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Early aging and postural control while listening and responding

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ABSTRACT:

It is not unusual for communication to take place while people are involved in another activity. This paper describes a study that measures the impact of listening while also completing an active postural control task. The focus was on whether the combination of listening and balancing was more detrimental to middle-aged adults than it was to younger adults as age-related changes in both hearing and postural control can occur within this age range. Speech understanding in the presence of noise and speech maskers was measured when participants (n = 15/group) were simply standing still, as well as when they were asked to complete a balancing-with-feedback postural control task, requiring different levels of effort. Performance on the postural control task also was measured in isolation. Results indicated that dual-task costs for postural control were larger when the masker was speech (vs noise) for the middle-aged group but not for the younger group. Dual-task costs in postural control increased with degree of high-frequency hearing loss even when age was controlled. Overall, results suggest that postural control in middle-aged adults can be compromised when individuals are communicating in challenging environments, perhaps reflecting an increased need for cognitive resources to successfully understand messages.
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I. INTRODUCTION

Difficulty following conversations in situations with multiple talkers is a common experience as people begin to age. Although a portion of this phenomenon is undoubtedly related to the pure-tone hearing loss that accompanies aging, research has demonstrated that middle-aged adults' ratings of self-perceived hearing problems in adverse acoustic conditions are greater than what would be expected by the amount of hearing sensitivity loss that they experience (e.g., Bainbridge and Wallhagen, 2014; Demeester *et al.*, 2012; Helfer *et al.*, 2017). Results of laboratory-based studies of speech understanding have found that middle-aged adults do not perform as well as younger adults, especially in certain situations with competing speech messages (e.g., Başkent *et al.*, 2014; Cameron *et al.*, 2011; Füllgrabe *et al.*, 2015; Goossens *et al.*, 2017; Glyde *et al.*, 2013; Hannula *et al.*, 2011; Helfer and Freyman, 2014, 2016; Helfer *et al.*, 2018; Shinn-Cunningham *et al.*, 2013; Tremblay *et al.*, 2015; Wiley *et al.*, 1998). Collectively, this information suggests that the ability to communicate in noisy situations may be compromised relatively early in the aging process.

Real-life communication frequently involves talking to someone while simultaneously performing another task: for example, taking a walk with a friend or cooking dinner while conversing with one's partner. This raises questions regarding whether age-related changes in hearing and/or motor control negatively impact the ability to negotiate a combination of tasks successfully and safely. Changes in postural control or balance become increasingly apparent as people age and can be demonstrated as early as mid-life (e.g., Ku *et al.*, 2016; Park *et al.*, 2016). Like listening, age-related changes in postural control become more substantial when individuals are engaged in multiple tasks (see Boisgontier, 2013; Frazier and Mitra, 2008; and Ruffieux *et al.*, 2015, for reviews of the extensive literature on dual-task costs on postural control in older adults). The purpose of this study was to examine how early age-related changes in speech understanding and balance are impacted when individuals are listening while performing a postural control task. Speech perception research is typically conducted when individuals are sitting. The identification of early aging changes in communicating while needing to maintain balance has implications for the potential sequence of adverse events that is linked to falls in older adults.

This type of research also may be able to uncover differences in speech processing between younger and middle-aged adults that occur even when the two groups perform similarly in terms of percent-correct speech recognition. There is a relatively extensive body of prior research using various types of dual-cost paradigms to quantify listening effort (see Gagné *et al.*, 2017, for a review of this information). Dual-task costs can provide a window into the underlying cognitive load that is necessary for individuals to complete tasks (including listening tasks) successfully. Resource-based theories (e.g., Kahneman, 1973) posit that

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humans have a limited capacity for information processing; if one task requires more resources, then performance on the other will decline. Our previous work in this area (Helfer *et al.*, 2020) directly addressed this idea. In that study, postural control in both younger and middle-aged adults was mediated by the difficulty of a concurrent speech perception task. Presenting the stimuli at a more adverse signal-to-noise ratio (SNR) led to a decline in postural control. Critically, even though speech understanding accuracy was essentially equivalent between the two groups, postural control in our middle-aged participants was poorer when the masker consisted of two competing talkers vs when the masker was steady-state noise (SSN). These results are consistent with the concept that listening in competing speech takes more cognitive resources than listening in less complex maskers. Age-related changes in cognitive resources revealed themselves in our middle-aged participants as increased dual-task costs when the masker was understandable speech. Moreover, our prior study (Helfer *et al.*, 2020) found that greater high-frequency hearing loss (rather than older age) was associated with poorer postural control in both single- and dual-task conditions. Similarly, a study by Bruce *et al.* (2017) found larger dual-task costs for older adults with hearing loss as compared to normally hearing older adults when combining an auditory task with a postural control task.

The present study extends our previous work by using a task that allowed us to manipulate postural control difficulty and effort via visual feedback. Prior work has demonstrated that tasks requiring controlled (vs automatic) postural control processing are more sensitive to subtle age-related changes (e.g., Boisgontier *et al.*, 2013) as they consume more cognitive resources. We speculated that using a postural control task which necessitated additional attentional resources would allow us to better quantify dual-task costs associated with listening while balancing as resources devoted to one of these tasks would leave fewer remaining for the other.

Another difference between our prior study and the present study is that our previous work compared single-task postural control measured in quiet to dual-task postural control measured in the presence of maskers (because the second task in that study was speech understanding in noise). Others have demonstrated that the presence of noise can lead to enhanced postural control (e.g., Dozza *et al.*, 2011; Gandemer *et al.*, 2017; Ross *et al.*, 2016), perhaps because it provides an auditory anchor or reference. This suggests that dual-task costs in studies that use postural control and speech-in-noise tasks should be derived from single-task postural control measured in noise rather than in quiet. Previous work in this area has suggested that the presence of some types of noise improves postural control in older adults (Deviterne *et al.*, 2005; Ross *et al.*, 2016; Stevens *et al.*, 2016) but perhaps to a lesser extent than for younger adults (Vitkovic *et al.*, 2016). In the present study, we measured single-task postural control in noise for two reasons: to provide a more appropriate comparison with our dual-task conditions, which were always conducted in the presence of maskers; and to determine whether the benefit to postural control provided by noise occurs to a similar extent for younger and middle-aged adults.

The study described in this paper also was designed to address the overall idea that communicating in the presence of competing speech is particularly effortful for middle-aged participants even if they can perform a speech perception task at accuracy levels at or approaching those achieved by younger adults. We tested this idea using a dual-task paradigm in which we assessed both speech understanding in the presence of noise and speech maskers and postural control using a balancing-with-feedback postural control task with two levels of difficulty. The postural control task consisted of real-time visual feedback through which participants had to limit the excursions of their postural sway. Our hypothesis was that postural control differences between middle-aged and younger adults would be exacerbated in dual-task conditions, especially when that task was completed in the presence of an understandable speech masker and when the more difficult postural control condition was used. Based on the results of our previous study (Helfer *et al.*, 2020), we also predicted that high-frequency thresholds would be more closely associated with postural control than age *per se*.

