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Research Article

Does Cognitive Impairment Influence Visual-Somatosensory Integration and Mobility in Older Adults?

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Abstract

Background: Deficits in visual-somatosensory (VS) integration are linked to poor mobility. Given that sensory, motor, and cognitive processes rely on overlapping neural circuitry that are compromised in dementia and pre-dementia stages like mild cognitive impairment (MCI), we hypothesize that cognitive impairment will be associated with reduced VS integration, which will, in turn, impact the relation between VS integration and mobility.

Methods: A total of 345 older adults (mean age 76.88 ± 6.45 years; 52% female) participated in the current study. Cognitive impairment was defined as presence of MCI or dementia. Magnitude of VS integration was quantified using probability models. All participants completed assessments of general cognition (Repeatable Battery for the Assessment of Neuropsychological Status; RBANS), quantitative gait, and balance (unipedal stance).

Results: The magnitude of VS integration was lower in the 40 individuals with MCI (p = .02) and 12 with dementia (p = .04), relative to the 293 individuals without cognitive impairment. In fully adjusted models, magnitude of VS integration was only a strong predictor of performance on attention-based tests of the RBANS (β = 0.161; p < .01), regardless of cognitive status. Results from mediation analyses, however, reveal that cognitive impairment causes variation in magnitude of VS integration, which in turn causes variation in unipedal stance 95% confidence interval (CI) (−0.265, −0.002) and spatial aspects of gait 95% CI (−0.087, −0.001).

Conclusions: Cognitive impairment influences multisensory integration, which adversely impacts balance and gait performance in aging. Future studies should aim to uncover the precise neural circuitry involved in multisensory, cognitive, and mobility processes.

Keywords: Dementia, Multisensory processing, Sensorimotor integration, Cognition, Mobility

Aging presents many challenges to the central nervous system, which concurrently disrupt cognitive, sensory, and motor functionality (1). Mobility disorders are common in dementia and pre-dementia stages like mild cognitive impairment (MCI) (2,3). Associations between cognition, specifically attention and executive functioning, and motor outcomes including gait (3–5), balance (6,7), and falls (8,9) have been well-established.

Gait, balance, and falls are individually associated with integration of visual and somatosensory inputs in aging (10,11). This is likely the result of motor and sensory processes relying on similar cortico-cortical, cortical-subcortical, and cortico-thalamic transmissions (12–16). We described a protective effect of visual-somatosensory (VS) integration abilities, whereby greater ability to integrate VS information was associated with better balance and decreased risk of falls (11). As well, greater VS integration was also associated with better gait performance, particularly with regards to spatial aspects of gait (10).

While our studies demonstrate that inefficient VS integration is linked to increased falls and poor gait, they fail to determine the potential influence, if any, of cognitive impairment on this association. There is a good reason to suspect that cognitive impairment will impact the association between VS integration and mobility, since selective attention is known to modulate multisensory integration processes (17,18) and disruption in executive attention involving prefrontal and frontal regions also compromises mobility (4,19).

To the best of our knowledge, the links between multisensory integration, mobility, and cognitive impairment have not been formally investigated. Given that these processes rely on similar fronto-subcortical-thalamic neural circuits, the main objectives of the current study were to (a) establish the link between the magnitude of VS integration and cognition and (b) determine whether cognitive impairment impacts the association of VS integration with gait and balance. We hypothesize that impairments in cognition will be associated with reduced magnitude of VS integration, which will, in turn, impact the relation between VS integration and balance/gait performance.

Materials and Methods

Three hundred ninety-five participants enrolled in the longitudinal Central Control of Mobility in Aging study in New York also completed a cross-sectional multisensory simple reaction time (RT) experiment between June 2011 and June 2018 (herein referred to as VSI study). Central Control of Mobility in Aging eligibility criteria required that participants be 65 years of age and older, reside in lower Westchester County, and speak English. Exclusion criteria included inability to independently ambulate, dementia diagnosis at baseline, significant bilateral vision and/or hearing loss, active neurological, or psychiatric disorders that would interfere with evaluations, recent or anticipated medical procedures that would affect mobility, and/or receiving hemodialysis treatment.

