects simultaneously (Preacher, Zyphur, & Zhang, 2010). That is, all variables, including mediators, are included in the model rather than having to use a two-step approach (for a review of mediational approaches, see Baron & Kenny, 1986, and MacKinnon, 2008; for a comparison of the two-step approach with the simultaneous indirect effects approach, see Rucker, Preacher, Tormala, & Petty, 2011). In assessing longitudinal mediation, each variable varies both within individuals across time and between individuals. These approaches allows researchers to examine processing speed (M) as a mediator between age (X) and cognitive abilities (Y), all of which are considered level-1 variables (referred to as lower level mediation or 1→1→1). Although previous approaches to testing mediation allow decomposition of between- and within-person *direct* effects, they do not separate the *indirect* effects that formally assess mediation. These more recent approaches allow us to separately estimate BP direct effects (level-2 effects) and within-person direct effects (level-1 effects) and to distinguish level-2 from level-1 indirect effects (Zhang, Zyphur, & Preacher, 2009). This is important given that combining between and within indirect effects can lead to biased results (Preacher et al., 2010). For example, Time 1 centering approaches (i.e., as in Sliwinski & Buschke, 1999, 2004) also do not fully distinguish the between and within levels of analysis given that Time 1 values may still be correlated with the degree of within-person change.

One method to separate between and within components discussed in MacKinnon (2008) is to group-mean center level-1 predictors and add the cluster mean as the level-2 predictor (referred to as unconflated multilevel modeling [UMM]; Preacher, Zhang, & Zyphur, 2011; Preacher et al., 2010; Zhang et al., 2009). Although this approach separates the between- and within-person effects, the BP effects are nevertheless biased toward the corresponding within effects when intraclass correlations (ICCs) are low and cluster sizes are small (Preacher et al., 2011; Preacher et al., 2010). Furthermore, using observed group means to represent level-2 variation assumes that there is no measurement error (perfect reliability) in those level-2 means. Instead, Preacher and colleagues suggest using Multilevel Structural Equation Modeling (MSEM) as an improved alternative (Preacher et al., 2010), which is the approach taken in the current study.

MSEM for longitudinal data combines the utility of MLM—for differentiation of level-1 and level-2 components—and SEM—for mediation models in which a single construct is both a predictor and an outcome (Mehta & Neale, 2005; Preacher et al., 2010). MSEM differs from traditional MLM in that the level-2 means are not added as predictors. Instead, level-1 predictors are directly decomposed between the level-2 random intercept and level-1 residual variances. We used Muthén and Asparouhov's (2008) approach to MSEM and applied it to mediation analysis as suggested by Preacher et al. (2010). In the context of our longitudinal data, observed variables that change as a function of time are decomposed into their BP and within-person sources of variation as just described (i.e., 1–1–1 MSEM; Preacher et al., 2010). Regressions are also estimated at both levels to allow examination of indirect effects both within time and between individuals, each controlling for the other. Figure 1 presents the 1–1–1 model of the proposed paths between the current variables. Although these models were initially only estimable for fixed slopes, they are now estimable with random slopes (Preacher et al., 2010). A random intercept represents BP differences in the overall level of the outcome variables, whereas random slopes represent BP differences in the effect of level-1 predictors like change over time or change in speed. More details about longitudinal mediation modeling can be found in Cheong, MacKinnon, and Khoo (2003); Cole and Maxwell (2003); MacKinnon (2008); Roth and MacKinnon (2011); and Selig and Preacher (2009).

Aims of the Current Study

The purpose of the current work is to examine the extent to which processing speed mediates BP age differences and within-person age changes on memory and reasoning abilities using 1–1–1 MSEM. This study extends previous research on the processing speed hypothesis by explicitly testing the importance of speed as a mediator to provide unbiased estimates of BP and within-person indirect effects while allowing for the inclusion of random slopes for BP differences in change. The current study also adds to previous research by examining numerous cognitive outcomes in two different longitudinal studies of aging to clarify the relationship between age-related changes in processing speed and multiple aspects of cognition. Cross-study comparisons (such as through collaborative networks like the Integrative Analysis of Longitudinal Studies on Aging [IALSA]) can offer unique advantages. Using data from multiple existing longitudinal studies allows the efficient replication of statistical analyses across different studies using identical model parameters and covariates and provides information about the extent to which study characteristics might impact results (Hofer & Piccinin, 2010; Piccinin & Hofer, 2008). To that end, the current study provides an opportunity to examine the extent to which speed mediation is generalizable across outcomes and samples given application of the same rigorous statistical methodology.

Method

Description of Origins of Variance in the Oldest-Old (OCTO-Twin)

The OCTO-Twin study includes dizygotic (DZ) and monozygotic (MZ) twin pairs aged 80 years of age and older (Johansson et al., 2004; McClearn et al., 1997) selected from older adults participating in the population-based Swedish Twin Registry (Cederlof & Lorich, 1978). The initial sample consisted of 702 individuals (351 same-gender pairs). Five cycles of longitudinal data were then collected at 2-year intervals. Individuals who were diagnosed with dementia (based on *Diagnostic and Statistical Manual of Mental Disorders, Third Edition, Revised* [DSM–III–R] criteria for dementia; American Psychiatric Association, 1987) over the course of the study (n = 225) were excluded from the current analyses. Seven cases missing education data were also removed from the analyses. The final sample consisted of 470 individuals: 165 men (35.1%) and 305 women (64.9%). The participants ranged in age from 79.4 to 97.9 years at Time 1. Of the 470 individuals at Time 1, 69 (15%) dropped out at Time 2, of these a further 108 (27%) dropped out at Time 3, 70 (24%) at Time 4, and 49 (22%) at Time 5. See Table 1 for descriptive statistics at each occasion.