II. METHODS

A. Participants

Groups of younger adults and middle-aged adults ($n = 15$/group) participated in this study. The younger adults (mean age 21 years old, range 19–24 years old) all had audiometrically normal hearing [pure-tone thresholds $\leq$ 25 dB hearing level (HL) from 250 to 8000 Hz]. Middle-aged participants (mean age 54 years old, age range 46–63 years old) were required to have average high-frequency pure-tone thresholds (between 2 and 6 kHz) $\leq$ 60 dB HL in either ear; the mean better-ear high-frequency average was 19.75 dB and ranged from 3 to 51 dB (audiograms for each participant group are shown in Fig. 1). None of the participants had ever worn hearing aids. Potential participants were screened to rule out self-reported otologic, vestibular, motor, or neurological problems that would affect hearing or balance. All participants had normal tympanograms on the test day. Middle-aged participants had scores within normal limits ($\geq$26) on the Montreal Cognitive Assessment (MoCA; Nasreddine *et al.*, 2005). Each participant gave informed consent for the protocol, which was approved by the University of Massachusetts Amherst Institutional Review Board.

B. Procedures

Participants completed a speech recognition task and a postural control task, singularly (single-task conditions) and simultaneously (dual-task conditions). The acoustic conditions for the speech perception task were selected with the goal of producing percent-correct performance that would

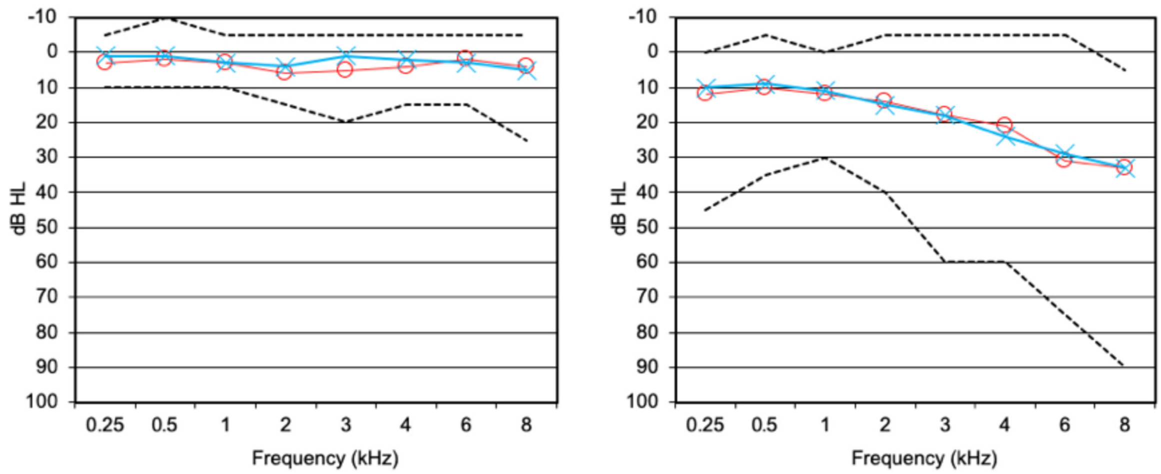

FIG. 1. (Color online) Mean audiograms for the younger (left) and middle-aged (right) participants. Dashed lines indicate the minimum and maximum thresholds. Thresholds for the right ear are in red; thresholds for the left ear are in blue.

be approximately equal between groups. This task consisted of target TVM-Colors sentences (Helfer *et al.*, 2016) presented with either competing TVM-Colors sentences or SSN shaped with the envelope of the long-term spectrum of utterances from two female talkers. The target sentence was presented from a loudspeaker located in front of the participant while the maskers were presented from speakers 60 deg to the left and right. Loudspeakers were adjusted to be ear-height for each participant. When the masker was competing sentences, all three talkers were the same sex with utterances from one masking talker presented from the left loudspeaker and the other presented from the right loudspeaker. Each masking sentence was presented in a looped fashion where it started at a random point within the sentence with the beginning portion of the sentence appended to the end of the sentence (see Helfer *et al.*, 2016). Independent samples of SSN were presented from the right and left loudspeakers during trials using that masker. Target sentences were presented at 67 dBA at −3 dB SNR. The SNR was quantified relative to the total masker energy (in other words, the combined levels of the maskers were 70 dBA). It should be noted that there was a second speech perception task [listening to the Connected Speech Test (Cox *et al.*, 1987) passages and answering questions] completed by all participants; those results are not discussed in the present paper.

Testing was completed in a double-walled sound-treated audiometric chamber (IAC No. 1604A, Naperville, IL). Participants were instructed to face forward and look at a computer monitor located directly in front for the duration of a block of trials and to keep their hands on their hips. The participants removed their shoes prior to testing, which was conducted with participants standing on a 40 × 60 cm piezoelectric force platform (Kistler Instruments Corporation, Amherst, NY) with a standard side-by-side foot placement. A custom LabView program (National Instruments, Austin, TX) time-synced with the audio tasks continuously recorded [at 100 Hz analog-to-digital (A/D) conversion rate] and displayed the participant's ground reaction force information (i.e., center of pressure, CoP) from the force platform.

Participants completed an active postural control task in which real-time visual feedback corresponding to the participant's CoP was shown as a moving point within a rectangular box displayed on the computer monitor located in front of the listener. They were instructed to keep the moving point within the boundaries of the box. Two levels of the postural control task were incorporated to manipulate the attentional resources needed to complete this task, with task difficulty manipulated by altering the size of the box. In the easier condition, the dimensions of the box (approximately 6 × 10 cm) were larger and less restrictive than in the harder postural control condition (approximately 4 × 6 cm). We recognized that CoP might not differ between the two levels of postural control task difficulty if participants were able to limit their movements to keep the visual feedback within the box. However, we anticipated that reducing the box size would lead to an increased demand on the postural control system with a corresponding increase in effort required to complete the task. Baseline postural control (measured in quiet with no visual feedback) also was assessed both before and after the active postural control blocks; participants were instructed to stand as still as possible on the force plate while looking straight ahead at a plus sign on a computer monitor during these two trials.

Conditions were blocked by postural control task (easier vs harder) and masker (SSN or competing speech) with blocks presented in randomized order. Each block involving speech understanding consisted of eight sentences (with four scoring words per sentence) with two blocks presented for each combination of masker and postural control task. Single-task postural control (that is, with the visual feedback described above) was measured in quiet as well as in the presence of the SSN masker, presented from the right and left loudspeakers at 70 dBA. Single-task speech perception was considered as the blocks in which participants were instructed to simply stand as still as possible.[1] During these single-task trials, the monitor displayed a plus sign, which participants were asked to visualize for the duration of the block of trials. For dual-task blocks, participants were instructed to place equal effort on both the speech perception task and the balancing-with-feedback task. At the end of each block of trials, they were asked to rate their perceived effort separately for the listening and postural tasks using a scale of one (very little effort) to ten (very high effort).

C. Data and statistical analyses

Postural control was defined as the CoP excursion area measured from the force platform (Duarte and Freitas, 2010; Swanenburg *et al.*, 2008). A 95% confidence ellipse based on the anterior-posterior and medial-lateral displacements of the CoP was calculated in a custom MATLAB script (The MathWorks, Natick, MA). Prior to all calculations, the CoP data were low-pass filtered with a 10 Hz zero-lag Butterworth filter. Ground reaction forces were collected continuously across an entire block of trials (approximately 80 s).

Our prior work in this area examined postural control only during the period of time when participants were listening as the focus of that paper (Helfer *et al.*, 2020) was on listening effort. However, most dual-task studies that combine a balance task with a listening or cognitive task using a verbal response consider postural control across the entire trial (that is, when the participant is listening and processing the information, as well as when they are responding). We conducted an initial analysis of the data in which we compared postural control for time intervals corresponding to when participants were listening vs when they were responding (see the Appendix). This analysis found that the listen-only and respond-only data did not differ significantly from each other in either postural control condition, and there were no significant interactions between the analysis interval and participant group. We therefore decided to conduct our full analysis on postural control data from the entire trial in order to be better able to compare our work to previous research. An additional benefit of using the entire trial is that a longer analysis window leads to a more stable measurement of postural CoP data (Carpenter *et al.*, 2001).