All participants undergo yearly clinical, psychological, neuropsychological, sensory, motor evaluations that typically take place over two testing sessions during a 1- to 2-week duration, depending upon the participant's availability. All participants were required to have bilateral visual acuity that was better or equal to 20/100 as measured by the Snellen eye chart. Individuals that were unable to hear a 2,000 Hz tone at 25 dB in both ears were not included in the VSI study. Presence or absence of neuropathy was diagnosed by study clinicians and participants with severe neuropathy (unable to feel somatosensory stimulation) were excluded (20). Additional exclusion criteria included inadequate multisensory behavioral performance (n = 44; see below) and missing clinical case consensus diagnosis (n = 6).

After exclusions, the overall study cohort consisted of 345 older adults (mean age 76.88 ± 6.45 years; 52% female). All participants provided written informed consent to the experimental procedures, which were approved by the institutional review board.

Experimental Design

Participants completed a simple RT paradigm employing three sensory conditions that were presented bilaterally: two unisensory (visual and somatosensory) and one multisensory (simultaneous VS). Specific details regarding the multisensory experimental protocol, equipment, and data processing procedures are available (21). Briefly, participants were instructed to respond to all stimuli by pressing a stationary foot pedal as quickly as possible (Figure 1a). The three stimulus conditions were presented randomly with equal frequency and consisted of three blocks of 45 trials (135 trials in total; Figure 1b). Anticipatory effects were prevented by utilizing an inter-stimulus-interval that varied randomly from 1 to 3 seconds. Each block was separated by a 20-second break in order to reduce fatigue and facilitate concentration.

Performance accuracy was defined as the number of accurate stimulus detections divided by 45 trials per condition. Data trimming

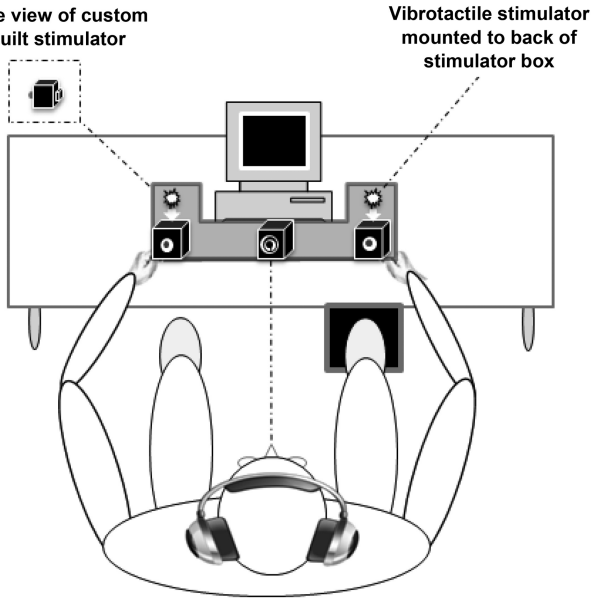

Figure 1. Experimental Apparatus: Participants were required to make speeded responses to bilateral visual, somatosensory, and visual-somatosensory stimuli by pressing a foot pedal located under their right foot (20).

procedures were purposefully avoided so as to not bias the distribution of RT data, and RTs for all inaccurate (ie, omitted) trials were set to infinity (22). As in our previous studies, participants with unreliable data (accuracy less than 70% [n = 41] and extremely long RTs > 1,100 ms [n = 3]) were excluded (10,11,20,23).

Visual and somatosensory stimuli were delivered through a custom-built stimulus generator (Zenometrics, LLC; Peekskill, NY) that consisted of two control boxes, each housing a 15.88 cm diameter blue light emitting diodes and a 30.48 × 20.32 × 12.70 mm plastic housing containing a vibrator motor with 0.8G vibration amplitude. A TTL (transistor-transistor-logic, 5 V, duration 100 ms) pulse was used to trigger the visual and somatosensory stimuli through E-Prime 2.0 software.

Control boxes were mounted to an experimental apparatus, which participants rested their hands upon comfortably, with index fingers placed over the vibratory motors on the back of the box and their thumb on the front of the box, under the light emitting diode (Figure 1a). A third dummy control box was placed in the center of the actual control boxes, at an equidistant length (28 cm) and contained a bull's eye sticker with a central circle of 0.4 cm diameter that served as the fixation point. To ensure that the somatosensory stimuli were inaudible, each participant was provided with headphones over which continuous white noise was played.