Measures

Processing speed. A modified (verbal rather than written) version of the Digit-Symbol Substitution Test was used to assess processing speed of participants. It is a performance subtest of the Wechsler Adult Intelligent Scale—Revised (Wechsler, 1991). Participants are given a record form with symbol-digit pairs followed by a series of digits. The participants are asked to provide a verbal

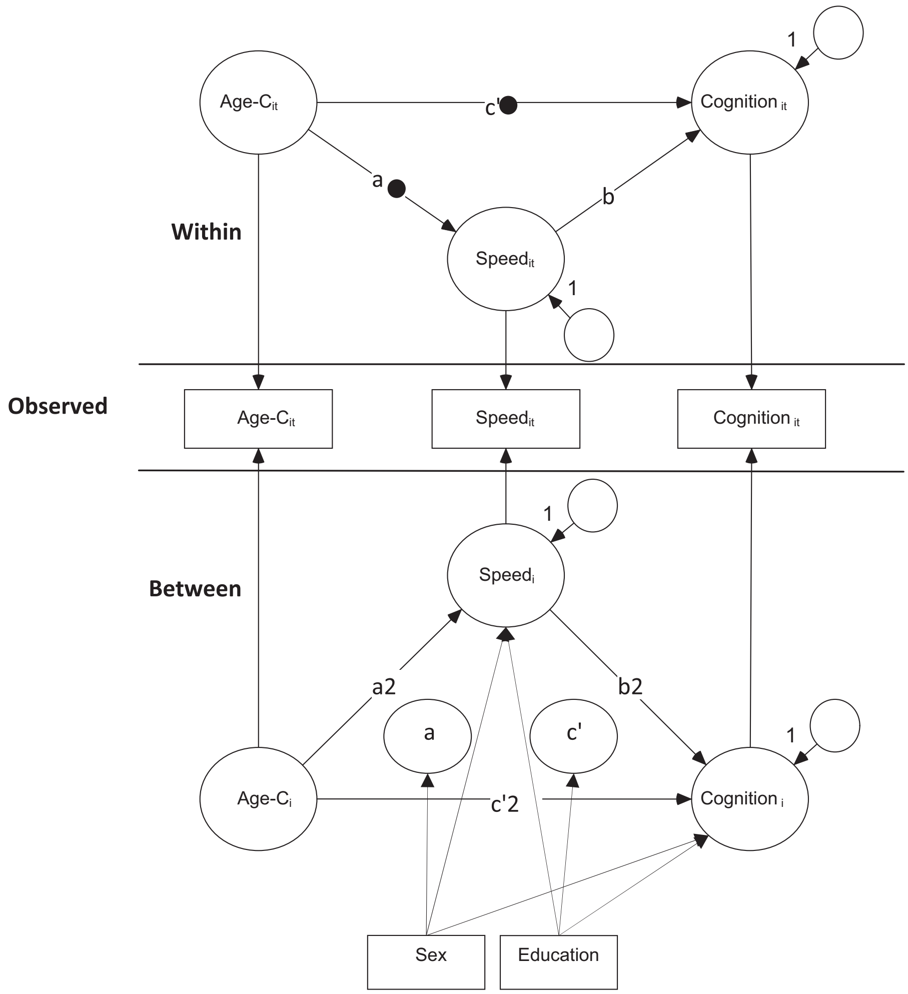

Figure 1. Illustration of the 1–1–1 (all of variables are considered level-1) MSEM model. Single headed arrows = fixed effects. Filled circles (dots) at the within-person level on the single headed arrows = random slopes. At the between level, random slopes are illustrated as a and c′ in circles because they are latent variables that vary across individuals. Age-c = grand mean centered age. For simplicity reasons, covariances between latent variables are not depicted but were estimated in the models.

response of the matching digit under each of the provided symbols as quickly as possible without skipping any numbers. Participants are given two 90-s trials to complete the task and are given 1 point for every correct symbol.

Spatial visualization. Kohs Block Design Test (Dureman & Salde, 1959) was used. Respondents are shown cards with designs and are instructed to replicate the patterns using colored blocks. Seven cards with white and red patterns are given to the participants, each with a maximum score of 6, depending on the speed and accuracy of the solution. A score of zero is given if the allotted time is surpassed. The maximum score is 42.

Memory. Two tests, Digit-Span forward and backward, were used separately to measure memory (Wechsler, 1991). (1) *Digit-Span forward:* respondents are asked to recall a list of numbers that were read out loud to them in the same order they were presented. (2) *Digit-Span backward*: respondents are asked to recall the digits in reverse order. The maximum score is nine for the forward subtest and eight for the backward subtest.

Verbal memory. The Prose Recall Test was used. Respondents are read a humorous story (100 words) and are instructed to freely recall the words from the narrative (Johansson, Zarit, & Berg, 1992). A coding system similar to the Wechsler Memory Test (Wechsler, 1945) was used, where respondents were scored based on the amount of information they recalled. The maximum score is 16.

Description of the Longitudinal Aging Study Amsterdam (LASA)

The objective of the interdisciplinary LASA cross-sequential longitudinal study was to examine the predictors and consequences of increasing age on autonomy and well-being of older adults. Data were collected in 1992/1993, 1995/1996, 1998/1999, 2001/2002, 2005/2006, covering 13 years of follow-up. Respondents for the LASA study were recruited from the 3805 respondents of the Living Arrangements and Social Network of

Table 1
Descriptive Statistics for Study Variables (Origins of Variance in the Oldest-Old [OCTO-Twin] and Longitudinal Aging Study Amsterdam [LASA])

Variables	*M* (*SD*)					ICC
	Baseline	Year 2	Year 4	Year 6	Year 8	
OCTO-Twin						
Age	83.4 (3.2)	85.4 (3.1)	87.1 (2.8)	88.9 (2.8)	90.7 (2.4)	.46
Digit-Symbol	25.5 (10.7)	26.0 (10.3)	26.5 (10.7)	26.1 (10.7)	23.5 (10.4)	.71
Block Design	12.1 (7.1)	12.7 (6.7)	12.7 (6.6)	12.2 (6.8)	11.4 (6.9)	.74
Digit-Span Forward	5.5 (1.2)	5.3 (1.1)	5.3 (1.1)	5.1 (1.0)	5.1 (1.0)	.43
Digit-Span Backward	3.4 (1.5)	3.4 (1.4)	3.3 (1.4)	3.2 (1.3)	3.0 (1.3)	.36
Prose Recall	10.0 (4.0)	10.5 (3.6)	10.5 (3.6)	10.9 (3.4)	10.1 (3.5)	.67
LASA	Baseline	Year 3	Year 6	Year 9	Year 12	
Age	69.3 (8.6)	71.2 (8.3)	73.2 (7.9)	75.1 (7.5)	77.8 (6.6)	.70
Coding	25.5 (7.0)	24.6 (6.7)	24.9 (6.4)	25.5 (6.6)	25.1 (6.6)	.81
Delayed recall	5.5 (2.7)	6.3 (2.8)	5.9 (2.9)	6.7 (3.0)	6.0 (3.0)	.57
Immediate recall	19.6 (6.0)	20.5 (5.9)	19.9 (6.1)	21.5 (6.1)	19.7 (6.1)	.57
Raven	18.4 (3.8)	18.7 (3.7)	18.5 (3.7)	18.6 (3.6)	18.6 (3.4)	.64

Note. ICC = intraclass correlation.

