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Vascular Health Modifies Theory of Mind Performance in Older Adults

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Objectives. Age reductions in theory of mind (ToM) are well documented, though underlying mechanisms are poorly understood. Research suggests that traditional cognitive abilities underlie ToM in part; however, whether age-associated health modifiers also predict ToM remains unknown. We investigated the role of pulse pressure (PP), an age-related marker of vascular risk, in modifying ToM performance.

Method. Sixty-six community-dwelling older adults (65–92 years) completed a short story paradigm assessing ToM. Participants also completed measures assessing blood pressure and cognitive abilities empirically linked to ToM. We used hierarchical regression to test our prediction that high PP would adversely influence associations between ToM and cognition.

Results. Reduced ToM was associated with older age and decreased verbal memory, processing speed, and working memory; however, associations between ToM and working memory were attenuated when PP was included in the regression model. Importantly, associations between ToM, memory, and processing speed were qualified by vascular health, in that participants with elevated PP showed stronger associations between reduced ToM and lower memory/speed.

Discussion. This is the first study to demonstrate that vascular risk modifies the strength of associations between ToM and age-sensitive cognitive resources. Results add to current perspectives on mechanisms influencing reduced ToM in older age.

Key Words: Blood pressure—Cognitive aging—Elderly— Mentalizing—Vascular risk.

THEORY of mind (ToM) is the ability to understand and reason about one's own or another person's mental states and to use this knowledge to explain and predict behavior (Happé, Winner, & Brownell, 1998; Premack & Woodruff, 1978). Older adults show greater difficulty appreciating mental states than do younger adults, which may hold important consequences for everyday life (Kemp, Després, Sellal, & Dufour, 2012). For example, consider the 80-year old man dressed in a dark suit who decides to cross an intersection on foot at night and is struck by a car whose driver does not see him. Tragically, the man failed to consider how visible he would be to others. Research demonstrates that reductions in ToM begin to emerge around age 60 and continue throughout older adulthood (Bernstein, Thornton, & Sommerville, 2011; see also O'Brien, Konrath, Grühn, & Hagen, 2012). Although such age reductions in ToM are often reported, their underlying mechanisms are poorly understood.

ToM has been associated with a broad array of cognitive abilities across the life span, though evidence is mixed regarding which domains are key (Moran, 2013). It is also unclear whether the age-related declines reported in ToM reflect changes in general (overall cognitive change) or specific functions (limited to certain cognitive domains). Both individual and composite measures of executive function (i.e., mental flexibility, cognitive inhibition, working memory; Bailey & Henry, 2008; Charlton, Barrick, Markus, & Morris, 2009; Duval, Piolino, Bejanin, Eustache, & Desgranges, 2011; McKinnon & Moscovitch, 2007; Phillips et al., 2011), as well as processing speed and verbal memory (German & Hehman, 2006; Maylor, Moulson, Muncer, & Taylor, 2002), have emerged as important predictors of ToM performance in aging. Nonetheless, variability in other cognitive abilities does not fully explain age reductions in ToM. For instance, Bernstein and colleagues (2011) reported that age differences in ToM (favoring younger adults) remain even after accounting for variations in executive functions, verbal memory, processing speed, and language. Thus, although age changes in other cognitive abilities appear to be related to reduced ToM at least in part, exploring a broader range of predictors is required to account for developmental changes in ToM in older age.

Accordingly, we sought to expand upon predictors explored in previous studies of ToM by including a comprehensive cognitive battery and examining vascular health, a known predictor of cognitive variability in aging (Spiro & Brady, 2011). Age-associated vascular risk factors, including high blood pressure, can adversely affect cerebral integrity and are associated with lower performance across individual cognitive domains and on measures of global cognitive status (Raz, Rodrigue, & Acker, 2003; Qiu, Winblad, & Fratiglioni, 2005). High blood pressure, in particular, is associated with

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reduced learning and memory, slowed processing speed, and reduced executive functions (Raz et al., 2003; Waldstein, Brown, Maier, & Katzel, 2005). Interestingly, these same domains also appear to underlie ToM performance in older age (Kemp et al., 2012). This functional overlap suggests that vascular health is one potential, yet unexplored mechanism for age-related reductions in ToM.