Repeated-measures multivariate analyses of variance (ANOVAs) were used to identify main and interaction effects in single-task and dual-task conditions for both postural control and speech recognition. ANOVAs were also used to analyze the self-reported effort data obtained in all conditions. We calculated two derived metrics that also were analyzed via ANOVA: the difference in postural control found during the easier vs the more difficult balance task; and absolute dual-task costs. All ANOVA results can be found in Table I. *Post hoc* t-tests or one-way ANOVAs were conducted to explore significant interactions. The question of how age and hearing loss contributed to postural control was addressed with Pearson r and partial correlation analyses (see Table II).

III. RESULTS

A. Single-task postural control

Performance on the baseline postural control trials (in which participants were instructed to stand as still as

TABLE I. Summary of ANOVA results. Statistically significant results ($p < 0.05$) are in bold typeface.

Baseline postural control:	F	p	η^2
Group	4.11	0.052	**0.128**
Single-task postural control:	F	p	η_p^2
Task	0.35	0.561	0.012
Noise	0.44	0.512	0.016
Group	**5.09**	**0.033**	**0.153**
Task × group	0.45	0.506	0.016
Noise × group	0.01	0.908	0.000
Task × noise	0.10	0.758	0.003
Task × noise × group	0.02	0.892	0.001
Single-task balance effort:	F	p	η_p^2
Task	**229.20**	**<0.001**	**0.891**
Noise	1.11	0.301	0.038
Group	**4.31**	**0.047**	**0.133**
Task × group	0.21	0.651	0.007
Noise × group	2.01	0.167	0.067
Task × noise	0.57	0.457	0.020
Task × noise × group	0.57	0.457	0.020
Speech recognition accuracy:	F	p	η_p^2
Task	1.04	0.369	0.071
Masker	**10.16**	**0.004**	**0.266**
Group	0.19	0.670	0.007
Task × group	0.46	0.638	0.033
Masker x group	2.31	0.139	0.076
Task × masker	**4.56**	**0.020**	**0.253**
Task × masker × group	2.20	0.130	0.140
Speech recognition effort:	F	p	η_p^2
Task	**5.13**	**0.013**	**0.275**
Masker	0.01	0.921	0.000
Group	**5.91**	**0.022**	**0.174**
Task × group	1.58	0.225	0.105
Masker × group	0.95	0.339	0.033
Task × masker	2.41	0.109	0.151
Task × masker × group	2.20	0.130	0.013
Dual-task postural control:	F	p	η_p^2
Task	4.05	0.054	0.126
Masker	2.49	0.126	0.082
Group	**4.48**	**0.043**	**0.138**
Task × group	**5.37**	**0.028**	**0.161**
Masker × group	**5.56**	**0.026**	**0.166**
Task × masker	0.74	0.402	0.025
Task × masker × group	0.39	0.536	0.014
Dual-task balance effort:	F	p	η_p^2
Task	**129.90**	**<0.001**	**0.823**
Masker	2.16	0.153	0.072
Group	**5.91**	**0.022**	**0.174**
Task × group	0.36	0.553	0.013
Masker × group	0.40	0.534	0.014
Task × masker	0.01	0.913	0.000
Task × masker × group	0.01	0.913	0.000

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TABLE I. (*Continued*)

Single-task: Harder–easier postural control:	F	p	η_p^2
Noise	0.10	0.758	0.003
Group	0.45	0.506	0.016
Noise × group	0.02	0.892	0.001
Dual-task: Harde–easier postural control:	F	p	η_p^2
Masker	0.72	0.402	0.025
Group	**5.37**	**0.028**	**0.161**
Masker × group	0.39	0.536	0.014
Dual-task costs:	F	p	η_p^2
Task	1.46	0.238	0.049
Masker	2.49	0.126	0.082
Group	0.10	0.759	0.003
Masker × group	**5.56**	**0.026**	**0.166**
Task × group	2.29	0.142	0.075
Task × masker	0.72	0.402	0.025
Task × masker × group	0.39	0.536	0.014

possible without visual feedback), as well as on the single-task active postural control blocks with visual feedback of their CoP, are shown in Fig. 2. The first analysis compared performance between the groups in the baseline condition. Larger CoP in this baseline condition is indicative of poorer postural control (that is, participants were less successful at standing still). Although middle-aged participants had poorer baseline postural control than younger participants, one-way ANOVAs showed that the difference between group baselines just missed statistical significance ($p = 0.052$).

A second analysis examined how single-task postural control was influenced by the balancing-with-feedback postural control task and the acoustic condition. A repeated-measures ANOVA was conducted with the postural control task (easier vs harder) and listening condition (quiet vs noise) as within-subject factors and the participant group as a between-subjects factor. Results of this analysis revealed a significant main effect of group ($p = 0.033$). Main and interaction effects involving task type or listening condition were not statistically significant. This demonstrates that the presence of noise did not have a significant effect on the ability to complete the postural control task, and middle-aged adults exhibited larger excursions during the active postural control task than did the younger participants.

Different results were found when analyzing how much effort participants perceived to use during the active postural control task. These data are shown in Fig. 3. A repeated-measures ANOVA with postural control task (easier vs harder) and listening condition (quiet or noise) as within-subject factors and participant group as a between-subjects factor revealed significant main effects of both group ($p = 0.047$) and postural task difficulty ($p < 0.001$). This verifies that although CoP values did not differ significantly between the easier and harder postural control task (see Fig. 2), participants judged the harder postural control task to be much more effortful than the easier postural control task. Overall, middle-aged adults found the postural control task to be more effortful than did the younger participants. However, the presence of background noise did not significantly influence the effort ratings.

B. Speech recognition

Percent-correct speech recognition data for single-task conditions (when participants were standing but not

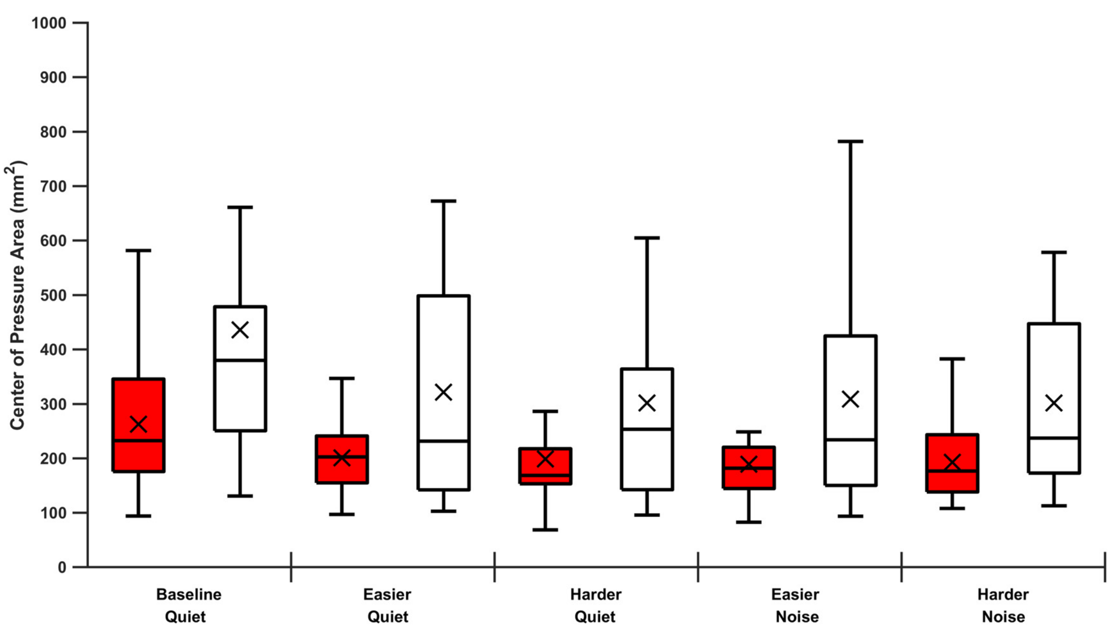

FIG. 2. (Color online) Baseline and single-task postural control for younger (red) and middle-aged (white) participants. Baseline postural control (left bars) was measured with no visual feedback provided. Single-task active postural control was assessed in easier and harder conditions by having participants use visual feedback. Each box is bounded by the 25th and 75th percentiles. The horizontal line within each box displays the median, "×" indicates the mean, and the whiskers show the minimum and maximum values.