Older Adults (LSN) study. At the first data collection time of LASA, 3107 respondents participated in LASA. Respondents were interviewed in their homes. More detailed information about LASA has been described elsewhere (Huisman et al., 2011). Respondents with scores of 23 or lower on the Mini-Mental State Examination (MMSE) at any of the five occasions were excluded from the analyses ($N = 798$). A further three cases were deleted because they were missing education information. The final sample for the current study consisted of 2,306 participants. Of the 2,306 individuals at Time 1, 423 (18%) dropped out at Time 2, of these a further 321 (17%) dropped out at Time 3, 262 (17%) at Time 4, and 279 (21%) at Time 5. Respondents' age at baseline ranged from 54.8 to 85.6 years of age. Half were men ($n = 1154$) and women ($n = 1152$). The number of years of education completed ranged from 5 to 18, with a mean of 9.2 years.

Measures

Processing speed. Processing speed was measured with a coding task adapted from the Alphabet Coding Task–15 (Savage, 1984). Participants were given a record form containing two rows with letters on the top row matching with different letters on the bottom row. The participants were then asked to name the letters in the empty rows under each of the provided top row letters as quickly as possible. Three trials of 60 s each were completed and scored with 1 point for every correct symbol. The total score of the three trials were used.

Nonverbal reasoning. An adapted version of the Raven Colored Progressive Matrices (RCPM; Raven, 1995) test was used to assess nonverbal reasoning. The RCPM version used in LASA includes 2 (A and B) of the 3 sections from the original version (A, Ab, and B). This adapted version has been found to correlate strongly with the original version (Smits, Smit, van den Heuvel, & Jonker, 1997). Respondents are shown 24 (12 per section) drawings of a pattern with a missing section that the respondent is instructed to complete using patterns given to them on a separate sheet. Respondents are given one point per correct response for a total score ranging between 0 and 24.

Memory. The 15 Words Test (15WT), derived from the Dutch version of the Auditory Verbal Learning Test (AVLT; Deelman, Brouwer, van Zomeren, & Saan, 1980; Rey, 1964; Saan & Deelman, 1986), was used to assess immediate and delayed recall. Participants were given three trials to learn 15 words and are asked to recall as many words as possible after each trial. A total score of the three trials was used with higher scores indicating better immediate recall. For the delayed recall score, participants were asked to recall the word list after 20 min.

Statistical Analyses

Mplus version 6.11 was used for fitting the MSEM models (Muthén & Muthén, 1998–2011). TYPE = TWOLEVEL RANDOM was used to model random intercepts and slopes using the multilevel framework. For the OCTO-Twin study, given that twin data were used, we employed cluster identifiers to account for the dependency among sample participants (Stapleton, 2006). By using TYPE = COMPLEX with CLUSTER, *SE*s and χ^2 tests of model fit take into account the nonindependence of observations because of the cluster sampling of twin data (Muthén & Muthén, 1998–2010). Given that random slopes were used and that Mplus only provides standardized estimates for fixed effects, only unstandardized estimates are reported. In MLM with fixed slopes, the effect of x on y is the same across levels. However, with random slopes the variance of y is dependent on x and therefore it is impossible to select a single appropriate variance for y. An alpha level of .01 was used rather than .05 given the increased probability of finding significant results with multiple models.

Mplus uses full information maximum likelihood (FIML) to include missing data of endogenous variables under the missing at random (MAR) assumption. Robust maximum likelihood (MLR) estimation was used (Muthén & Muthén, 1998–2010; Yuan & Bentler, 2000). The MLR estimator is robust to non-normality and provides adjusted χ^2 and *SE*s. The MODEL CONSTRAINT command was used to estimate the within and between indirect effects. The delta method confidence intervals provided by Mplus used for the indirect effects may be inaccurate given the lack of normality in indirect effects (Preacher et al., 2010). Therefore, a Web utility developed to provide indirect effects through a Monte Carlo Method, which is applicable to MSEM, was used (Selig & Preacher, 2008).

We followed Preacher et al.'s (2010) approach to MSEM. First, we developed our mediation model based on the processing speed hypothesis. Given that all variables (processing speed, memory, spatial visualization, reasoning, and age) were measured at level 1, and given that both within-person changes (level 1) and BP differences (level 2) in speed could mediate the relationship between increasing age and cognitive functioning, both levels of the model were modeled, as shown in Figure 1. We first examined the percentage of BP variance for each variable by calculating the intraclass correlation from empty models (i.e., with no predictor effects), in which ICC = $BP_{var}/[BP_{var} + WP_{var}]$). We then examined indirect effects at both the BP and within-person levels of analysis. The models were estimated with random intercepts and random age slopes adjusted for gender and education (centered at baseline mean). Age was grand mean centered. We attempted to estimate the model with all three random slopes but given its complexity, it would not converge. Therefore, random speed slopes were not included. Although fit indices are not available when random slopes are modeled, these models had few degrees of freedom with which to allow mis-fit in the first place.

Effect Size

As recommended by Preacher and Kelley (2011), we report κ^2 values for the ratio of the indirect effect in comparison to the maximum possible effect size. Given upper and lower boundaries for the *a* path, *b* path, and *ab* indirect effect a measure of the indirect effect size is created by comparing the obtained indirect effect to the maximum possible effect. The κ^2 measure of effect size addresses many of the limitations of other approaches and thus represents an additional contribution of the present research. The necessary computations can be conducted via simple spreadsheets (i.e., as can be requested by the first author). To facilitate interpretation, we further label κ^2 values as small (.01) medium (.09) or large (.25) based on the guidelines provided by Cohen (1988).

Results

Origins of Variance in the Oldest-Old (OCTO-Twin)

1–1–1 MSEM models were estimated for each outcome. The ICC values indicate that between 36% and 81% of the variance was BPs, hence warranting the multilevel approach (Table 1). Accordingly, unstandardized estimates, *p* values, and 95% confidence intervals for all direct and indirect effects are provided in Tables 2 and 3. Higher education was associated with higher Speed (we use Speed rather than Digit Symbol to differentiate Speed from the other cognitive outcomes), but not with Digit-Span Forward, Digit-Span Backward, Block Design, or Prose. Gender was not significantly associated with Speed nor with any other cognitive outcome. Gender and education were not related to random age slopes for any of the outcomes, suggesting individual differences in within-person change did not relate to gender and education.