Vascular Health as a Potential Modifier of ToM

The role of blood pressure—including systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse pressure (PP)—in predicting cognitive performance is well established (Qiu et al., 2005). Blood pressure readings provide valid and reliable estimates of current vascular risk in older individuals (Nichols, O'Rourke, & Vlachopouolos, 2011). Normal age-related stiffening of large central arteries is reflected in changes to pulsatile blood flow, which can be estimated by PP (Franklin, 2004). Pulse pressure calculated as SBP − DBP, is a useful marker for systemic vascular risk in individuals with blood pressure in the low to normal range (Haider, Larson, Franklin, & Levy, 2003). The prognostic significance of PP rises with advancing age, as the static components of blood pressure diverge (i.e., SBP and DBP), resulting in elevated PP (Franklin, 2004). As such, PP is an optimal index to characterize vascular health in older age (Franklin, 2004; Swaminathan & Alexander, 2006). Indeed, by age 75, many older adults have significantly elevated PP and may be at increased risk for comorbid illness, including cardiovascular disease, stroke, all-cause mortality, and early and/or accelerated dementia onset (Scuteri et al., 2007).

Higher PP (i.e., >60 mmHg) in older age also relates to lower performance on tests of memory, processing speed, and executive functions (Dahle, Jacobs, & Raz, 2009; MacDonald, DeCarlo, & Dixon, 2011; Raz, Dahle, Rodrigue, Kennedy, & Land, 2011; Waldstein et al., 2008). White matter pathology and small vessel disease resulting from arterial stiffening are suggested as potential mechanisms underlying these associations (Scuteri et al., 2007; Swaminathan & Alexander, 2006). Notably, the cognitive domains affected by high PP are also linked to reduced ToM, which raises the possibility that high PP may be associated with variations in ToM. To address this question, we assessed PP as a surrogate marker of vascular risk and examined its association with ToM performance in older age.

To this end, we investigated the roles of age, traditional cognitive abilities, and vascular health in predicting individual differences in ToM. Existing models of ToM in aging presume that intact functioning of underlying cognitive abilities is necessary for mental state reasoning across contexts (Kemp et al., 2012). Accordingly, one may expect other processes (e.g., poor vascular health) to influence ToM insomuch as they are associated with the same underlying cognitive abilities. Because previous work demonstrates direct and indirect associations between blood pressure and cognitive performance (Thornton, Deria, Gelb, Shapiro, & Hill, 2007; Yeung & Thornton, 2011), a primary question motivating this study was whether PP is a useful independent predictor and/or modifier of ToM performance in older age. First, given previously reported associations between high PP and decreased cognitive performance (Raz et al., 2011; Waldstein et al., 2008), we predicted that PP would relate directly to ToM, such that higher PP would be associated with reduced ToM. Our second aim was to examine PP as a potential modifier of associations between ToM and cognitive performance. We predicted that high PP would moderate ToM, thereby affecting the strength of associations between ToM and underlying cognitive abilities.

METHOD

Participants

We recruited 66 community-dwelling older adults (65–92 years) from the Vancouver area using newspaper advertisements and flyers. Testing occurred in one session at the Simon Fraser University (SFU) Cognitive Aging Laboratory and took approximately 2.5 hr. Participants completed a battery of measures assessing blood pressure, health and demographics, ToM, and traditional cognitive abilities. Trained research assistants administered these measures to participants individually and scored the measures using standardized procedures. Participants received $20 remuneration for their time and travel expenses. All participants met the following inclusion criteria: (a) English fluency as screened by an acculturation measure (Thornton et al., 2007), (b) minimum grade 6 education, and (c) no major impairments in vision (corrected vision ≤ 20/50), hearing, or other sensory/motor functions. We screened eligibility using a questionnaire developed to assess general medical history (Thornton et al., 2007). Participants were ineligible if they reported a history of diagnosed cognitive impairment and/or dementia, color-blindness, or any concurrent major illness with known central nervous system effects. All participants reported alcohol consumption of less than 3 oz/day. We also collected information regarding the presence and severity of vascular illness, including any relevant medications taken at the time of testing. We screened global cognitive status using the Mini-Mental Status Examination (MMSE; Folstein, Folstein, & McHugh, 1975). No participant scored less than 24, a cutoff recommended by current standards to control for undiagnosed cognitive impairment (Lezak, Howieson, & Loring, 2004). The SFU Research Ethics Board approved all study protocol.

Measures

Blood pressure.—We took four separate blood pressure readings at the beginning of the testing session for each participant using an automatic oscillometric upper arm monitor, on the right arm unless contraindicated (A&D LifeSource, Model Number: UA-774). After an initial reading to ensure comfort with the protocol, participants rested with the cuff in place for 5 min. Next, we took three individual readings, separated by 1-min rest intervals. Administrators faced away from participants during readings to minimize the effects of observation. These protocols meet current standards for blood pressure assessment in research settings (Campbell, Joffres, & McKay, 2005). We derived our PP variable of interest by averaging the difference of the last three SBP and DBP readings (PP = SBP − DBP).