Quantification of Multisensory Integration Using the Race Model Inequality

The methods employed for quantifying magnitude of VS integration have been comprehensively outlined (21). Briefly, robust probability (P) models that compare the cumulative distribution function (CDF) of combined unisensory visual (V) and unisensory somatosensory (S) reaction times with an upper limit of one [min ($P(RT_V \leq t) + P(RT_S \leq t)$, 1)] to the CDF of multisensory VS reaction times [$P(RT_{VS} \leq t)$] were used (24,25). For any latency t, the race model inequality

(RMI) *holds* when the CDF of the "actual" multisensory condition [$P(RT_{VS} \leq t)$] is less than or equal to the "predicted CDF" [min ($P(RT_V \leq t) + P(RT_S \leq t)$, 1)]. When the "actual CDF" is greater than the "predicted CDF," the RMI is *rejected* and the RT facilitation is the result of multisensory interactions that allow signals from redundant information to integrate or combine nonlinearly.

Figure 2a depicts the group-averaged difference between "actual" and "predicted" CDFs (dashed trace) for the entire cohort, where positive values (shaded area between 0 and 10th percentile) are indicative of VS integration (ie, violation of the race model). The RMI was tested using Gondan's permutation test over the fastest 10% of responses. A robust violation was observed $t_{max} = 13.93$, $t_{crit} = 2.18$, $p < .001$ (22,26). As in our most recent work, the *area under the curve* (AUC) during the violated percentile bins (0–10th) served as the independent measure of "magnitude of VS integration" (10,11).

Clinical Evaluation

As part of the Central Control of Mobility in Aging study, individuals participated in a neuropsychological battery that provided comprehensive assessment of cognitive function, which has been validated in our previous longitudinal studies (27). Global cognitive function was assessed using the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) which is a validated cognitive assessment with established test–retest reliability and age-appropriate normative data (28). The RBANS measures attention, immediate memory, delayed memory, language, and visuospatial skills, as well as global cognitive functioning.

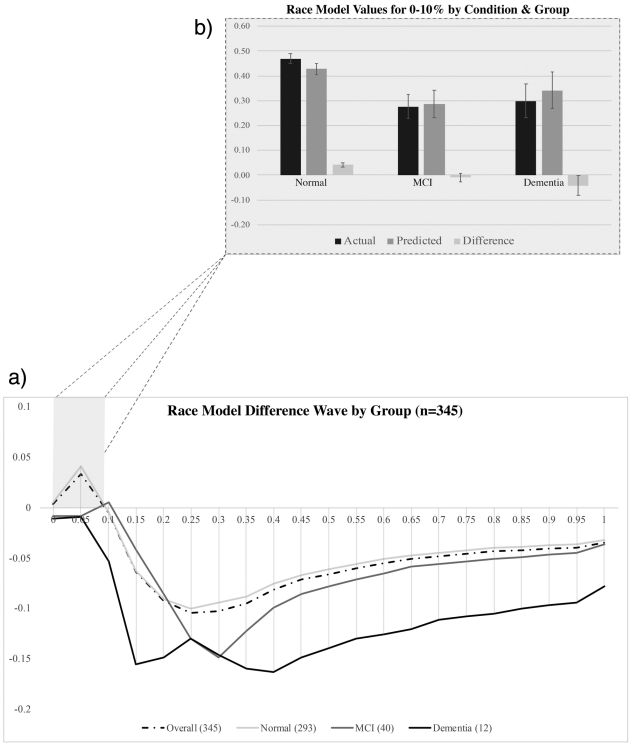

Figure 2. Test of the race model. **(a)** The cumulative distribution function (CDF) difference waves over the trajectory of averaged responses for the entire study cohort (dashed trace) and for each of the three cognitive status groups (solid traces). **(b)** Race model values (area-under-the-curve values during the 0–10th percentiles) for actual and predicted conditions, along with their difference (positive values represent violation of the race model inequality [RMI]).

Cognitive status (normal, MCI, or dementia) was assessed at baseline and again during yearly follow-up visits using reliable cut-scores from the AD8 Dementia Screening Interview cutoff score ≥2 (29); and the Memory Impairment Screen (MIS) cutoff score < 5 (30). A multidisciplinary clinical team conducted consensus case conferences where participant's demographic, neuropsychological, neurological, psychosocial, and functional test data were reviewed, and cognitive status diagnosis (normal, MCI, or dementia) was assigned yearly (31). Here, cognitive impairment was defined as presence of either MCI or dementia at current VSI study wave.

Global health scores (GHS; range 0–10) were obtained from dichotomous ratings (presence/absence) of physician-diagnosed diabetes, chronic heart failure, arthritis, hypertension, depression, stroke, Parkinson's disease, chronic obstructive pulmonary disease, angina, and myocardial infarction (20,23).