Within-person direct effects. For all models, mean random slopes (i.e., the fixed slope for the average effect in the sample) for the effect of age on Speed (X→M) were significant, suggesting that advancing age was associated with a within-person slowing of Speed. In addition, mean random slopes for the effect of age on cognitive outcomes (X→Y) were significant for all outcomes except Prose. That is, advancing age was also related to concurrent decreases in Block Design, Digit-Span Forward, and Digit-Span Backward scores (but not Prose, $p = .08$). Further, at occasions where Speed was lower than usual (M→Y), Block Design and Prose (but not Digit-Span Backward, $p = .01$, and Digit-Span Forward, $p = .75$) were also lower than usual. Together, these results indicate a longitudinal (within-person) relationship for age with memory and fluid intelligence, and for Speed with memory and fluid intelligence.

BP direct effects. For all models, BP differences in age (i.e., in the intercept) failed to predict BP differences in Speed (Digit Symbol intercept; X→M). Older people on average had lower Digit-Span Forward scores (X→Y; coefficient = −0.08, SE = 0.03). Age was not associated with Block Design, Prose, or Digit-Span Backward. However, BP differences in Speed significantly predicted BP differences in all cognitive variables (M→Y; e.g., coefficient for Block Design = 0.56, SE = 0.03). That is, individuals with lower Speed scores on average had lower scores on all other cognitive outcomes (even after controlling for time-specific Speed scores within persons).

Between- and within-person indirect effects. The indirect effects of the MSEM model convey the extent to which Speed mediates the relationship between age and cognitive functioning at each level. In terms of within-person mediation, changes in Speed mediated the relationship between increasing age and changes in all cognitive outcomes except for Digit-Span Backward and Forward. This means that increases in age within-individuals were associated with time-specific decreases in processing Speed scores which were, in turn, related with decreases in the other cognitive outcomes for those same occasions (e.g., within-person indirect effect for Block Design = −0.06, SE = 0.02). No significant BP indirect effects were found (e.g., BP indirect effect for Block Design = −.10, SE = .15). That is, individual differences in the relationship between age and cognition were not mediated by Speed.

Effect size. All indirect effect sizes, calculated as the ratio of the indirect effect to the maximum possible indirect effect (κ^2) for between and within-person effects, were small, as provided in Table 6.

LASA

Turning to the LASA study, the ICC values indicate that between 61% and 83% of the variance across outcomes was between persons. Unstandardized estimates, *p* values, and 95% confidence intervals for all direct and indirect effects are provided in Tables 4 and 5. Higher education was associated with higher scores on Speed (we use Speed rather than Coding to differentiate Speed from the other cognitive outcomes), Raven's Progressive Matrices, and Immediate Recall, but not on Delayed Recall. Women per-

Table 2
Unstandardized Estimates and SE*s for the Multilevel Structural Equation Modeling (MSEM) Models (Origins of Variance in the Oldest-Old [OCTO-Twin])*

Models	Spatial visualization (Block Design)					Memory (Digit-Span Forward)				
				95% Confidence interval					95% Confidence interval	
	Est.	*SE*	*p*	Lower	Upper	Est.	*SE*	*p*	Lower	Upper
Within-person effect										
Speed→Cognition(b)	0.13	0.03	<.0001	0.07	0.19	0.02	0.007	.01	0.004	0.03
Variance age[a]	8.13	0.15	<.0001	7.84	8.42	8.14	0.15	<.0001	7.84	8.43
Variance speed[b]	25.87	1.89	<.0001	22.16	29.58	25.73	1.90	<.0001	22.01	29.45
Variance cognition[b]	9.88	0.61	<.0001	8.69	11.07	0.60	0.04	<.0001	0.52	0.68
Indirect effect (κ^2)	−0.06	0.02	.006	−0.10	−0.02	−0.008	0.004	.04	−0.02	0.00
Between-person effect										
Intercept speed	22.30	0.86	<.0001	20.61	23.99	23.00	0.86	<.0001	21.32	24.68
Intercept cognition	−1.91	0.78	.01	−3.43	−0.38	4.59	0.17	<.0001	4.25	4.93
Intercept A	−0.46	0.13	<.0001	−0.71	−0.22	−0.45	0.12	<.0001	−0.69	−0.22
Intercept C	−0.31	0.07	<.0001	−0.44	−0.17	−0.07	0.02	<.0001	−0.11	−0.04
Age→Speed(a)[c]	−0.17	0.28	.53	−0.71	0.37	−0.26	0.28	.36	−0.81	0.29
Speed→Cognition(b)	0.56	0.03	<.0001	0.50	0.62	0.03	0.006	<.0001	0.02	0.04
Age→Cognition(c′)[c]	−0.26	0.16	.10	−0.57	0.05	−0.08	0.03	.001	−0.13	−0.03
Education →Speed	1.49	0.22	<.0001	1.06	1.92	1.56	0.22	<.0001	1.12	1.99
Gender→Speed	1.85	1.04	.07	−0.18	3.89	1.47	1.05	.16	−0.58	3.52
Education →Cognition	−0.17	0.12	.17	−0.41	0.07	0.05	0.02	.01	0.01	0.08
Gender →Cognition	0.13	0.52	.80	−0.89	1.16	−0.06	0.09	.49	−0.25	0.12
Education →A	−0.03	0.04	.42	−0.10	0.04	−0.03	0.03	.36	−0.10	0.04
Gender →A	−0.12	0.15	.42	−0.41	0.17	−0.09	0.15	.55	−0.38	0.20
Education →C	0.001	0.02	.94	−0.04	0.04	0.001	0.003	.69	−0.005	0.008
Gender →C	0.05	0.09	.58	−0.12	0.22	0.02	0.02	.24	−0.02	0.06
Variance age[a]	6.84	1.24	<.0001	4.42	9.26	6.82	1.23	<.0001	4.40	9.24
Variance speed[b]	66.35	5.70	<.0001	55.18	77.53	64.91	5.63	<.0001	53.87	75.96
Variance cognition[b]	10.97	1.30	<.0001	8.42	13.52	0.36	0.04	<.0001	0.28	0.44
Variance A[b]	0.41	0.13	.001	0.16	0.66	0.44	0.13	.001	0.18	0.70
Variance C[b]	0.10	0.05	.03	0.01	0.20	0.008	0.003	.008	0.002	0.01
Indirect effect(κ^2)	−0.10	0.15	.53	−0.40	0.20	−0.007	0.008	.36	−0.03	0.008

Note. N = 477. Est. = unstandardized estimates. Parametric bootstrap CIs based on the Monte Carlo method were obtained for the indirect effects. A = Random slope of speed regressed on age. C = Random slope of cognition regressed on age. κ^2 = Effect size for the between- and within-person indirect effects.
[a] Variance. [b] Residual variance. [c] The between-person effect was calculated by adding the within slope to the contextual effect.

formed better on Immediate and Delayed Recall, Speed, and more poorly on Raven.