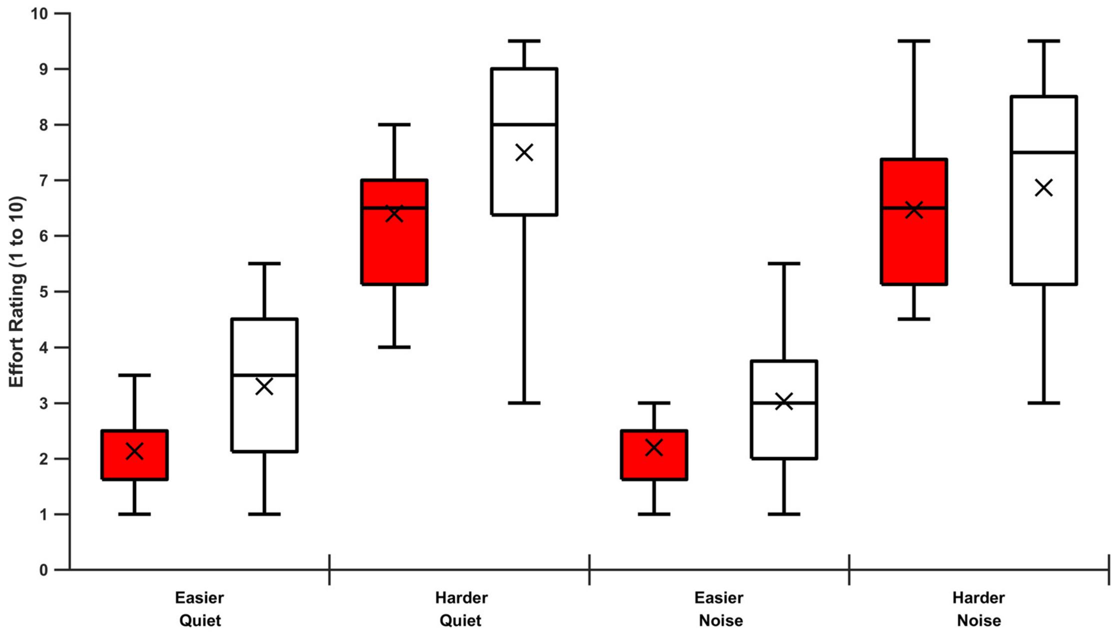

FIG. 3. (Color online) Self-rated effort for single-task postural control for younger (red) and middle-aged (white) participants (1 = very little effort, 10 = very high effort).

completing the postural control task) and dual-task conditions (when participants completed both the speech perception task and postural control task) can be seen in Fig. 4. Minimal differences were found between the two groups in any of these conditions. A repeated-measures ANOVA, with masker (SSN vs speech) and postural control task (none/single-task speech perception vs easier postural control task vs harder postural control task) as within-subject factors and group as a between-subjects factor, found significant main effects of masker ($p = 0.004$) and a significant masker × task interaction ($p = 0.020$). *Post hoc* analysis of this interaction (paired-samples *t*-tests with adjustment for multiple comparisons) showed that percent-correct speech recognition was better for the easier postural control condition (vs the harder postural control condition) when the masker was speech but not when the masker was noise. However, the numerical difference in percent-correct between conditions was small (between two and five percentage points).

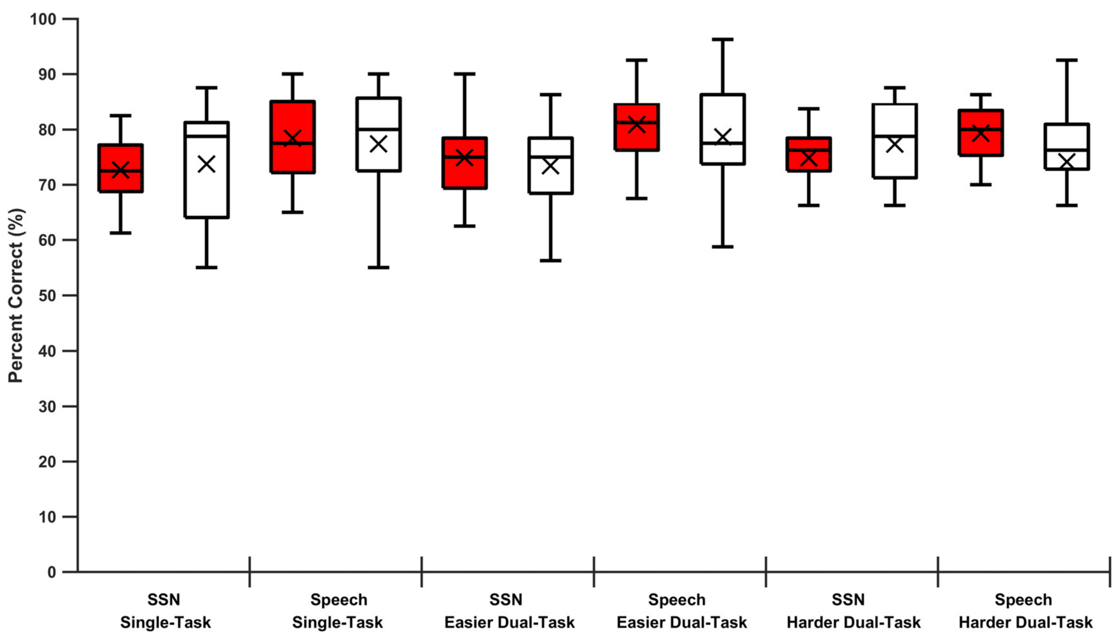

FIG. 4. (Color online) Speech perception (in percent correct) by group (red, younger; white, middle-aged), masker (SSN or competing speech), and postural control task.

Self-rated listening effort for the speech recognition task is shown in Fig. 5. Although, as seen in Fig. 4, there were only minimal differences between groups in terms of accuracy in speech perception scores, middle-aged participants consistently reported that the speech recognition task was more effortful, as compared to the younger participants. Participants also rated the speech perception task as more effortful when conducted in the harder postural control condition than in the easier postural control condition. A repeated-measures ANOVA using the same variables as for the percent-correct analysis showed significant main effects for task ($p = 0.013$) and group ($p = 0.022$). *Post hoc t*-tests indicated that listening effort ratings were higher for the harder postural control task vs either the single-task ratings or the easier postural control task ratings.

