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## RESEARCH ARTICLE

# Age-Related Differences in the One Target Advantage: Exploring the Impact of Augmented Sensory Feedback

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**ABSTRACT.** The one-target advantage (OTA) refers to faster execution of single-target movements compared to the same movement embedded in a two-target reaching sequence. While well documented in younger adults, little is known about OTA in older adults with age-related motor changes. This study examined whether augmented sensory feedback modulates goal-directed aiming during the OTA paradigm. Thirty right-handed participants (15 younger, 15 older adults) performed one- and two-target aiming tasks under vibrotactile (VT), auditory (A), and no-feedback (NF) conditions. Results showed that reaction time was shorter in the two-target task than in the one-target task under VT feedback ( $p = .002$ ). Older adults demonstrated significantly shorter movement times with VT than with NF. Older adults showed greater undershooting in the two-target task under NF, which was reduced with VT feedback ( $p = .011$ ). Additionally, older adults typically spent longer in the time after peak velocity, but VT feedback significantly reduced this duration. Overall, VT feedback improved both temporal and spatial measures, particularly for older adults. Auditory feedback showed limited effects, influencing only TAPV1 ( $p = .036$ ). Together, these results highlight the potential of VT feedback to mitigate age-related motor performance declines.

**Keywords:** one-target advantage, goal-directed movement, aging, augmented feedback

## Introduction

The one-target advantage (OTA) refers to the phenomenon where a rapid goal-directed movement is executed faster when performed as a single isolated movement compared to when it is followed by a second movement. This effect, primarily characterized by a shorter movement time (MT) to the first target (MT1) when reaching to only one target compared to when a second target is subsequently reached toward, has been extensively studied (Adam et al., 2000; Khan et al., 2006; Lawrence et al., 2013, 2016). Two main hypotheses have been proposed to explain OTA: the movement integration hypothesis and the movement constraint hypothesis. The movement integration hypothesis suggests that movement segments are pre-planned (preloaded) before motor onset, where planning a second segment can influence the first, prolonging MT1 (Adam et al., 2000; Khan et al., 2010). The movement constraint hypothesis argues that increased limb-trajectory

variability in two-target motor sequences leads to more cautious first-segment execution, particularly in older adults, resulting in prolonged MT1 as an accuracy-stabilizing strategy rather than impaired peak acceleration control (Bested et al., 2018; Lawrence et al., 2016).

While the OTA has primarily been examined in terms of movement time (MT), it also extends to the preparatory phase of movement, including reaction time (RT). Foundational work by Henry and Rogers (1960) demonstrated that increased movement complexity such as additional movement segments leads to longer RTs, a concept known as the “memory drum” theory. This principle aligns with findings in the OTA paradigm, where changes in RT occur when participants are aware in advance of how many targets they will encounter. For instance, Khan et al. (2006) and Klapp (1995, 2003) found that RT for two-target movements is longer than for one-target movements when the number of targets is known beforehand, but this difference disappears when the target number is uncertain. More recent work has explored the influence of foreperiod duration on OTA, showing that while OTA-related differences in RT remain stable, the OTA effect on MT increases with longer preparation times (Khan et al., 2024). These findings collectively highlight the importance of motor planning, response complexity, and advance knowledge in optimizing movement performance.

Despite the growing body of OTA research in young adults and populations with developmental disabilities such as Down syndrome (Adam et al., 2000; Khan et al., 2010; Lawrence et al., 2013), the OTA remains underexplored in the context of aging. This gap is critical to address, as age-related motor deficits such as slower movement execution, increased dependence on sensory feedback, and challenges in motor planning may alter or diminish the OTA effect. Since the OTA is thought to reflect the benefits of advanced planning and efficient feedforward control, investigating how it manifests in

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older adults could provide important insight into age-related changes in sensorimotor processing and the preservation or decline of predictive control mechanisms.

Age-related differences in motor performance have been well documented using manual aiming tasks (Elliott et al., 2020; Welsh et al., 2007). Older adults generally exhibit longer movement times, driven primarily by prolonged time after peak velocity (TAPV) - the corrective phase of the movement- rather than differences in time to peak velocity (TTPV), which reflects initial planning. This extended corrective phase is often characterized by slower peak velocities (PV) and a cautious movement strategy that prioritizes accuracy over speed. Such strategies are believed to result from age-related declines in consistent force production (Welsh et al., 2007) and reduced ability to refine motor plans across repeated trials (Seidler-Dobrin & Stelmach, 1998).