Within-person direct effects. For all models, mean random age slopes were significant, indicating declines in Speed, Raven, and Immediate and Delayed Recall scores as a function of change in age. Further, on occasions where Speed was lower than usual, Immediate and Delayed Recall were also lower. Raven was not associated with Speed.

BP direct effects. Higher age (age intercept) was associated with lower Speed (Speed intercept). Higher age (age intercept) was also associated with lower Raven, Immediate and Delayed Recall (intercept). Higher Speed was related to higher Recall and Raven.

BP and within-person indirect effects. Speed mediated the relationship between age and all cognitive outcomes at the BP level and Immediate and Delayed Recall but not Raven at the within level. These results indicate that with increasing age individuals scored more poorly on Speed tasks and, in turn, on time points where Speed was lower, Memory was also more likely lower. Also, older individuals were more likely to have lower Speed scores. This in turn relates to lower performance on Memory and Reasoning.

Effect size. All indirect effect sizes, calculated as the ratio of the indirect effect to the maximum possible indirect effect (κ^2) were medium for BP effects and small for within-person effects, as provided in Table 6.

Discussion

The current article made use of recent developments in longitudinal mediation to evaluate whether changes in processing speed mediate the effect of age on changes in various cognitive outcomes. More specifically, we tested the speed—mediation hypothesis at both the within-person and BP levels with MSEM (Preacher et al., 2011), allowing us to separately decompose these effects in two major longitudinal studies. We consider this as a valuable extension to the previous longitudinal research that generally has focused on a two-step approach to mediation.

Summary and Considerations of Results

At the BP level, after accounting for BP differences in gender and education at baseline and for within-person changes, age

Table 3
Unstandardized Estimates and Standard Errors for the Multilevel Structural Equation Modeling (MSEM) Models (Origins of Variance in the Oldest-Old [OCTO-Twin])

Models	Memory (Prose Recall) Est.	*SE*	*p*	95% Confidence interval Lower	Upper	Memory (Digit-Span Backward) Est.	*SE*	*p*	95% Confidence interval Lower	Upper
Within-person effect										
Speed→Cognition(b)	0.07	0.02	.001	0.03	0.11	0.003	0.009	.75	−0.01	0.02
Variance age[a]	8.15	0.15	<.0001	7.86	8.44	8.13	0.15	<.0001	7.84	8.42
Variance speed[b]	25.89	1.90	<.0001	22.16	29.62	25.71	1.91	<.0001	21.97	29.44
Variance cognition[b]	4.41	0.34	<.0001	3.74	5.08	1.16	0.08	<.0001	.99	1.32
Indirect effect (κ^2)	−0.03	0.01	.01	−0.06	−0.007	−0.001	0.004	.75	−.009	0.006
Between-person effect										
Intercept speed	22.69	0.85	<.0001	21.02	24.36	22.82	0.87	<.0001	21.11	24.53
Intercept cognition	3.69	0.54	<.0001	2.63	4.75	1.70	0.21	<.0001	1.30	2.11
Intercept A	−0.49	0.12	<.0001	−0.73	−0.25	−0.45	0.12	<.0001	−0.68	−2.11
Intercept C	−0.10	0.06	.08	−0.21	0.01	−0.06	0.02	.007	−0.11	−0.02
Age→Speed(a)[c]	−0.36	0.29	0.21	−0.91	0.20	−0.21	0.28	.46	−0.76	0.34
Speed→Cognition(b)	0.23	0.02	<.0001	0.19	0.27	0.06	0.007	<.0001	0.05	0.07
Age→Cognition(c′)[c]	−0.13	0.10	.20	−0.33	0.07	−0.06	0.03	0.09	−0.12	0.008
Education →Speed	1.60	0.22	<.0001	1.17	2.02	1.55	0.22	<.0001	1.12	1.98
Gender→Speed	1.66	1.03	.11	−0.36	3.68	1.65	1.05	.12	−0.41	3.71
Education→Cognition	0.07	0.07	.31	−0.06	0.19	0.04	0.03	.12	−0.01	0.09
Gender→Cognition	0.79	0.36	.03	0.07	1.50	0.13	0.10	.22	−0.08	0.33
Education →A	−0.03	0.03	.31	−0.10	0.03	−0.03	0.03	.34	−0.10	0.03
Gender →A	−0.06	0.15	.67	−0.35	0.23	−0.09	0.15	.52	−0.38	0.19
Education →C	−0.009	0.01	.43	−0.03	0.01	0.003	0.004	.35	−0.004	0.01
Gender →C	0.02	0.07	.78	−0.11	0.15	−0.009	0.02	.71	−0.06	0.04
Variance age[a]	6.78	1.23	<.0001	4.38	9.19	6.84	1.24	<.0001	4.41	9.27
Variance speed[b]	65.31	5.60	<.0001	54.34	76.28	66.67	5.79	<.0001	55.32	78.02
Variance cognition[b]	4.68	0.58	<.0001	3.55	5.81	0.33	0.07	<.0001	0.20	0.46
Variance A[b]	0.43	0.13	.001	0.18	0.69	0.43	0.14	.002	0.16	0.71
Variance C[b]	0.05	0.02	.04	0.001	0.09	0.002	0.003	.49	−0.004	0.009
Indirect effect(κ^2)	−0.08	0.07	.22	−0.21	0.05	−0.01	0.02	.46	−0.045	0.02

Note. $N = 477$. Est. = unstandardized estimates. Parametric bootstrap confidence intervals based on the Monte Carlo method were obtained for the indirect effects. A = Random slope of speed regressed on age. C = Random slope of cognition regressed on age. κ^2 = Effect size for the between- and within-person indirect effects.
[a] Variance. [b] Residual variance. [c] The between-person effect was calculated by adding the within slope to the contextual effect.

differences in OCTO-Twin respondents failed to predict processing speed differences. In contrast, age differences for LASA respondents did predict processing speed differences, with older adults scoring lower on the speed task. Similarly, for the OCTO-Twin study, age differences failed to predict differences in most cognitive outcomes except Digit-Span Forward, whereas BP age differences significantly predicted cognition in the LASA data. These differing results are likely to be ascribed to the fact that the LASA study was more age heterogeneous (55–86; 70% of the age variation was between persons) than the OCTO-Twin study (80–92; 46% of the age variation was between persons). The OCTO-Twin results do not align with those of Sliwinski and Buschke (1999, 2004), who found that processing speed did mediate the BP relationship between processing speed and cognitive functioning. However, the OCTO-Twin sample was also more age homogeneous (80–92 years of age) than the sample used by Sliwinski and Buschke (1999), which ranged in age from 66 to 92. The age range of the Sliwinski and Buschke (1999) study aligns more closely with that of the LASA study where BP indirect effects were found. Furthermore, the OCTO-Twin and the age-restricted LASA samples were much smaller than the complete LASA sample, suggesting a possible lack of power to detect significant results. This highlights the importance of taking study characteristics, particularly age heterogeneity, into account when interpreting results.