Theory of mind.—In the Strange Stories test, participants' reasoning about different mental states (ToM stories) was compared with their reasoning about the physical causality of events (control stories; Happé, 1994). This short story paradigm is designed to tease apart circumscribed errors in ToM from more global errors in story comprehension and is frequently used in studies of ToM and aging (e.g., Charlton et al., 2009; Maylor et al., 2002; Sullivan & Ruffman, 2004). We used a subset of eight stories that were published in Happé and colleagues (1998) and were selected based on aging-relevant content. The four ToM stories required participants to reason about the mental states of multiple characters (e.g., decide whether a character was lying, infer the intentions of a character playing on another character's sympathy). In contrast, the four control stories did not involve mental states but required inferences about physical outcomes beyond what was stated explicitly (e.g., compare item costs, make decisions given outcome information). One critical question assessed participants' reasoning about each story and took the form "Why did [the character] say/do that?" Examples of ToM and control stories have been published previously in Happé et al. (1998).

Participants viewed the stories alongside black and white drawings depicting significant characters and were encouraged to take the reading time necessary to ensure complete understanding. Administrators recorded participants' responses verbatim and scored them according to criteria outlined in Happé and colleagues (1998) (2 = complete and accurate, 1 = partial or implied, and 0 = incorrect or irrelevant). When participants provided both correct and incorrect responses, the better answer received full credit. Similarly, if a response contained both mental state and non–mental state inferences, it was scored for the mental state. Three independent raters scored all responses with high inter-rater agreement ($r = .94$). Scores were summed to create variables representing ToM and control performance (range = 0–8 for each). High scores on the ToM stories reflected accurate understanding of mental states, whereas high scores on control stories reflected good reasoning and comprehension of story material.

Verbal memory.—Verbal memory was assessed with the California Verbal Learning Test-II (Delis, Kramer, Kaplan, & Ober, 2000). Participants were presented with 16 words over 5 learning trials. Recall was assessed after each learning trial, after an interference trial, and again after a 20-min delay. Participants' raw scores from the delayed free recall trial reflected verbal memory.

Executive functions.—The Trail Making and Color–Word Interference tests from the Delis–Kaplan Executive Function System were used to examine mental flexibility and cognitive inhibition (Delis, Kaplan, & Kramer, 2001). For the Trail Making test, we used the commonly reported "Trails B" (number–letter switching) condition to assess mental flexibility. For the Color–Word Interference test, or "Stroop" test, participants had to inhibit their dominant verbal response (word reading) in favor of a less dominant response (color naming). Because these tests measure performance by time to completion, we used recommended procedures to minimize the effect of processing speed by subtracting the baseline (i.e., processing speed) conditions from the mental flexibility and cognitive inhibition conditions, respectively (Delis et al., 2001). We assessed working memory using the Wechsler Adult Intelligence Scale-III (WAIS-III; Wechsler, 1997) Letter–Number Sequencing subtest. In this test, administrators read aloud sequences containing numbers and letters. Participants recalled each sequence stating first the numbers in ascending order, followed by the letters in alphabetical order. The number of sequences correctly recalled reflected working memory.

Processing speed.—Processing speed was assessed using the WAIS-III Digit Symbol Coding test (Wechsler, 1997). In this test, participants quickly and accurately matched numbers to symbols contained in a coding key. The number of symbols correctly transcribed within 120 s reflected processing speed.

Statistical Analysis

Across all relevant variables, we identified 6 data points (out of 1,122 possible, 0.5% of the data) as extreme outliers (>3 *SD* from the mean) and altered these to be more contiguous with the rest of the data while maintaining their distal-most rank as recommended by Tabachnick and Fidell (2007). Indicators of normality suggested that the ToM data fell within the normal range and satisfied requirements for parametric testing (Tabachnick & Fidell, 2007). We used a series of hierarchical regression analyses to test our hypotheses of interest. Prior to conducting the regression analyses, we examined bivariate Pearson and partial correlations between ToM and the cognitive, blood pressure, and demographic predictors to identify variables important for inclusion in the regression model. To reduce the possibility of capitalizing on chance associations, we included only those variables in the regression model that showed significant ($p < .01$) correlations with ToM.