Notably, these differences persist even when visual feedback is limited. For instance, Van Halewyck et al. (2015) showed that restricting central visual input *via* eye movement limitations did not disproportionately impair older adults' performance, suggesting they may rely more heavily on proprioceptive cues to guide movements. While this compensatory reliance supports correction in the homing-in phase, it likely contributes to the overall slower and less efficient movement execution seen in aging populations. Augmented sensory feedback has emerged as a promising strategy to improve motor control in older adults. Humans rely primarily on vision and proprioception for fast, accurate reaching. The multiple-process model (Elliott et al., 2010, 2017) posits that movements involve an initial feedforward phase and a feedback-driven correction phase. Visual feedback plays a key role but is often limited by processing delays (Goodman & Tremblay, 2018; Keele & Posner, 1968). In the absence of reliable visual input, proprioception becomes dominant. However, proprioceptive function deteriorates with age, leading to impaired coordination and increased movement variability (Konczak et al., 2007; Herter et al., 2014), which can elevate the risk of falls and injury.

In an effort to find strategies which may compensate for reduced proprioception, researchers have investigated the potential of augmented feedback, particularly vibrotactile (VT) and auditory cues, to enhance motor performance.

Recent evidence supports the cognitive and neuromotor benefits of augmented feedback. O'Meara et al. (2021) found that real-time sensory cues enhance movement efficiency by lowering the cognitive demands of planning, thereby enabling more effective motor control under challenging conditions. This is particularly relevant for older adults performing sequential movements, where both planning and execution must be precisely coordinated and adjusted to ensure smooth and accurate

performance. By incorporating augmented sensory feedback into training and rehabilitation, it may be possible to mitigate age-related motor decline and improve upper limb movement efficiency. Vibrotactile (VT) feedback mechanical vibration delivered through small actuators placed on the skin provides real-time, body-centered cues that guide movement. These tactile signals bypass the need for visual monitoring, helping users make immediate corrections without relying on slower visual processing. This reduction in visual dependency allows for faster and more accurate responses, particularly in older adults who often experience declines in visual acuity and increased reliance on external cues. This aligns with current theories emphasizing the role of multisensory integration in motor learning and control (O'Meara et al., 2021; Scott, 2016). Furthermore, enriched sensory environments have been shown to enhance motor function in older adults, improving outcomes such as balance and lower limb activation (Yazdani et al., 2020). These findings provide a strong rationale for investigating how sensory feedback modulates upper limb goal-directed movements and the OTA in older adults.

In older adults, age-related declines in motor planning and sensorimotor control may reduce the advantages gained (decreased MT and RT) by reaching to one target rather than two targets sequentially. Augmented feedback, particularly VT cues may support these control processes by simplifying the sensory demands of movement planning and allowing more efficient corrective actions.

On the other hand, Auditory feedback has consistently been shown to facilitate motor performance by improving temporal precision, movement efficiency, and neuromuscular engagement. For example, Peters and Glazebrook (2021) demonstrated that auditory stimulation, including rhythmic and non-rhythmic stimuli, reduced reaction times, increased peak velocity, and shortened movement time during goal-directed reaching, suggesting that auditory cues enhance both the planning and execution phases of movement through mechanisms such as temporal predictability and external focus of attention. Complementing these findings, Yazdani et al. (2020) observed that rhythmic auditory cueing significantly increased the motor performance during cycling in older adults, indicating enhanced motor output and coordination when movements are synchronized to an external rhythm. Together, these results highlight the potential of auditory feedback as a simple yet effective tool to support motor control, particularly in aging populations with declining sensory-motor integration.

Thus, the present study aimed to examine how VT and auditory feedback influence goal-directed aiming in younger and older adults using the OTA paradigm. Specifically, we hypothesized that vibrotactile feedback

would enhance performance by reducing both RT and MT, especially in the more complex two-target task, and that the OTA effect would be attenuated in older adults due to reduced planning efficiency and greater reliance on feedback-based control. We further hypothesized that Auditory feedback (A) would be associated with reduced reaction time and faster movement execution in the first and second movement segments through temporal alerting effects (Hatfield et al., 2010), and that, compared to vibrotactile feedback, auditory feedback may show smaller effects in later spatially dependent deceleration limb-target control.