Motor Outcomes

Mobility measures included balance and gait (ie, pace factor), given their previously established link with VS integration in older adults (10,11,23). Static balance was assessed using the unipedal stance time test (32,33). This test was administered twice, and participants' stance time on one leg for a maximum of 30 seconds served as the outcome measure.

Quantitative gait assessments were conducted using a 28-foot instrumented walkway with embedded pressure sensors that provide various spatial and temporal gait parameters (GAITRite, CIR Systems, Havertown, PA). GAITRite, a valid system for measuring gait performance with excellent test–retest reliability (34), is widely used in clinical and research settings (35). Steady-state locomotion was captured over a distance of 20 feet (6.10 m); data from the first and last 4 feet (1.22 m) of the instrumented walkway (void of sensors) were purposefully excluded to eliminate initial acceleration and terminal deceleration. Participants were asked to walk on the mat at their "normal walking speed" in a quiet and well-lit room.

Principal component method was performed on eight individual spatiotemporal gait parameters: gait velocity, stride length, percentage of double support, stride time, stance time, cadence, stride length variability, and swing time variability. We identified three independent gait factors (namely: Pace, Rhythm, and Variability), but given our previous findings (10), only spatial aspects of gait captured under the pace factor were examined. The pace factor score, which includes gait velocity, stride length, and percentage of immobilized gait or double support, served as the dependent variable in subsequent analyses.

Statistical Analysis

Data were inspected descriptively and graphically and the normality of model assumptions was formally tested. Descriptive statistics ($M \pm SD$) were calculated for continuous variables and between-group analysis of variances were conducted (Table 1). All analyses were run using IBM's Statistical Package for the Social Sciences (SPSS)—Version 25. The distribution of maximum unipedal stance time was skewed; therefore, a natural log transformation was applied to achieve normality, and all statistical analyses utilize the transformed value.

A linear mixed effect model, adjusted for age, gender, education, ethnicity, visual impairment, neuropathy, and global health score was implemented to examine the main effects of VS integration and cognitive status, as well as their interaction. The linear mixed effect model employed a first-order autoregressive covariance type

Table 1. Demographic and Clinical Characteristics Overall and by Cognitive Status Group†

Variable		Overall (n = 345)	Normal (n = 293)	MCI (n = 40)	Dementia (n = 12)	p Value*
% Female		52	54	45	33	.13
% Caucasian		77	80	58	58	.00
% Visual impairment		30	27	55	17	.01
% with neuropathy		6	5	8	17	.16
Age (y)		76.88 (6.45) 65–93	76.31 (6.19) 65–93	79.45 (6.59) 70–93	82.42 (7.89) 72–92	.00
Education (y)		14.92 (2.97) 5–21	15.02 (2.93) 5–21	14.75 (2.80) 9–21	13.08 (4.19) 2–19	.14
GHS (0–10)		1.12 (0.96) 0–4	1.10 (0.95) 0–4	1.35 (0.95) 0–3	0.75 (1.06) 0–3	.45
RBANS total		93.44 (12.12) 62–132	96.09 (10.51) 73–132	80.28 (9.37) 65–104	72.50 (7.62) 62–83	.00
Immediate Memory Index		100.45 (11.88) 65–138	102.38 (10.79) 81–138	92.70 (11.14) 70–119	79.17 (8.41) 65–94	.00
Delayed Memory Index		95.07 (11.59) 62–132	97.20 (10.41) 65–132	84.03 (11.16) 62–118	79.92 (8.39) 65–100	.00
Visual Spatial Index		91.66 (13.30) 62–130	93.30 (13.03) 62–130	82.85 (11.47) 65–104	80.92 (10.93) 62–97	.00
Language Index		93.03 (9.97) 62–121	94.54 (9.08) 62–121	85.98 (10.09) 62–115	79.58 (10.93) 65–94	.00
Attention Index		100.93 (14.07) 62–138	103.11 (13.33) 62–138	89.68 (11.22) 70–111	85.25 (13.10) 62–101	.00
Overall RT (ms)		405.21 (112.62) 243–1,061	395.40 (105.16) 243–1,061	447.64 (126.85) 275–781	503.24 (162.54) 334–897	.00
Somatosensory RT (ms)		444.28 (121.53) 252–1,073	434.84 (113.03) 252–1,067	483.42 (136.37) 285–848	544.44 (194.64) 357–1,073	.00
Visual RT (ms)		405.94 (118.40) 233–1,050	394.57 (107.37) 233–1,027	460.93 (155.87) 296–1,050	500.21 (148.55) 335–785	.00
Multisensory VS RT (ms)		366.28 (113.42) 213–1,086	356.96 (107.33) 213–1,086	403.39 (118.43) 246–702	470.15 (166.31) 310–867	.00
VS integration		0.03 (0.14) –0.36 to 0.46	0.04 (0.14) –0.33 to 0.46	–0.01 (0.11) –0.32 to 0.29	–0.04 (0.15) –0.36 to 0.28	.00
Unipedal stance time (s)		14.52 (11.20) 0–30	15.10 (11.29) 0–30	11.67 (9.49) 0–30	9.89 (12.59) 0–30	.02
Pace	Velocity (cm/s)	100.01 (21.63) 47–167	102.63 (21.18) 49–167	85.70 (16.84) 52–125	83.71 (22.28) 47–119	.00
Pace	Stride length (cm)	116.82 (18.84) 66–165	119.08 (18.32) 66–165	103.83 (16.36) 70–134	104.97 (18.38) 70–138	.00
Pace	Double support %	31.45 (4.85) 18–48	31.03 (4.77) 18–48	33.88 (4.45) 27–41	33.66 (5.60) 28–43	.00