Our first aim was to examine the prediction that PP would account for unique variance in ToM beyond age and traditional cognitive abilities. Entry into the regression model comprised three steps corresponding to demographic, cognitive, and PP influences on ToM (Step 1 = age/demographic covariates, Step 2 = cognitive performance, and Step 3 = PP). We predicted that participants with the highest PP readings would show the lowest ToM performance.

Our second aim concerned PP as a potential modifier of ToM performance. We predicted that PP would moderate associations between ToM and cognitive functioning, as evidenced by a significant interaction between PP and cognitive performance. To test moderation, we centered continuous predictors and calculated interaction terms as product vectors of the centered variables (cognitive performance × PP). We entered the interaction terms hierarchically after the main predictors and age (Cohen, Cohen, Aiken, & West, 2003). We also tested whether quadratic and logarithmic transformations of PP better characterized the blood pressure data (Waldstein, Giggey, Thayer, & Zonderman, 2005). All analyses were conducted using SPSS 19.0 software (SPSS Inc., Chicago, IL).

Table 1. Demographic and Clinical Characteristics

Variables	Participants (*N* = 66)	Range
Age (years)	73.49 ± 5.78	65–92
Female (*n*; %)	39; 59.10	
Ethnicity (% Caucasian)	86.40	
Education (years)	14.45 ± 2.81	8–20
MMSE	28.80 ± 1.10	25–30
Hypertension (*n*; %)	29; 43.90	
PP (mmHg)	54.20 ± 14.78	31–96
SBP (mmHg)	126.59 ± 18.35	95–179
DBP (mmHg)	72.38 ± 8.94	52–91
Cardiovascular risks (% diagnosed)[a]		
Hypertension	43.94	
Type 2 diabetes	12.12	
High cholesterol	39.39	
Cardiovascular disease	18.18	
History of stroke	6.06	
Smoking Status (% current)	6.06	

Notes. Unless otherwise indicated, means and standard deviations are presented as $M \pm SD$. MMSE = Mini-Mental Status Examination; SBP = systolic blood pressure; DBP = diastolic blood pressure; PP = pulse pressure.

[a] Cardiovascular risk percentages include all individuals who self-reported a physician's diagnosis of a cardiovascular illness and reported relevant medication and/or lifestyle modification for treatment.

RESULTS

Descriptive Characteristics and Data Reduction

Table 1 presents descriptive information regarding sample demographics and health characteristics. High mean years of education (M = 14.45, SD = 2.81) and MMSE scores greater than 28/30 (M = 28.80, SD = 1.10) indicate that the sample was well educated and had intact global cognitive status. As seen in Table 1, 43.9% of the sample reported a physician's diagnosis of hypertension, which falls slightly below prevalence estimates for North American adults aged 65 years and older (i.e., 58% women and 53% men; Roger et al., 2012).

Preliminary Analyses

We first assessed bivariate correlations between ToM and cognitive performance to determine which cognitive variables to include in the regression analyses (Table 2). Regarding the individual cognitive measures, reduced ToM was associated with lower performance on tests of verbal memory (r = .35, p = .004), processing speed (r = .31, p = .01), and working memory (r = .32, p = .01). We found no association between ToM and our measures of mental flexibility or cognitive inhibition (Table 2). To reduce potential collinearity between cognitive predictors in the regression model, we considered the formation of a composite variable using the cognitive predictors associated with ToM: verbal memory, processing speed, and working memory. Verbal memory and processing speed were significantly associated (r = .55, p < .001) and therefore converted to z-scores, summed, and rescaled to create a composite z-score reflecting memory and speeded cognitive performance (memory/speed; Edgington, 1995). Working memory was weakly associated with verbal memory (r = .16, p = .21) and processing speed (r = .20, p = .10) and was therefore analyzed separately as an independent z-score variable.

Table 2. Mean Performance and Correlations With Theory of Mind (ToM) for Individual Cognitive Measures

Cognitive Measure	Mean (*SD*)	ToM Stories *r*	Control Stories *r*
CVLT-II delayed recall[a]	8.76 (3.41)	.35**	.07
Letter–number sequencing[a]	9.30 (2.80)	.32*	.07
Digit symbol coding[a]	55.56 (10.81)	.31*	.13
Trail Making (mental flexibility)[b]	1.60 (.88)	–.18	–.02
Color–word (cognitive inhibition)[b]	0.97 (.37)	–.00	.03
Control stories[a]	6.27 (1.46)	.30*	—
ToM stories[a]	5.63 (1.66)	—	—

Notes. CVLT = California Verbal Learning Test-II.