C. Dual-task postural control

Participants' performance on the postural control task when completed in conjunction with the speech perception task is shown in Fig. 6. Repeated-measures ANOVA with task (easier vs harder) and masker (noise vs speech) as within-subject variables and group as a between-subjects variable was completed for these data. While there was considerable overlap in CoP values between groups, this analysis indicated a significant main effect of group ($p = 0.043$), as well as a significant task × group interaction ($p = 0.028$) and a significant masker × group interaction ($p = 0.026$). *Post hoc t*-tests on the masker × group interaction indicated that the difference in postural control between noise and speech maskers was significant for middle-aged adults ($p = 0.034$) as the CoP area was greater (that is, participants made more or larger postural movements) in the presence of the speech masker vs in the presence of the the noise masker. This was not the case for the younger participants, for whom postural control in dual-task conditions was essentially stable across conditions.

We further examined the significant task × group interaction by comparing the difference in postural control for the easier postural control task vs the harder postural control task (CoP for the harder task minus CoP for the easier task). This derived metric, which indexes the toll on postural control that occurs when that task increases in difficulty, is shown in Fig. 7. Difficulty of the postural control task had only a small effect on CoP for single-task blocks. However, when participants were asked to complete the postural control task at the same time as the speech perception task, a different pattern emerged. Making the postural control task more difficult in dual-task blocks had an adverse effect on postural control for the middle-aged participants but not for the younger participants. This pattern was confirmed with repeated-measures ANOVA. For the single-task blocks, neither the effect of acoustic condition (noise or quiet) nor group nor their interaction was significant. Conversely, a significant main effect of group ($p = 0.028$) was found for the dual-task data: during dual-task conditions, middle-aged participants had more difficulty negotiating the harder postural control task than the easier postural control task. It appears that when faced with performing both a speech perception task and a postural control task, middle-aged adults made more or larger corrections in order to keep their CoP within the boundaries of the smaller box used in the harder postural control condition.

Dual-task self-rated postural control effort can be seen in Fig. 8. ANOVA revealed only a significant main effect of task ($p < 0.001$) with no significant main or interaction effects involving either masker or group (Table I).

Finally, we calculated absolute dual-task costs by subtracting the CoP values obtained in the single-task condition

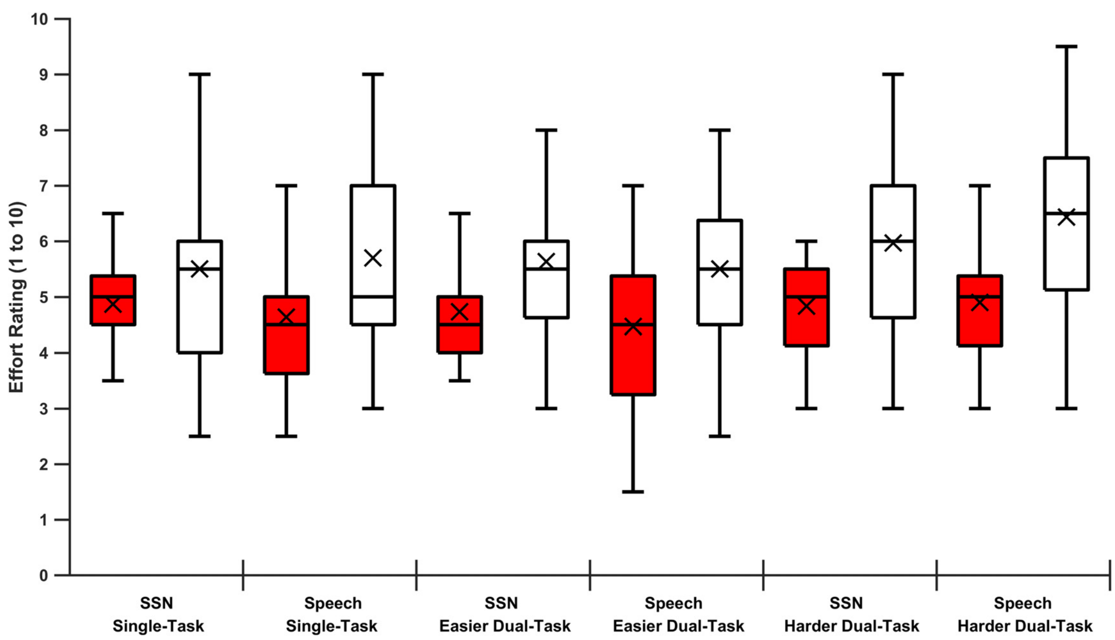

FIG. 5. (Color online) Self-rated effort for the speech perception task for younger (red) and middle-aged (white) participants (1 = very little effort, 10 = very high effort).

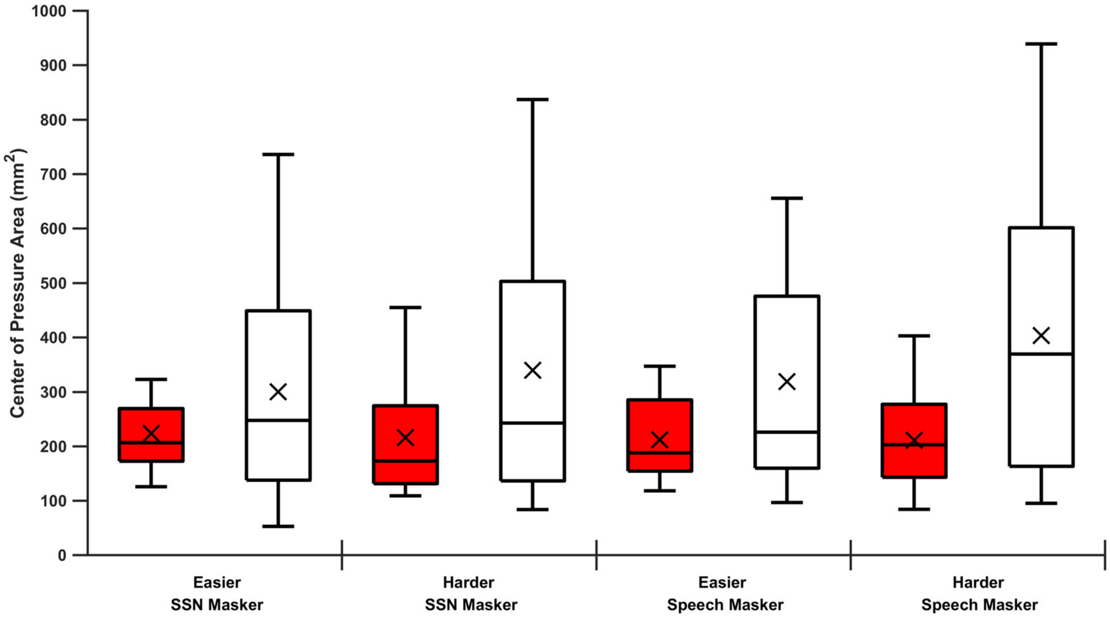

FIG. 6. (Color online) Postural control for dual-task conditions for younger (red) and middle-aged (white) participants.

in noise from the dual-task CoP for both the easier and harder postural control tasks (see Fig. 9). ANOVA with task (easier vs harder) and masker (noise vs speech) as within-subject factors and group as a between-subjects factor revealed a significant main effect of group ($p = 0.003$) and a significant masker × group interaction ($p = 0.026$). *Post hoc* t-tests indicated that dual-task costs were significantly larger for the speech vs the noise masker for middle-aged participants ($t = -2.35$, $p = 0.034$) but not for younger participants ($t = 0.71$, $p = 0.489$).