Notes: GHS = Global Health Score; RBANS = Repeatable Battery for the Assessment of Neuropsychological Status; RT = reaction time; VS = visual-somatosensory.

†Values are presented as mean ± *SD* and range for continuous variables and % for dichotomous variable.

*Between-group (Cognitive Status) one-way analysis of variance results.

and a random intercept was included to allow for variability across individuals (ie, subject was treated as a random effect). The linear mixed effect model aimed to determine whether older adults with MCI and dementia manifested significantly less magnitude of VS integration compared to older adults with normal cognition (reference group).

Linear regression analyses were performed for the total score as well as the five domain-specific indices of the RBANS test serving as the dependent variables (calculated using age- and education-based norms (28)) and magnitude of VS integration serving as the independent variable. Models were run unadjusted and then adjusted for age, gender, education, ethnicity, visual impairment, neuropathy, and global health status (GHS) score. The regressions aimed to determine which aspects of cognitive function were significantly associated with VS integration, regardless of cognitive status.

Lastly, in order to determine whether variation in *cognitive status* (normal vs impaired; independent variable) causes variation in *magnitude of VS integration* (mediator), which in turn causes variation in *specific motor outcomes* (dependent variables), two separate mediation models were conducted using the SPSS version of Haye's PROCESS (36). Mediation analyses demonstrate how a variable's effect on an outcome can be partitioned into direct and indirect effects that can be quantified using ordinary least squares regression (36). The first mediation model employed unipedal stance time (natural log transformation) as the dependent variable, while the second model employed pace factor scores as the dependent variable (Figure 3). The direct effect of cognitive impairment on each motor outcome is represented by path *c′*. The indirect effect of cognitive impairment on each motor outcome through VS integration is the product of path *a* and path *b (ab)*. The values for each path in Figure 3 are

equal to the regression coefficients, followed by the corresponding *p*-value. For the indirect effect (*ab*), the mediation analyses utilize 10,000 bootstrap samples to generate empirically derived representations of the sampling distribution and a 95% bootstrapped confidence interval (CI; 36).

Results

Demographic information is presented in Table 1 for the entire cohort and by cognitive status group. In terms of between-group differences, there were significant differences in percentage of Caucasians by group, percentage of individuals with visual impairments by group, as well as group-related differences in age, RBANS scores, VS integration, and motor outcomes.