In both OCTO-Twin and LASA, BP differences in processing speed were associated with differences in the other measures of cognitive functioning, with higher scores on processing speed being associated with higher memory, spatial visualization, and reasoning scores. These findings align with previous research that has reported a strong correlation between speed and other cognitive outcomes (Sliwinski & Buschke, 1999, 2004).

As for within-person direct effects, processing speed declined as a function of age for both OCTO-Twin and LASA respondents. Memory, spatial visualization, and reasoning also declined as a function of age. This suggests that, after controlling for BP differences, increasing age is associated with declining cognitive performance. These findings also align with results from some previous studies (Ghisletta, Rabbitt, Lunn, & Lindenberger, 2012; MacDonald et al., 2003; Sliwinski & Buschke, 1999; Sliwinski & Buschke, 2004). Furthermore, within-person decreases in processing speed were associated with decreases in Block, Prose, Immediate Recall, and Delayed Recall but not Digit-Span Backward,

Table 4
Unstandardized Estimates and SEs for the Multilevel Structural Equation Modeling (MSEM) Models (Longitudinal Aging Study Amsterdam [LASA])

Models	Memory (Immediate Recall)					Memory (Delayed Recall)				
				95% Confidence interval					95% Confidence interval	
	Est.	*SE*	*p*	Lower	Upper	Est.	*SE*	*p*	Lower	Upper
Within-person effect										
Speed→Cognition(b)	0.21	0.03	<.0001	0.14	0.27	0.09	0.02	<.0001	0.06	0.12
Variance age[a]	21.74	0.14	<.0001	21.46	22.03	21.73	0.14	<.0001	21.45	22.02
Variance speed[b]	6.12	0.23	<.0001	5.67	6.56	6.11	0.23	<.0001	5.67	6.55
Variance cognition[b]	14.80	0.43	<.0001	13.97	15.64	3.32	0.10	<.0001	3.12	3.52
Indirect effect (κ^2)	−0.07	0.01	<.0001	−0.09	−0.05	−0.03	0.005	<.0001	−0.04	−0.02
Between-person effect										
Intercept speed	24.32	0.18	<.0001	23.96	24.67	24.32	0.18	<.0001	23.96	24.68
Intercept cognition	11.30	0.54	<.0001	10.25	12.35	2.00	0.26	<.0001	1.49	2.50
Intercept A	−0.34	0.02	<.0001	−0.37	−0.31	−0.34	0.02	<.0001	−0.37	−0.31
Intercept C	−0.10	0.02	<.0001	−0.14	−0.06	−0.02	0.009	.12	−0.03	0.004
Age→Speed(a)[c]	−0.36	0.02	<.0001	−0.40	−0.32	−0.36	0.02	<.0001	−0.40	−0.32
Speed→Cognition(b)	0.30	0.02	<.0001	0.26	0.34	0.13	0.01	<.0001	0.11	0.15
Age→Cognition(c′)[c]	−0.17	0.02	<.0001	−0.21	−0.13	−0.07	0.01	<.0001	−0.09	−0.05
Education →Speed	0.78	0.04	<.0001	0.70	0.85	0.78	0.04	<.0001	0.70	0.85
Gender→Speed	1.89	0.25	<.0001	1.40	2.37	1.90	0.25	<.0001	1.41	2.38
Education→Cognition	0.18	0.03	<.0001	0.12	0.25	0.04	0.02	.02	0.005	0.07
Gender→Cognition	2.70	0.20	<.0001	2.32	3.09	1.29	0.10	<.0001	1.10	1.48
Education →A	−0.003	0.003	.18	−0.008	0.002	−0.004	0.003	.17	−0.008	0.001
Gender →A	0.04	0.02	.04	0.002	0.07	0.04	0.02	.04	0.002	0.07
Education →C	−0.004	0.003	.13	−0.01	0.001	−0.002	0.001	.18	−0.005	0.001
Gender →C	−0.02	0.02	.20	−0.06	0.01	−0.007	0.009	.48	−0.03	0.01
Variance age[a]	51.14	1.25	<.0001	48.69	53.60	51.18	1.25	<.0001	48.72	53.64
Variance speed[b]	26.06	0.96	<.0001	24.19	27.94	26.04	0.95	<.0001	24.17	27.91
Variance cognition[b]	11.96	0.62	<.0001	10.74	13.18	2.94	0.15	<.0001	2.65	3.23
Variance A[b]	0.04	0.006	<.0001	0.03	0.05	0.04	0.006	<.0001	0.03	0.05
Variance C[b]	0.007	0.006	.25	−0.005	0.02	0.004	0.001	.003	0.001	0.007
Indirect effect (κ^2)	−0.11	0.01	<.0001	−0.13	−0.09	−0.05	0.005	<.0001	−0.06	−0.04

Note. N = 2306. Est. = unstandardized estimate; Std. = standardized estimates. Parametric bootstrap confidence intervals based on the Monte Carlo method were obtained for the indirect effects. A = Random slope of speed regressed on age. C = Random slope of cognition regressed on age. κ^2 = Effect size for the between- and within-person indirect effects.
[a] Variance. [b] Residual variance. [c] The between-person effect was calculated by adding the within slope to the contextual effect.

Digit-Span Forward, and Raven. These findings suggest that changes in speed are associated with concurrent changes in memory and spatial visualization. These findings, as well as the aforementioned relationship between processing speed and all other cognitive outcomes found at the BP level, align with previous studies reporting moderate to high correlations between cognitive measures (Anstey, Hofer, & Luszcz, 2003; Sliwinski & Buschke, 1999, 2004; Sliwinski, Hofer, & Hall, 2003).

Following previous research highlighting the importance of processing speed (e.g., Verhaeghen & Salthouse, 1997), the current study specifically aimed to replicate previous research examining processing speed as a mediator using statistical advances in mediation analysis. However, this does not mean that processing speed is the only mediator worthy of investigation. In fact, numerous studies have highlighted the importance of both global and specific characterizations of the cognitive aging process, in which processing speed is but one of many correlated cognitive predictors of change (Anstey et al., 2003; de Frias, Lövdén, Lindenberger, & Nilsson, 2007; Ghisletta et al., 2012; Hartley, 2006; Tucker-Drob, 2011). To gain a comprehensive understanding of mechanisms that drive cognitive aging, more research about both specific and global processes is needed.