## Materials and Methods

### Participants

An a priori power analysis was conducted using G\*Power 3.1.9.7 (Faul et al., 2007), based on effect sizes reported by Khan et al. (2024), who conducted similar sequential aiming tasks: RT ( $\eta_p^2 = .47$ ), MT1 ( $\eta_p^2 = .58$ ), and CE1 ( $\eta_p^2 = .40$ ). The estimated required sample sizes ranged from 9 to 15 participants per group. To ensure adequate statistical power across dependent variables, a total of 30 neurotypical right-handed participants were recruited, including 15 younger adults (9 female, 6 male;  $M = 25.00 \pm 5.58$  years) and 15 older adults (7 female, 8 male;  $M = 66.26 \pm 4.02$  years). All participants reported normal or corrected-to-normal vision and hearing, no orthopedic injuries to the dominant arm in the past 6 months and provided written informed consent. Ethics approval was granted by the University of Manitoba Research Ethics Board under the approval number of HE2023-0292 and all procedures adhered to the Declaration of Helsinki (2013 revision).

### Apparatus

Participants performed reaching movements using a custom stylus on a 22-inch Dell-E2222H touchscreen monitor mounted horizontally on a table 76 cm above ground. Participants were seated so that their midline was parallel to the center of the touchscreen. The stylus was equipped with an infrared-emitting diode (IRED), placed on the distal and lateral end of the custom handheld stylus, to be tracked in 3D using an Optotrak 3D Investigator (Northern Digital Inc., Waterloo, ON) sampling the position of the IRED at 300 Hz. Augmented feedback was delivered *via* E-Prime 3.0 software (Psychology Software Tools, Sharpsburg, PA, USA) and a Chronos response and stimulus device (Model Chronos v1.4, Psychology Software Tools, Sharpsburg, PA, USA). Auditory feedback consisted of a 1000 Hz tone emitted by a piezoelectric buzzer (Adafruit, Product ID: 1739) for 200 ms. Vibrotactile feedback was provided *via* a brushless DC vibration motor (Precision