For the Trail Making and Color-word tests, values presented were calculated based on derived scores of mental flexibility and cognitive inhibition where the influence of processing speed has been subtracted out.

[a] Higher scores = better performance.

[b] Lower scores = better performance.

*p = two-tailed correlation < .05. **p < .01. ***p < .001.

Consistent with the individual predictors, low scores on the memory/speed composite were associated with reduced ToM (r = .37, p = .002; Table 3). To determine whether general story comprehension could account for ToM–cognition associations, we assessed partial correlations between ToM and cognitive performance while controlling for control stories. The association between reduced ToM and lower memory/speed remained significant after accounting for control stories (partial r = .36, p = .003), suggesting that this

Table 3. Intercorrelations Among Demographic Variables, Cognitive Function, Theory of Mind (ToM), and Pulse Pressure (PP)

Variables	ToM	2	3	4^a	5	6	7	8	9	10	11
1 ToM stories	—										
2 Control stories	0.30*	—									
3 Age	−0.27*	0.09	—								
4 Gender^a	0.21	0.11	−0.22	—							
5 Years of education	0.26*	0.10	−0.04	0.10	—						
6 Memory/speed	0.37**	0.11	−0.37**	0.51***	0.14	—					
7 Working memory	0.32*	0.11	−0.21	0.09	0.24	0.21	—				
8 PP	−0.23^b	−0.10	0.07	−0.05	−0.17	−0.16	−0.27*	—			
9 SBP	−0.23	−0.08	−0.03	−0.07	−0.16	−0.05	−0.17	0.88***	—		
10 DBP	−0.09	−0.01	−0.18	−0.06	−0.06	0.15	0.08	0.14	0.60***	—	
11 Diagnosed hypertension	−0.19	−0.17	−0.12	−0.01	−0.21	−0.21	−0.20	0.26*	0.22	0.02	—
12 Antihypertensive use	−0.10	−0.18	−0.09	0.05	−0.18	−0.11	−0.16	0.02	−0.06	−0.15	0.82***

Notes. N = 66; ToM = raw score on ToM stories; Control = raw score on control stories; Memory/speed = summed z-score composite reflecting performance on tests of verbal memory and processing speed (higher scores = better performance); Working memory = z-score for performance on the Letter–Number Sequencing test (higher scores = better performance). Diagnosed hypertension and antihypertensive use reflect dichotomous variables (0 = no; 1 = yes). SBP = systolic blood pressure; DBP = diastolic blood pressure.

^{a}0 = male, 1 = female.

$^b p = .06$.

*p = two-tailed correlation < .05. **$p < .01$. ***$p < .001$.

association was independent of general story comprehension. The association between lower working memory and reduced ToM was attenuated after accounting for control stories (partial $r = .15$, $p = .25$).

Next, we assessed bivariate associations between ToM and blood pressure (Table 3). High PP correlated with high SBP ($r = .88$, $p < .001$) but not with DBP. None of the blood pressure predictors displayed a significant correlation with age. Given the strong SBP–DBP association ($r = .60$, $p < .001$), we examined only PP in the regression model as planned to reduce potential collinearity in our measure of vascular risk. We observed a small-medium association between high PP and reduced ToM that approached statistical significance ($r = -.23$, $p = .06$). High PP was also associated with reduced working memory ($r = -.27$, $p = .03$) but not with the memory/speed composite.

To determine which demographic variables to include in the regression model, we assessed partial correlations between ToM and cognitive performance, while controlling for age, education, and gender. Associations between ToM and memory/speed remained significant after controlling for age (partial $r = .30$, $p = .01$), education (partial $r = .35$, $p = .004$), and gender (partial $r = .32$, $p = .01$), suggesting that demographics did not influence associations between ToM and memory/speed. In contrast, the association between ToM and working memory was attenuated after accounting for age (partial $r = .16$, $p = .21$), education (partial $r = .10$, $p = .44$), and gender (partial $r = .15$, $p = .24$). To maximize statistical power, we retained only age as a covariate given its theoretical importance to our hypotheses.