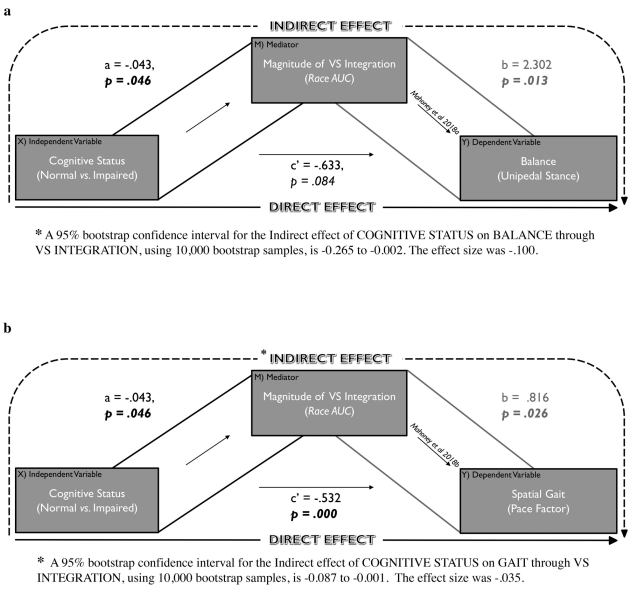

Figure 3. Mediation analyses. Mediation models along with the results for **(a)** the influence of cognition on balance through magnitude of visual-somatosensory (VS) integration and **(b)** the influence of cognition on spatial aspects of gait through magnitude of VS integration. Models are adjusted for Age, Gender, Education, Ethnicity, Visual Impairment, Neuropathy, & Global Health Score (GHS).

Overall, our results demonstrate significant and robust VS integration effects over the fastest 10% of RTs using an established permutation test (26) (Figure 2a—dashed trace). Figure 2a also depicts the race model difference waveform by cognitive status (solid traces) and as expected, individuals with normal cognitive status appear to have the largest race model violation, while individuals with MCI and dementia have little to no race model violation over the fastest 10% of RTs. In fact, the race model difference waveform of older adults with MCI and dementia, is quite reminiscent to older adults with poor and deficient integration capacities defined in our previous studies (10,11). Figure 2b illustrates the area under the curve over the violated percentile bins (0%–10%) for the actual, predicted, and difference CDFs by cognitive status group. As depicted in the normal group, the actual CDF is greater than the predicted CDF; thus, the RMI is *rejected* in favor of significant multisensory interactions. However, in the case of the impaired cognitive group (MCI and dementia) there is no violation of the race model (the actual CDF is less than the predicted CDF), suggesting that individuals in these two groups do not benefit from VS integration processes.

Results of the fully-adjusted linear mixed effect model model examining the effect of VS integration (actual vs predicted AUC over the 0–10th percentile), cognitive group status (normal, MCI, and dementia), and their interaction revealed a main effect of VS Integration ($p \leq .001$) and a main effect of cognitive group status ($p = .01$). However, these main effects are better explained by the interaction term, where significant differences in magnitude of VS integration exists between individuals with MCI ($p = .02$) and individuals with dementia ($p = .04$), relative to individuals with normal cognitive status (see Table 2 and also Figure 2).

Results from fully adjusted linear regression analyses (Table 3) revealed that regardless of cognitive status, magnitude of VS integration was significantly associated with RBANS Attention Index score ($\beta = 0.16$, $p \leq .001$); however, there was a noteworthy trend in the association between magnitude of VS integration and RBANS Total score ($\beta = 0.10$, $p = .055$).

Fully-adjusted mediation models were investigated to determine whether *cognitive impairment* causes variation in *magnitude of VS integration*, which in turn causes variation in *specific motor outcomes*. Results from the first mediation model (Figure 3a) did not reveal a direct effect (c'; $p = .08$) of cognitive impairment on unipedal stance time. However, the indirect effect (*ab*) of cognitive impairment on unipedal stance time through magnitude of VS

Table 2. Linear Mixed Effect Model Results for (a) Visual-Somatosensory (VS) Integration; (b) Cognitive Status; (c) VS Integration × Cognitive Status; (d) Adjustments

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
VS Integration (Actual vs Predicted)	−0.04	0.01	342.00	−5.22	0.00	−0.06	−0.03
Normal vs MCI	−0.20	0.06	358.13	−3.26	0.00	−0.33	−0.08
Normal vs Dementia	−0.16	0.11	358.53	−1.45	0.15	−0.37	0.06
VS Integration * (Normal vs MCI)	0.05	0.02	342.00	2.32	0.02	0.01	0.10
VS Integration * (Normal vs Dementia)	0.08	0.04	342.00	2.11	0.04	0.01	0.16
Age	0.00	0.00	335.00	0.29	0.77	−0.01	0.01
Gender	0.05	0.04	335.00	1.33	0.19	−0.02	0.13
Education	0.01	0.01	335.00	2.00	0.05	0.00	0.03
Ethnicity	0.06	0.05	335.00	1.27	0.21	−0.03	0.15
Visual impairment	0.04	0.04	335.00	0.92	0.36	−0.04	0.12
Neuropathy	−0.04	0.08	335.00	−0.48	0.63	−0.20	0.12
Global Health Score	−0.03	0.02	335.00	−1.72	0.09	−0.07	0.00

Table 3. Fully Adjusted Association Between Visual-Somatosensory (VS) Integration and Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) Performance