D. Hearing loss and individual variability

A series of correlation analyses was conducted to identify associations between age, hearing, and postural control. The specific variables used in the analyses were age, better-ear high-frequency pure-tone average (beHFPTA; average of thresholds from 2 to 6 kHz) and single- and dual-task CoP values for the easier postural control task and the harder postural control task. These CoP metrics were calculated by averaging across all other factors (for single-task, this averaging was across values obtained in quiet vs in the presence

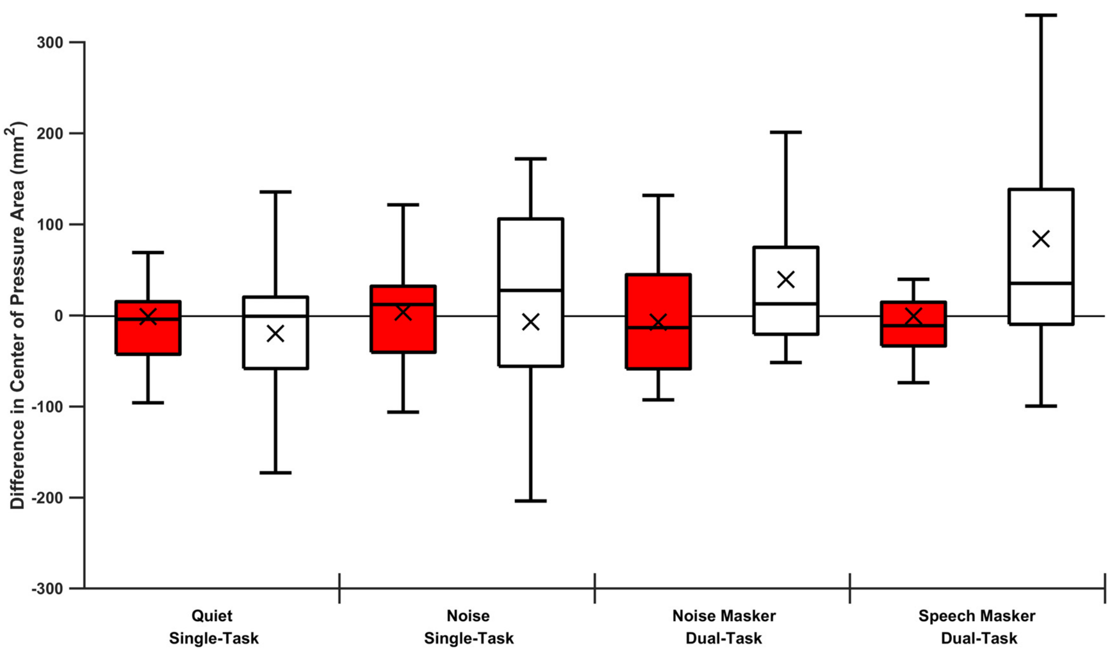

FIG. 7. (Color online) The difference in postural control between the easier task and the harder task (CoP for harder task minus CoP for easier task); red = younger participants; white = middle-aged participants.

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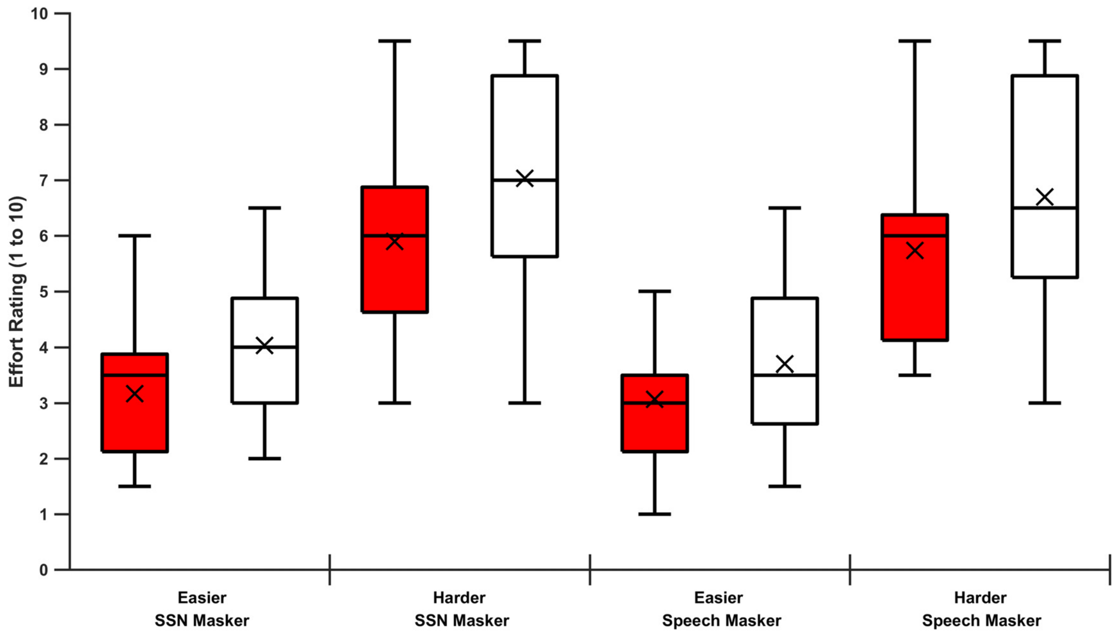

FIG. 8. (Color online) Self-rated effort for dual-task postural control for younger (red) and middle-aged (white) participants (1 = very little effort, 10 = very high effort).

of noise; for dual-task, the averaging was across trials with speech maskers and noise maskers). Results of these analyses can be found in Table II.

As anticipated, age and beHFPTA were strongly intercorrelated. Both age and beHFPTA were significantly associated with all four CoP metrics; the older the participant and the more hearing loss they had, the larger the excursions they exhibited during the postural control task. Two partial correlation analyses were then conducted: one controlling for age and the other controlling for beHFPTA. When age was controlled, beHFPTA continued to be associated with dual-task CoP measures for both the easier task and the harder task. When beHFPTA was controlled, age was no longer significantly associated with either of these variables. These results replicate those of our previous study (Helfer *et al.*, 2020), demonstrating that amount of high-frequency hearing loss in our middle-aged participants was associated with poorer postural control, especially in dual-task conditions.

IV. DISCUSSION

The study described in this paper was designed to determine the extent to which having to complete an active postural control task and a challenging speech understanding task together (i.e., a dual-task) compromises performance on

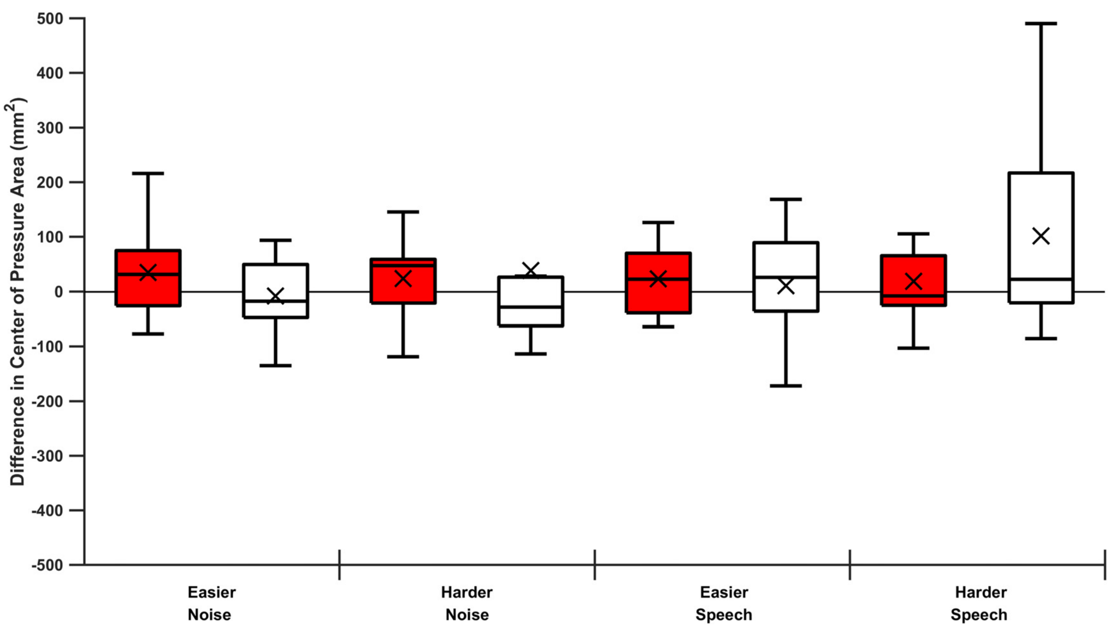

FIG. 9. (Color online) Dual-task costs for postural control for younger (red) and middle-aged (white) participants (CoP for dual-task - CoP for single-task).