Main Analyses

Participants performed worse on ToM than control stories, $t(65) = -2.79$, $p < .01$, indicating that age reductions were specific to mental state reasoning and not due to difficulties in general story comprehension. Better performance on the control stories was associated with increased ToM ($r = .30$, $p = .01$); however, the control stories were not significantly associated with any demographic, blood pressure, or traditional cognitive variables. Based on the bivariate associations described earlier, we examined memory/speed, working memory, and PP as predictors of ToM. Although the association between ToM and working memory was attenuated by accounting for demographic covariates, we included working memory as a predictor in the regression model given strong empirical support for its association with both ToM and PP (e.g., German & Hehman, 2006; McKinnon & Moscovitch, 2007; Raz et al., 2011).

Our first aim was to examine whether PP predicted individual differences in ToM over and above age and cognitive performance (Table 4). As predicted, older age predicted reduced ToM ($\beta = -0.27$, $p = .03$). The memory/speed composite predicted significant variance in ToM, such that reduced ToM was associated with lower scores on the memory/speed composite ($\beta = 0.28$, $p = .003$). Lower working memory also predicted reduced ToM ($\beta = 0.23$, $p = .05$), although this association was attenuated when PP was added to the regression model. Altogether, cognitive performance accounted for 14% of the variance in ToM, $\Delta R^2 = 0.14$, $F(2, 62) = 5.34$, $p = .01$. On its own, PP did not account for significant variability in ToM ($\beta = -0.18$, $p = .14$). We tested whether quadratic and logarithmic transformations of our PP variable might better characterize PP associations with ToM, but similar to others, we found no statistical advantage using this approach (Waldstein, Giggey, et al., 2005).

Our second aim was to examine potential modifiers of the ToM–cognition relationship. To evaluate our prediction that elevated PP moderates associations between ToM and cognitive performance, we calculated interaction terms for memory/speed × PP and working memory × PP and entered them hierarchically after age and the main effects in our regression model (Cohen et al., 2003). We observed a significant interaction between memory/speed and PP ($\beta = 0.26$, $p = .02$ but not between working memory and PP ($\beta = 0.06$, $p = .63$). We ran a final regression model examining moderation by removing all nonsignificant variables from the previous analysis (working memory, working memory × PP interaction term). Together, the final model accounted for 26% of variance in ToM, with the memory/speed × PP interaction accounting for 7% of unique variance in ToM performance (Table 4).

Table 4. Final Regression Model Summarizing Significant Main and Interaction Effects

Predictors	*B*	*SE*	β	*P*	R^2
Step 1					
Age	−0.08	0.04	−0.27	.03	
R^2					.07
Step 2					
Age	−0.04	0.04	−0.15	.22	
Memory/speed	0.48	0.21	0.29	.02	
PP	−0.02	0.01	−0.18	.14	
ΔR^2					.12
R^2					.19
Step 3					
Age	−0.06	0.04	−0.20	.10	
Memory/speed	0.40	0.20	0.24	.05	
PP	−0.02	0.01	−0.19	.10	
Memory/speed × PP	0.03	0.01	0.27	.02	
ΔR^2					.07
R^2					.26

Note. PP = pulse pressure.

We used recommended cutoffs for clinically elevated PP to depict interaction effects graphically according to PP level as follows: high PP was defined as PP ≥ 60 mmHg and low to normal PP was defined as PP < 60 mmHg (Swaminathan & Alexander, 2006). As seen in Figure 1, older adults with high PP displayed a strong association between reduced ToM and lower memory/speed ($r = .63$, $p = .002$). This association was not apparent among older adults with low to normal PP ($r = .18$, $p = .26$).

DISCUSSION

To our knowledge, this is the first study to examine vascular health as a predictor of ToM performance in aging. Our results support and extend previous work in ToM and aging in several important ways. First, as expected, participants

Regression Slopes for the Effects of Memory/Speed, PP, and their Interaction on ToM Performance