Model	Unstandardized Coefficients		Standardized Coefficients			95% Confidence Interval for B	
	B	*SE*	Beta	*t*	Sig.	Lower Bound	Upper Bound
RBANS Total Score	8.77	4.56	0.10	1.93	0.06	−0.19	17.74
Immediate Memory Index	6.23	4.52	0.07	1.38	0.17	−2.66	15.13
Delayed Memory Index	7.71	4.48	0.09	1.72	0.09	−1.10	16.51
Visuo-Spatial Construction Index	1.94	5.17	0.02	0.38	0.71	−8.22	12.10
Language Index	−3.22	3.87	−0.04	−0.83	0.41	−10.82	4.39
Attention Index	16.94	5.35	0.16	3.17	0.00	6.41	27.47

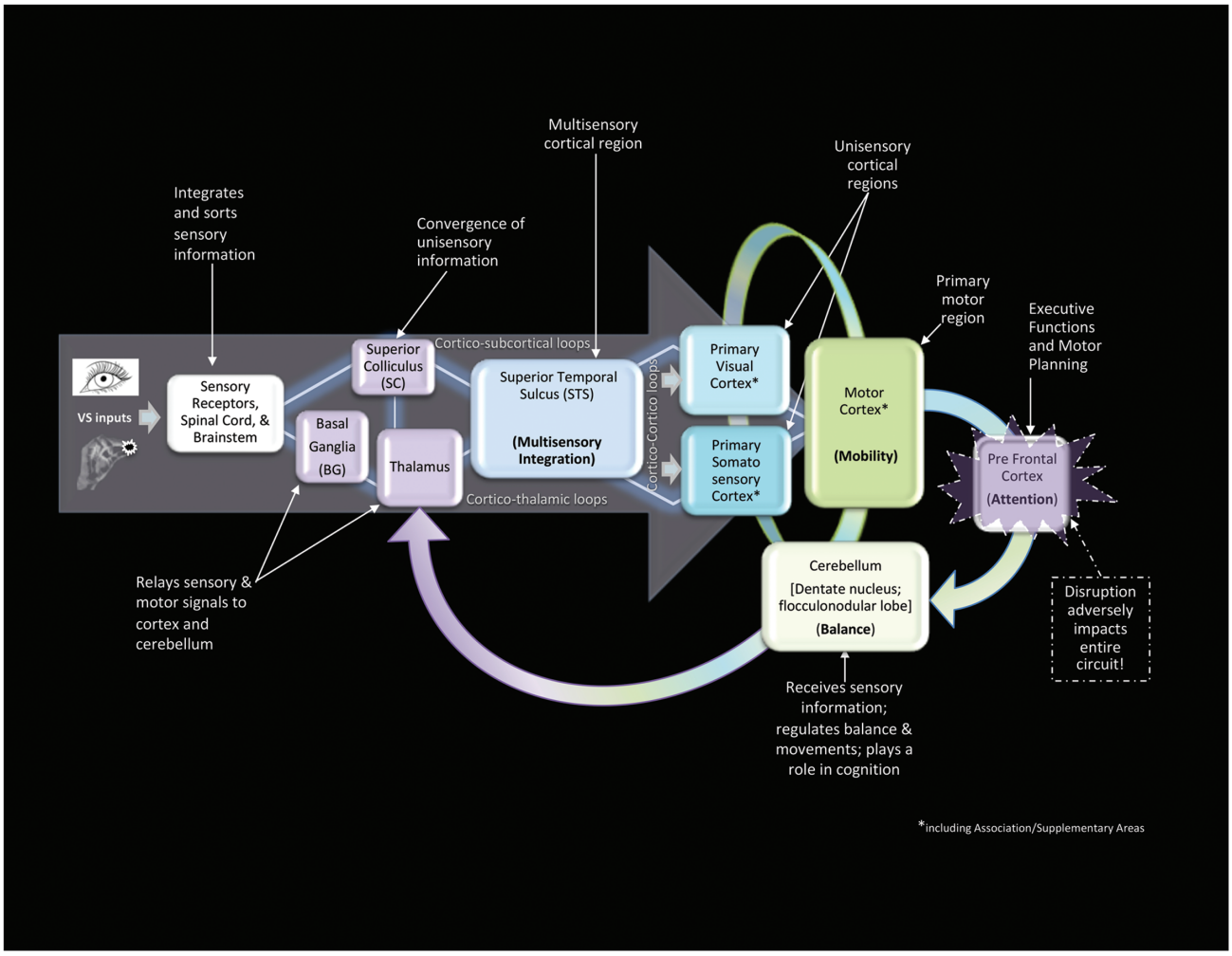

Figure 4. Proposed neural circuit. Overlapping connections from prefrontal cortex (PFC) to other cortical, subcortical, cerebellar regions. Disruption of circuit at PFC impacts cognitive, sensory, and motor processes dependent upon the circuit's functionality. The proposed circuit is hypothetical and by no means representative of all potential connections and pathways.