TABLE II. Correlation coefficients for analyses examining associations among age, better-ear high-frequency average (beHFPTA; average of thresholds from 2 kHz to 6 kHz), and postural control in the single-task (SingE for the easier postural control task; SingH for the harder postural control task) and dual-task (DualE for the easier postural control task; DualH for the harder postural control task) conditions. *, significant at the 0.05 level; **, significant at the 0.01 level.

Pearson r	beHFPTA	SingE	SingH	DualE	DualH
Age	0.701**	0.452*	0.419*	0.349	0.415*
beHFPTA		0.465*	0.428*	0.541**	0.694**
Partial correlation controlling for age		SingE	SingH	DualE	DualH
beHFPTA		0.233	0.208	0.443*	0.621**
Partial correlation controlling for beHFPTA		SingE	SingH	DualE	DualH
Age		0.199	0.185	−0.050	−0.139

each of those tasks. Results indicate that it was primarily the balance task that was negatively impacted during dual-task conditions. Although there was a significant task × masker interaction in the speech perception data (where performance was poorer during the harder postural control task vs the easier postural control task when the masker was speech), the numerical difference in means between these conditions was quite modest (two percentage points for the younger participants and five percentage points for the middle-aged participants). As was our intention, percent-correct speech understanding varied little between groups for either the single- or dual-task condition. Adding this speech perception task to the postural control task had minimal impact for our younger adults but, at least for some of our middle-aged participants, led to a decrement in postural control, especially when the masker was competing speech. Even though the middle-aged participants were able to achieve approximately the same speech perception accuracy as the younger adults during dual-task conditions, it came at a cost to postural control. Additionally, on average, our middle-aged participants judged the speech understanding task to be more effortful than did the younger adults.

Our interpretation of this pattern of results is that communicating in the presence of competing messages required greater cognitive resources for our middle-aged than for our younger participants, leaving fewer resources for performing the postural control task. This is consistent with prior work showing that speech understanding in noise is more effortful for middle-aged adults than it is for younger adults (e.g., Degeest *et al.*, 2015; Helfer *et al.*, 2020), and that middle-aged adults are particularly susceptible to masking by competing speech (e.g., Başkent *et al.*, 2014; Cameron *et al.*, 2011; Füllgrabe *et al.*, 2015; Glyde *et al.*, 2013; Goossens *et al.*, 2017; Hannula *et al.*, 2011; Helfer and Freyman, 2014, 2016; Helfer *et al.*, 2018; Shinn-Cunningham *et al.*, 2013; Tremblay *et al.*, 2015; Wiley *et al.*, 1998). Moreover, it extends findings of prior work showing greater dual-task costs in older than younger adults when postural control tasks are combined with a cognitive or speech perception task requiring a verbal response (e.g., Bohle *et al.*, 2019; Bruce *et al.*, 2017; Granacher *et al.*, 2011). Finally, the present results also confirm a smaller body of work indicating that dual-task costs for motor control tasks can be demonstrated in middle-aged adults (Brustio *et al.*, 2017; Helfer *et al.*, 2020; Hollman *et al.*, 2007; Lindenberger *et al.*, 2000).

As reported in our previous paper on balancing while listening (Helfer *et al.*, 2020), greater hearing loss in the present study's participants was associated with poorer postural control. When age was controlled, beHFPTA was correlated with postural control in dual-task conditions. Other research has shown that hearing loss in older adults can impact posture and gait (e.g., Kowalewski *et al.*, 2018; Li *et al.*, 2013; Thomas *et al.*, 2018; Tomioka *et al.*, 2015; Viljanen *et al.*, 2009a) and is associated with an increased risk of falls (e.g., Jiam *et al.*, 2016; Lin and Ferrucci, 2012; Viljanen *et al.*, 2009b). Also relevant to the current work is the finding that older adults with hearing loss have greater dual-task costs than younger adults in a paradigm that combined an auditory working memory task with a postural control task involving recovery from perturbations (Bruce *et al.*, 2017).

Our research extends the previously established connection between hearing and postural control to middle-aged adults. Perhaps the most parsimonious explanation for this association is that the early age-related changes in the inner ear that bring about hearing loss in middle-aged adults coexist with subtle changes in vestibular function. However, there are several other potential explanations, including that hearing loss may lead to a need to allocate more cognitive resources to listening, or that age-related changes reduce the ability to use auditory cues to monitor one's body position in space (Campos *et al.*, 2018). Although additional studies need to be conducted to clarify the factors underlying the connection between hearing loss and postural control, it appears that hearing loss that occurs relatively early in the aging process is accompanied by changes in balance performance. This may help explain why individuals with mild hearing loss are three times more likely to fall than their age-matched normally hearing peers (Lin and Ferrucci, 2012).

Prior work has shown that noise can reduce postural sway in both younger (e.g., Gandemer *et al.*, 2017; Zhong and Yost, 2013) and older (Vitkovic *et al.*, 2016) adults, although there are reports of hearing loss reducing this effect (Vitkovic *et al.*, 2016). We sought to determine whether the presence of noise would improve postural control to the same degree in our younger and middle-aged participants. We were unable to adequately address this question as in the present study noise was not significantly beneficial for either group, whether quantified in terms of objectively measured CoP or subjectively measured self-rated postural control effort. Perhaps the nature of our active postural control task, which required greater cognitive mediation and postural guidance than the tasks used in previous studies, led to this negative finding. We did not measure baseline postural control (with participants simply standing without an active postural task) in the presence of noise, and it is feasible that having to perform a second task at the same time as the postural control task masked any potential benefit of noise. If additional research confirms this finding, it would suggest that the presence of noise is not beneficial to postural control performance when individuals are simultaneously engaged in another task.