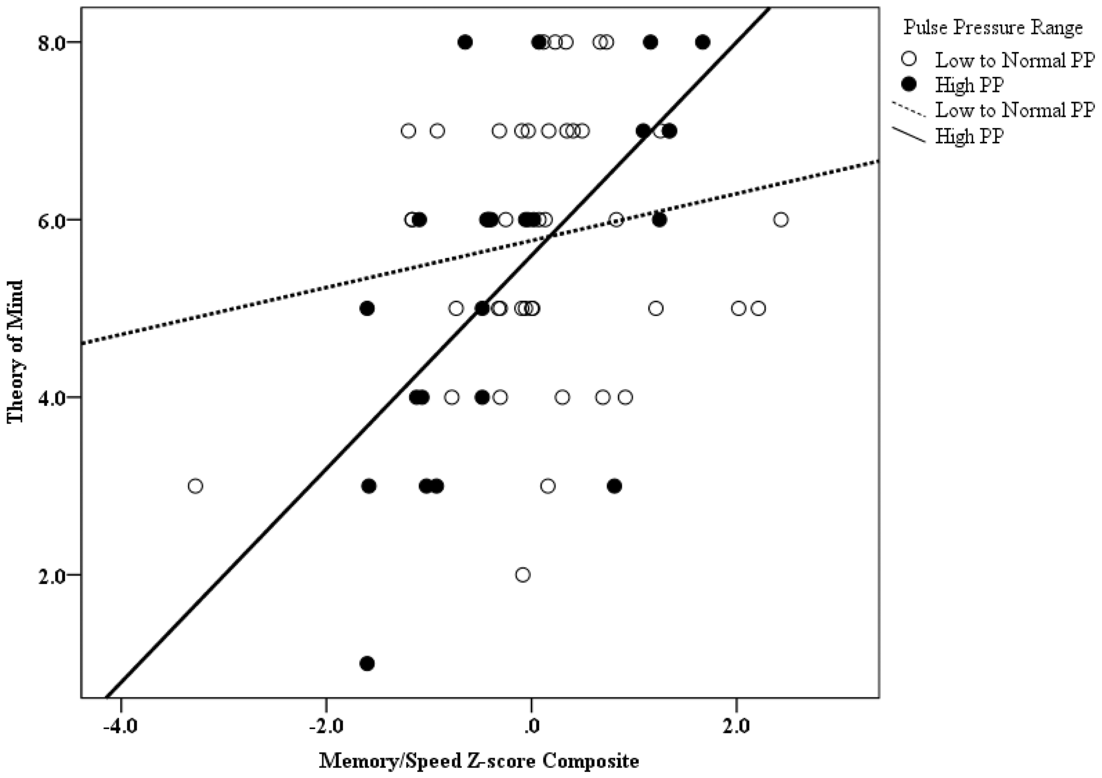

Figure 1. Low to normal pulse pressure (PP) is equal to PP < 60mmHg. The low to normal PP group contained 44 older adults, whose PP range was equal to 31–59 mmHg (mean ± *SD* = 45.61 mmHg ± 7.43). High PP is equal to PP ≥ 60 mmHg. The high PP group contained 22 older adults, whose PP range was 60–96 mmHg (mean ± *SD* = 71.39 mmHg ± 9.94).

performed worse on ToM than control stories. Although the control stories were significantly associated with ToM, they displayed no association with age, blood pressure, or any of the cognitive measures, perhaps due to the less demanding nature of these items (Charlton et al., 2009). This suggests that the age reductions captured by the Strange Stories test are specific to mental-state reasoning and not due to general difficulties in reasoning about stories. Second, consistent with previous research, we found that reduced ToM was associated with decreased performance on tasks of verbal memory, processing speed, and working memory but not with other executive functions (German & Hehman, 2006; Maylor et al., 2002; McKinnon & Moscovitch, 2007). Third, an important novel contribution of this study is that we demonstrated that associations between reduced ToM and lower memory and processing speed were qualified by vascular health, specifically, individuals with poor vascular health showed stronger associations between ToM and memory and processing speed.

Our finding that decreased verbal memory and processing speed were associated with reduced ToM in older age is consistent with the work of German and Hehman (2006) and Maylor and colleagues (2002), who found that processing speed and memory were the most robust predictors of ToM on story-based tests. We also found that lower working memory predicted reduced ToM; however, this association was attenuated when PP was added to the regression model. Though this finding contrasts with McKinnon and Moscovitch's (2007) report that working memory is essential for ToM performance, it is in line with other cognitive aging research suggesting that associations between ToM and working memory disappear when other predictors of ToM are modeled concurrently (i.e., processing speed, cognitive inhibition; German & Hehman, 2006).

Similarly, our finding that aspects of executive functions (mental flexibility and cognitive inhibition) were unrelated to ToM in older age is inconsistent with some previous research (Bailey & Henry, 2008; Duval et al., 2011; McKinnon & Moscovitch, 2007). One reason for this discrepancy is that past research has often examined composite indicators of executive functions instead of assessing individual aspects as in the current study (Charlton et al., 2009; Duval et al., 2011). Moreover, those studies that have examined individual aspects have not reliably minimized the influence of processing speed in their measures (Duval et al., 2011; Phillips et al., 2011). This is important because tests of executive functions are often timed, and thus cannot be considered "pure" measures when raw scores are used without correction. Together these findings suggest that age reductions in ToM most likely reflect underlying changes specific to cognitive operations associated with memory and processing speed. Accordingly, the usefulness of individual cognitive variables in predicting ToM appears to be limited by their associations with other cognitive abilities (processing speed, in particular) as well as by vascular health. It is prudent that future researchers consider interrelationships among specific predictors of ToM carefully when assessing links between ToM and cognitive performance in later life.