integration was significant 95% CI (−0.265, −0.002), as was each path *a* and *b*. Results from the second mediation model (Figure 3b) revealed a significant direct effect (*c′*; $p = .001$) of cognitive impairment on spatial aspects of gait. Additionally, the indirect effect (*ab*) of cognitive impairment on spatial gait through magnitude of VS integration was also significant 95% CI (−0.087, −0.001), as was each path *a* and *b*. Collectively, these findings suggest that cognitive impairment influences magnitude of VS integration, which in turn directly affects its association with both balance and gait performance in aging.

Discussion

In the current study, we demonstrate that magnitude of VS integration is associated with attention-based performance in older adults. Magnitude of VS integration is greatest in individuals maintaining normal cognitive functioning. In line with our hypothesis, we provide support that cognitive impairment significantly influences magnitude of VS integration, which in turn impacts its association with both balance and gait performance. That is, older adults with MCI and dementia demonstrate significantly reduced VS integration and worse unipedal stance/spatial gait performance compared to elders without cognitive impairments. In fact, race model difference waveforms of individuals with MCI and dementia depict virtually no VS integration, which is commensurate with the race model difference waveforms of both poor and deficient integrators identified in our previous studies (10,11).

Why should VS integration be influenced by cognitive impairment? The answer is related to the fact that VS integration processes likely require activation of similar neural networks that are known to be compromised in dementia and MCI. Here we employed a simple RT test with very limited cognitive demands: participants were asked to respond to all sensory stimulation. The task requires attentional resources to be divided across all stimuli, and these processes are known to be impacted by age-related cognitive deficits (37). The frontal lobe hypothesis of aging postulates that functions mediated by the frontal and prefrontal cortex (PFC) including attention and executive functions are among the first cognitive processes to decline with age (38). We and others have linked multisensory integration processes in aging to selective attention processes (18) which rely on similar PFC networks. Here, we demonstrate that attentional capacity, as measured by the RBANS, was the only cognitive domain associated with VS integration.

The thalamus is known to play an important role in the integration of sensory information, through cortico-cortical and cortical-subcortical transmissions (16). VS integration has been individually associated with critical mobility outcomes in aging (10,11) likely due to shared cortico-cortical, cortical-subcortical, and cortico-thalamic connectivity (12,15,16). Similarly, the basal ganglia maintain connections with brain regions involved in balance like the thalamus, brainstem, and the cerebellum which also plays a role in cognition given its connections back to PFC (39). Consequently, if these processes all rely on shared and overlapping circuitry from PFC to other cortical, subcortical, cerebellar regions, and back, then any disruption could theoretically impact cognitive, sensory, and motor processes dependent upon the circuit's functionality (Figure 4). The current article provides support for a link between VS integration and cognition (specifically attention-related processes) in aging and further demonstrates that dementia and MCI adversely influence the association of VS integration processes with balance and gait performance.

Limitations and Future Directions

A number of other variables likely contribute to the decline of multisensory integration processes in older adults, including but not limited to chronological age, impairments in unisensory function, and medical comorbidities that directly alter sensory, motor, and cognitive functions. While we controlled for the presence of these variables in our statistical models, residual or unmeasured confounding can exist. Future studies should specifically investigate the effect of these important variables (and their interactions) on multisensory processes in aging. We did not investigate brain substrates that may be responsible for our observations. Future neuroimaging studies should determine whether VS integrative processes maintain direct connections to PFC, or whether PFC is just one of the many components of a larger shared neural circuit involved in multisensory integration, cognition, and mobility processes.

Conclusions

We established a significant link between VS integration and cognitive impairments in aging. The magnitude of VS integration is largest in older adults with normal cognitive functioning. Presence of MCI and dementia significantly decreases magnitude of VS integration, which in turn adversely impacts both balance and gait performance. Collectively, these studies continue to stress the importance of successful multisensory integration in aging and point towards establishment of multisensory based interventions that could potentially ameliorate disability.

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Conflict of Interest

None reported.

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