As is typical in most dual-task studies that combine a motor control task with a second task that requires a verbal response, postural control in the current work was measured across the entire trial (that is, when the participant was listening as well as when they were responding). Research has established that talking influences performance on balance and kinematic tasks (Dault *et al.*, 2003; Frazier and Mitra, 2008; Raffegeneau *et al.*, 2018; Yardley *et al.*, 1999), perhaps to a greater extent in older adults than in younger adults (Ayers *et al.*, 2014; Kemper *et al.*, 2003). This raises a question regarding the extent to which group differences in postural control identified in our work, as well as in similar studies, are due to age-related changes in speech processing (i.e., speech perception) vs age-related changes in talking (i.e., speech production). Our preliminary analysis on the postural control data excised into listen-only and respond-only intervals (shown in the Appendix) found that CoP values did not differ systematically between listen-only and respond-only data for either participant group. However, there was a significant interaction between analysis interval and postural task difficulty: the difference between postural control for the easier vs the harder postural task was significant in the listen-only intervals but not in the respond-only intervals. Additionally, group differences in postural control during dual-task conditions analyzed across the entire trial (listen + respond) were larger when the masker was competing speech than when it consisted of SSN (see Fig. 6). Since there is no reason to think that the influence of talking on postural control would differ between trials with competing speech vs with the SSN masker (especially since the maskers were not being presented when individuals were making their verbal responses), we believe that group differences in CoP in the present study were primarily driven by degradations in speech understanding. This idea is supported by previous studies showing that middle-aged adults, under certain conditions, have more difficulty understanding speech in the presence of competing speech vs when speech is presented in less complex noise (e.g., Goossens *et al.*, 2017; Helfer and Freyman, 2014, 2016; Helfer *et al.*, 2018).

The active postural control task that we incorporated in the present study is an example of an augmented information feedback task, commonly used in motor learning, aging, and rehabilitation studies. One potential limitation is that this task is not one that individuals would encounter in their day-to-day lives. Nevertheless, we believe that it can inform the postural challenges that people may face during everyday tasks as they age. People inherently use the feedback provided by the visual, proprioceptive, and the vestibular systems to stay balanced. Both older and younger adults also can use extrinsic visual feedback to enhance balance. For example, Pinsault and Vuillerme (2008) reported reductions in postural displacement in older individuals when given visual feedback of their CoP as compared to conditions with no visual feedback. Vaillant *et al.* (2004) found that adding external postural information from a mirror reduced postural sway when both younger and older individuals were asked to stand still. In our study design, the visual CoP feedback was intentionally manipulated to allow us to alter task difficulty and increase cognitive demands. Further, our methodology required participants to constrain their CoP excursions, similar to what occurs naturally when we move closer to stability boundaries formed by the base of support at the feet, such as when we lean to reach forward, move backward or sideways (Van Emmerik and Van Wegen, 2002; Van Wegen *et al.*, 2002).

V. CONCLUSIONS AND FUTURE DIRECTIONS

Overall, our results support the idea that middle-aged adults can be challenged in complex listening situations, especially when they are also performing another task concurrently. It is worth noting that there has been relatively little research devoted to identifying functional hearing changes in middle age, even though people in this age group are likely to still be working and so may frequently need to multitask in adverse acoustical environments. Additional research is needed to define the nature of tasks that interfere with multitasking in middle-aged adults and how we might help remediate these problems. For example, there is some evidence that postural control is better in people with hearing loss when they are using their hearing aids vs when they are unaided (Negahban *et al.*, 2017; Rumalla *et al.*, 2015; Weaver *et al.*, 2017), although other studies have failed to show this beneficial effect (Kowalewski *et al.*, 2018; McDaniel *et al.*, 2018). Conceptually, if hearing aids can reduce listening effort, they should lead to smaller dual-task costs, including less of an impact on balance. To date, research has not examined whether hearing aids can improve postural control in dual-task studies involving listening while balancing. Clearly, more research needs to be conducted to clarify whether providing amplification leads to enhanced postural control when individuals are called upon to perform more than one task at a time. Future research also should be conducted to identify the real-life implications of early aging changes in the ability to multitask.

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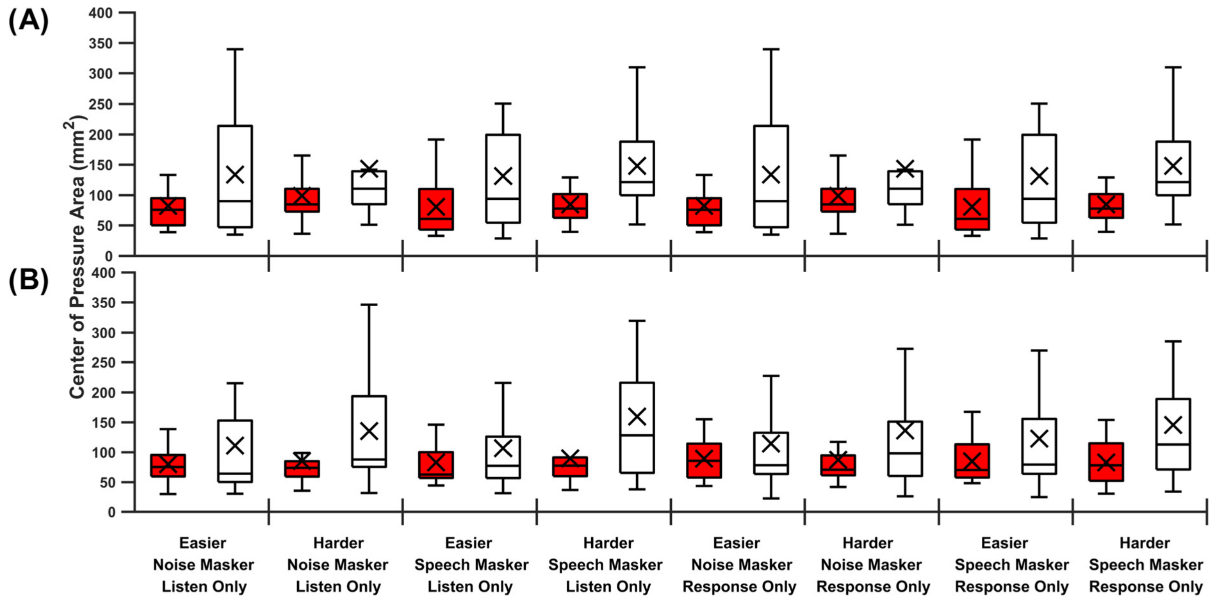

FIG. 10. (Color online) Postural control (CoP) for listen-only intervals and respond-only intervals for single-task conditions (A) and dual-task conditions (B). Red, younger participants; white, middle-aged participants.

APPENDIX

We conducted an initial analysis that compared CoP excised just for the intervals of time during each trial when participants were listening to CoP measured during the time intervals when participants were responding (i.e., repeating back what they heard). The trends in these two sets of data were quite similar (see Fig. 10). ANOVAs were conducted separately for single-task and dual-task data with analysis interval (listen-only vs respond-only), postural control task difficulty (easier vs harder), and masker (noise vs speech) as within-subject variables and group as a between-subjects variable. The single-task analysis showed nonsignificant main effects of analysis interval and task difficulty with no significant interactions. The main effect of group just missed statistical significance [$F(1,28) = 4.07$, $p = 0.054$, $\eta_p^2 = 0.127$]. For the dual-task data, there was a significant main effect of task difficulty [$F(1,28) = 10.21$, $p = 0.003$, $\eta_p^2 = 0.267$], a significant task difficulty × group interaction [$F(1,28) = 7.80$, $p = 0.009$, $\eta_p^2 = 0.218$], and a significant interaction of analysis interval × task difficulty [$F(1,28) = 6.43$, $p = 0.017$, $\eta_p^2 = 0.187$]. *Post hoc* pairwise *t*-tests adjusted for multiple comparisons indicated that the analysis interval × task difficulty interaction was due to the fact that the easier and the harder postural control conditions differed for the listen-only data but not for the respond-only data.

[1]It could be argued that our single-task speech recognition condition was also dual-task because it was measured with participants standing rather than seated. Indeed, research has shown that reaction time measured during an attentional task is longer when individuals are standing vs when they are seated (Lajoie *et al.*, 1993), suggesting that standing may be more attentionally demanding than sitting.

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