Although the association between ToM and PP approached significance ($r = -.23$, $p = .06$), we found that PP was an important moderator of ToM, wherein elevated PP exacerbated the effects of age reductions in memory and processing speed on ToM performance. Specifically, older adults with the highest PP readings showed the strongest links between reduced ToM and lower memory/speed, whereas associations were considerably weaker among older adults with low to normal PP. This interaction explained 7% of the variance in ToM beyond age, cognitive performance, and PP alone, and highlights the important role played by vascular health in understanding how ToM changes with advancing age. Assuming that ToM relies on a diverse cortical network (Abu-Akel & Shamay-Tsoory, 2011), functional disruptions related to arterial stiffening may underlie declines in memory and processing speed and thereby influence ToM (Swaminathan & Alexander, 2006). It is also possible that PP is simply a marker for systemic cerebrovascular burden. Thus, older adults with poorer overall vascular health may be especially vulnerable to reductions in cognitive functioning (MacDonald et al., 2011; Raz et al., 2011).

Our results should be considered within the context of certain limitations. First, our sample was comprised of healthy, well-educated individuals with lower rates of hypertension than generally reported among older adults (Roger et al., 2012). Likewise, we excluded individuals with concurrent major illness, including severe vascular comorbidity, which artificially lowered the range of PP we were able to assess and may have weakened the associations we observed (PP range = 31–96 mmHg, compared with previous 22–161 mmHg, Robbins, Elias, Elias, & Budge, 2005; 18–136 mmHg, Waldstein et al., 2008). Our power to detect small effects was restricted by the sample size, and we expect that the association between PP and ToM ($p = .06$) would become significant within a larger sample (Cohen et al., 2003). Nonetheless, our findings align with previous reports of associations between vascular health and cognitive functioning in healthy aging samples (Dahle et al., 2009; Yeung & Thornton, 2011). Future studies targeting older adults with greater medical comorbidity and cognitive variability will be necessary to elucidate the role of vascular integrity in maintaining ToM in older age.

A caveat of the ToM literature in general is that ToM tests vary widely across studies, thereby making the interpretation and applicability of our findings to extant research challenging (see Moran, 2013 for an overview of this issue). Low correlations among ToM tests suggests that ToM is a multifaceted construct and further implies that cognitive and health predictors may display different associations depending on how ToM is operationalized and theoretically defined (e.g., written stories *vs* video tests; Bernstein et al., 2011; Duval et al., 2011). Thus, it will be prudent for future research to pay attention to the conceptualization and measurement of ToM and its underlying predictors.

Finally, although PP and SBP are both considered optimal predictors of vascular risk in older age (Haider et al., 2003), some authors have argued that SBP may be prognostically superior (Oliver & Webb, 2003). One reason for this controversy involves the derivation of PP from its static blood pressure components (SBP and DBP). After age 60, SBP steadily rises, whereas the trajectory of DBP is less stable (Nichols et al., 2011). As such, the measurement of DBP may introduce error into PP indices, though this error is minimized in individuals with normal to high–normal blood pressure, such as in this study (Pannarale et al., 1993). Thus, we feel that PP, as derived by oscillometric measurement, was valid for our purpose of establishing preliminary associations among ToM, cognitive performance, and vascular health to inform ongoing research on ToM in aging. However, we acknowledge that more sophisticated noninvasive measures of arterial stiffening are needed in future studies to directly address the hypothesis that decreased arterial compliance underlies associations with cognitive performance (e.g., carotid–femoral pulse wave velocity or systolic pulse contour analysis; Elias et al., 2009).

In conclusion, we demonstrated that age changes in ToM were driven in part by age-related reductions in memory and processing speed. Although working memory was also associated with ToM, this association was attenuated after accounting for demographic characteristics (age, gender, and education) and PP. Importantly, we found that the relationship between ToM and memory and processing speed is qualified by vascular health, namely, participants with poor vascular health showed stronger associations between ToM and memory/speed. Together, these findings provide important groundwork for future investigation into how and under what conditions cognitive and health mechanisms adversely affect older adults' ToM.

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