For both LASA and OCTO-Twin, within-person indirect effects for the association between age and the cognitive outcomes mediated through speed were significant for Block and for Immediate and Delayed recall (Prose and Digit-Span Forward were significant at the .05 level).This suggests that, as individuals increase in age, they tend to have slower speed scores; in turn, these lower speed scores are associated with changes in other cognitive outcomes. More precisely, time-specific variation in processing speed appears to account for some of the longitudinal relationship between age and cognitive functioning. These findings align with the processing speed hypothesis, but they do not appear to align with those of previous results that suggest that processing speed does not mediate the relationship between cognitive functioning and processing speed at the within-person level (Sliwinski & Buschke, 1999, 2004).

However, a more in-depth examination into our findings through measures of effect size suggests that, for the LASA study, the within-person indirect effects were small for Immediate Recall and Delayed Recall (.07 and .07, respectively). The BP indirect effects were consistently larger, with all effect sizes at least medium (.15–.20) and nearing the large range. For example, for Immediate Recall we obtained a BP indirect effect estimate of

Table 5
Unstandardized Estimates and SE*s for the Multilevel Structural Equation Modeling (MSEM) Models (Longitudinal Aging Study Amsterdam [LASA])*

Models	Reasoning (Raven)				
				95% Confidence interval	
	Est.	*SE*	*p*	Lower	Upper
Within-person effect					
Speed→Cognition(b)	0.01	0.02	.59	−0.03	0.05
Variance age[a]	21.75	0.14	<.0001	21.46	22.03
Variance speed[b]	6.12	0.23	<.0001	5.68	6.57
Variance cognition[b]	4.78	0.15	<.0001	4.49	5.07
Indirect effect (κ^2)	−0.003	0.006	.59	−0.02	0.009
Between−person effect					
Intercept speed	24.25	0.18	<.0001	23.89	24.60
Intercept cognition	12.63	0.33	<.0001	12.00	13.27
Intercept A	−0.33	0.02	<.0001	−0.36	−0.30
Intercept C	−0.15	0.01	<.0001	−0.18	−0.13
Age→Speed(a)[c]	−0.36	0.02	<.0001	−0.40	−0.32
Speed→Cognition(b)	0.24	0.01	<.0001	0.21	0.26
Age→Cognition(c′)[c]	−0.16	0.01	<.0001	−0.19	−0.14
Education →Speed	0.78	0.04	<.0001	0.71	0.85
Gender→Speed	1.89	0.25	<.0001	1.41	2.37
Education →Cognition	0.18	0.02	<.0001	0.14	0.22
Gender →Cognition	−0.45	0.12	<.0001	−0.68	−0.22
Education →A	−0.004	0.003	.15	−0.009	0.001
Gender →A	0.03	0.02	.06	−0.001	0.07
Education →C	0.000	0.002	.96	−0.003	0.003
Gender →C	0.02	0.01	.04	0.002	0.05
Variance age[a]	51.13	1.26	<.0001	48.67	53.59
Variance speed[b]	26.18	0.97	<.0001	24.29	28.07
Variance cognition[b]	4.58	0.23	<.0001	4.13	5.04
Variance A[b]	0.04	0.006	<.0001	0.03	0.05
Variance C[b]	0.008	0.003	.001	0.003	0.01
Indirect effect (κ^2)	−0.09	0.007	<.0001	−0.10	−0.07

Note. $N = 2306$. Est. = unstandardized estimate; CI = confidence intervals. Parametric bootstrap confidence intervals based on the Monte Carlo method were obtained for the indirect effects. A = Random slope of cognition regressed on age. C = Random slope of cognition regressed on age. κ^2 = Effect size for the between- and within-person indirect effects.
[a] Variance. [b] Residual variance. [c] The between-person effect was calculated by adding the within slope to the contextual effect.

−.11 when the maximum possible value was −.66, whereas the within-person effect obtained was −.07 when the maximum possible value was −.93, highlighting that the effect size is much larger for the BP effect. This magnitude difference between within- and BP mediation aligns closely with previously published results (Sliwinski & Buschke, 1999; Sliwinski & Buschke, 2004). For the OCTO-Twin study, BP indirect effects were nonsignificant, likely as a result of the previously mentioned homogeneity of the data. Within-person indirect effect sizes were in the small range (.003–.05) such that much of the indirect-effect between age and cognitive functioning likely remains unexplained.

Limitations and Opportunities for Future Research

In comparing the results from current and previous research, it is important to consider methodological or statistical differences that may contribute to any discrepancies. To that end, we note that in Sliwinski and Buschke (1999, 2004), only baseline values were used to index cross-sectional, BP variation in speed; change from baseline was used to index longitudinal, within-person variation in speed. In contrast, the modeling in the current study used *all* occasions to distinguish BP from within-person effects. While we believe the current approach provides a clearer separation, it does have some disadvantages with respect to potential bias created by attrition. That is, attrition-related processes may bias BP representations of age given that persons who have less data included will be viewed as "younger" on average relative to other persons who began the study at the same age, whereas a BP representation from age at Time 1 will not have this bias. The longstanding issue of how to best account for effects of attrition and differential selection in longitudinal data are a limitation of the current work, as is the case for all studies of aging.

In addition, differential sampling may also be related to discrepancies in results across studies. In this case, there is also the possibility that respondents with preclinical dementia were included in our samples (Sliwinski, Lipton, Buschke, & Stewart, 1996), which might have affected the mediation effect of processing speed on cognition (Sliwinski & Buschke, 1997). In order to limit this shortcoming, individuals with MMSE scores 23 or lower

Table 6
Effect Size (K^2) For All Between- and Within-Person Indirect Effects

Variable	Between-person	Within-person
Origins of Variance in the Oldest-Old (OCTO-Twin)		
Block Design	.07	.05
Digit-Span Forward	.03	.03
Digit-Span Backward	.05	.003
Prose Recall	.09	.04
Longitudinal Aging Study Amsterdam (LASA)		
Delayed recall	.15	.07
Immediate recall	.16	.07
Raven	.20	.006

in LASA and those with a dementia diagnosis at any point in OCTO-Twin were removed from the analyses.

Another relevant issue is the extent to which practice effects may have biased the obtained within-person effects. The possibility of performance gains over time as a result of repeatedly taking the same test is pervasive across many areas of functioning, and such practice effects may be different across the various cognitive measures (Ferrer, Salthouse, McArdle, Stewart, & Schwartz, 2005).Unfortunately, in estimating separate BP and within-person effects of age, one cannot distinguish practice effects from cohort effects as the source of differences across within-person and BP effects, given the complete confound of within-person changes in age and number of test exposures (Hoffman, Hofer & Sliwinski, 2011).

In addition, it is important to consider how the choice of models and choice of measures may impact the conclusions of the current article. We note that, as in every statistical model, the conclusions drawn are necessarily specific to the variables included, and omitted variables may have had an impact of the degree of mediation observed (i.e., a suppression effect). In addition, as in all observational studies, ours does not permit causal inferences (despite the fact that SEM is sometimes described as "causal modeling").

Only one measure of each cognitive ability was used, but it may be preferable to measure each ability in multiple ways to limit mono-operation bias (Shadish, Cook, & Campbell, 2003). For example, Hertzog et al. (2003) reported different relations between cognitive functions when using different measures of the same construct. In the current study, our efforts toward enhancing generalizability were manifested by using two different longitudinal studies of aging and multiple cognitive abilities, and thus the measures used for the current study were those available in the LASA and OCTO-Twin data. However, the extent to which multiple measures of the same cognitive ability may show different patterns of BP and within-person mediation is an important avenue for future research.

Relatedly, in assessing speed mediation specifically, one must consider the extent of potential overlap between measures of processing speed (the supposed mediator) and measures of other cognitive abilities (the targeted outcomes) in terms of the abilities these tasks require. For instance, the Digit-Symbol test has been shown to not only measure speed, but to also measure memory and novel reasoning (Piccinin & Rabbitt, 1999). However, so-called "pure" measures of processing speed like simple reaction time (RT) have not been found to account for as much variance in other cognitive abilities as the digit symbol task (Hartley, 2006), limiting their utility as mediators of age-related change. Likewise, Block Design scoring is affected by speed of response, and thus other measures of spatial visualization may have shown different mediation results. More generally, similarities and differences in the ability requirements of different measures are important to consider in drawing conclusions about the longitudinal relationship between processing speed and cognitive performance—this is yet another reason why replication analyses using different variables collected in different longitudinal samples is a critical avenue for further research.

Finally, we note that the complexity of the latent variable mediation models utilized in the current study could potentially have been increased further by considering additional effects. For instance, given the estimation of multiple random linear slopes already, the models did not include quadratic age trends. It is possible that age accelerated changes in processing speed explain age accelerated changes in cognitive functioning (Finkel et al., 2005). They also found that speed at baseline was unrelated to linear rate of change in cognitive performance but was associated with less accelerated decline for spatial abilities and memory. Studies with greater amounts of within-person information (i.e., spanning more time or including more occasions of measurement) should further explore the extent to which nonlinear effects of processing speed may also account for (potentially nonlinear) trends in cognitive performance.

In the context of cognitive aging, we expect that rate of age change in speed and cognition would vary across individuals, and thus we included both random age slopes. Notably, random slopes are only rarely incorporated in longitudinal mediation models, and this is an important advantage of using MSEM to study mediational questions (Preacher et al., 2010). Although we also attempted to estimate random slopes for the effect of speed on cognition, given the computational complexity, the models would not converge when including all three random slopes. Thus, another avenue for future research would be, when data permit, to examine the extent of individual differences in the within-person effect of speed on cognition (as well as prediction of all three within-person effects, as in more traditional growth curve modeling).

Conclusion

The extent to which age-related cognitive primitives like processing speed are responsible for age-related declines in other aspects of cognition has been a recurring question in studies of cognitive aging. The present work made use of recent developments in MSEM to shed new light on this question by examining direct and indirect effects of age and processing speed both between persons and within persons. The major finding was that processing speed accounts for relatively little of the within-person age-related effects on memory, reasoning, and spatial visualization. Its effect as a mediator is small to medium, indicating that other predictors, mediators, and moderators need to be considered in predicting cognitive decline with increasing age. In addition, we believe that continued methodological developments within MSEM and other related approaches will be an integral component in further exploring these important questions of longitudinal mediation.

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	Washington, DC 20002-4242

11. Known Bondholders, Mortgagees, and Other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, or Other Securities. If none, check box ☒ None

Full Name	Complete Mailing Address
None	

12. Tax Status (For completion by nonprofit organizations authorized to mail at nonprofit rates) (Check one)
The purpose, function, and nonprofit status of this organization and the exempt status for federal income tax purposes:
☒ Has Not Changed During Preceding 12 Months
☐ Has Changed During Preceding 12 Months (Publisher must submit explanation of change with this statement)

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13. Publication Title: Psychology and Aging
14. Issue Date for Circulation Data Below: September 2013

15. Extent and Nature of Circulation	Average No. Copies Each Issue During Preceding 12 Months	No. Copies of Single Issue Published Nearest to Filing Date
a. Total Number of Copies (Net press run)	1500	950
b. Paid Circulation (By Mail and Outside the Mail) (1) Mailed Outside-County Paid Subscriptions Stated on PS Form 3541 (Include paid distribution above nominal rate, advertiser's proof copies, and exchange copies)	761	526
(2) Mailed In-County Paid Subscriptions Stated on PS Form 3541 (Include paid distribution above nominal rate, advertiser's proof copies, and exchange copies)		
(3) Paid Distribution Outside the Mails Including Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Paid Distribution Outside USPS®	181	152
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d. Free or Nominal Rate Distribution (By Mail and Outside the Mail) (1) Free or Nominal Rate Outside-County Copies included on PS Form 3541		
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(4) Free or Nominal Rate Distribution Outside the Mail (Carriers or other means)	16	16
e. Total Free or Nominal Rate Distribution (Sum of 15d (1), (2), (3) and (4))	16	16
f. Total Distribution (Sum of 15c and 15e)	958	694
g. Copies not Distributed (See Instructions to Publishers #4 (page #3))	542	256
h. Total (Sum of 15f and g)	1500	950
i. Percent Paid (15c divided by 15f times 100)	98%	98%

16. ☐ **Total circulation includes electronic copies. Report circulation on PS Form 3526-X worksheet.** [redacted]

17. Publication of Statement of Ownership
☒ If the publication is a general publication, publication of this statement is required. Will be printed in the December 2013 issue of this publication.
☐ Publication not required.

18. Signature and Title of Editor, Publisher, Business Manager, or Owner: Barbara Spruill
Dir., Service Center Operations
Date: 10/1/2013

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