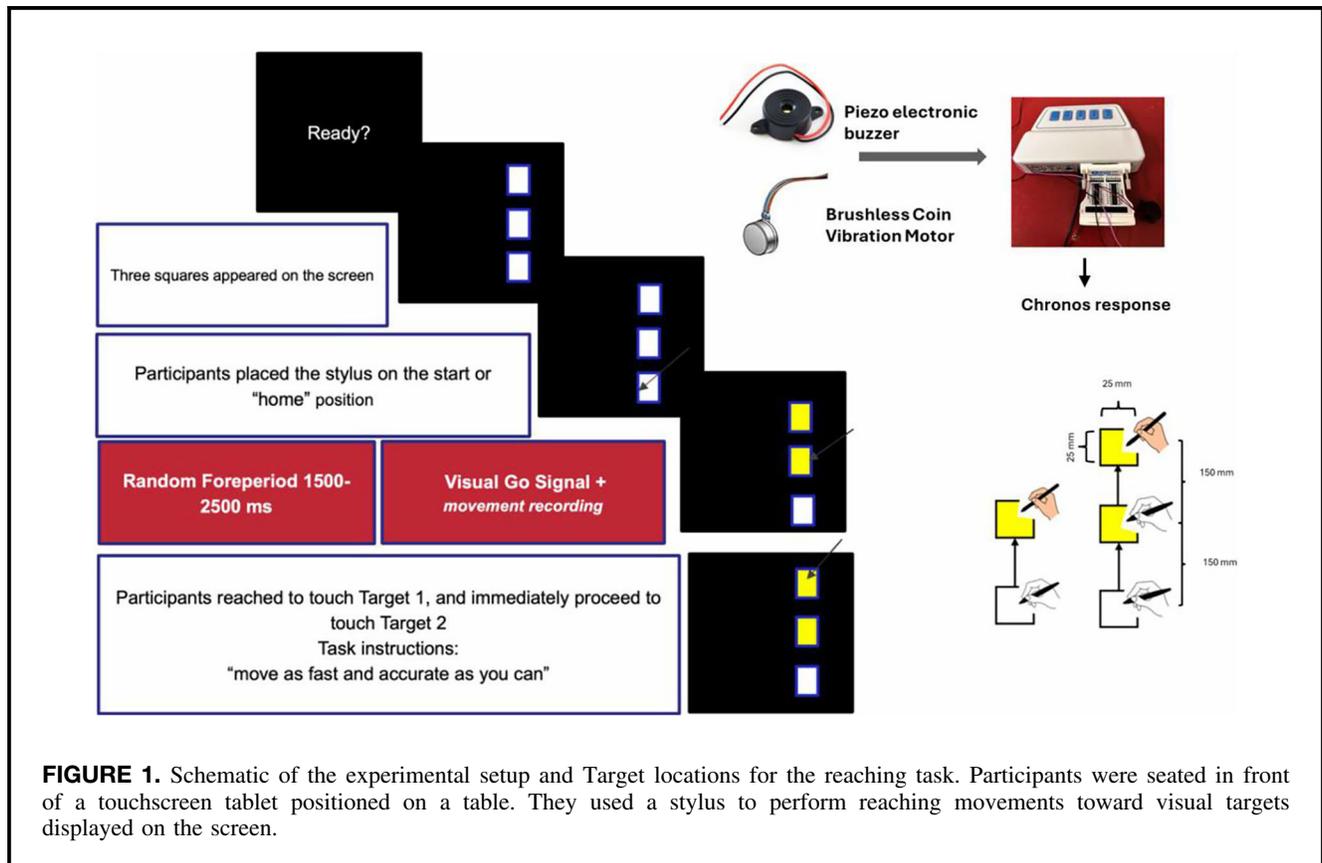
Microdrives, Model 913-101), mounted on the distal tip of the stylus and activated for 200 ms. The motor delivered vibrations at approximately 12,000 RPM ( $\sim 200$  Hz) with an acceleration amplitude of 1.2 g, controlled using a custom-built driver circuit powered *via* USB. All augmented feedback was triggered immediately following contact with the first target. As illustrated in Figure 1, for the one-target task participants were able to see two squares ( $2.5 \times 2.5$  cm each) on the touchscreen: one designated as the home position (the closest to them) and the other as the target. For the two-target task, participants could see three squares aligned in a row on the screen, with the home position (the closest target to them), Target 1 in the middle, and Target 2 as the farthest target away from them.

### Procedure

Participants were required to perform one and two-target goal-directed aiming movements that included lifting the stylus from the screen before moving through 3D space to touch the target. Before starting the main experiment, participants completed a pretest to ensure they could detect the visual, auditory, and vibrotactile stimuli used in the experiment. The pretest included five trials for each of the three conditions (no feedback, auditory, and vibrotactile), for a total of 15 trials, in which participants were instructed to lift the stylus whenever they detected a stimulus. Participants knew in advance what type of stimulation they would take. Once it was confirmed that participants could detect the stimuli, they proceeded to the main experiment.

Each trial for the main experiment began with participants placing the stylus on the home position. Once the home position was contacted, a randomly selected foreperiod (1500–2500 ms) was initiated. Following the foreperiod, the target(s) changed from white to yellow, which was the ‘go’ signal to lift the stylus from the start position and touch the first target. In the two-target task, participants were instructed to move to target one and then continue their movement to the second target. Once participants touched target one, they received the augmented feedback (i.e. auditory or vibrotactile). Participants were instructed to move as quickly and as accurately as they could to touch target one and proceed to target two in the same fashion.

Participants were instructed to touch the target center, with the requirement that the stylus tip must land inside the square target boundary on the capacitive touchscreen. Touches outside the square region were not registered by the program. That is, the next trial could not begin until a valid contact inside the target area was registered on the touchscreen. No specific constraints were imposed on touch force or hold duration beyond standard capacitive touch detection.



Participants performed 20 trials of each sensory condition (auditory, vibrotactile, no feedback) in the one-target condition and 20 trials of each sensory condition in the two-target condition, for a total of 120 trials. The target task and sensory condition were blocked such that all trials with the same condition were grouped together, with the order of blocks being counterbalanced between participants. Participants were provided with instructions prior to each block so that they knew in advance if they would be performing one-target or two-target movements, and which sensory condition they could expect. Participants received a break of approximately 5 min between blocks of trials if they reported any fatigue. Testing took between 30 to 60 min for each participant and was completed in one session.

### Dependent Variables

Temporal and spatial performance measures, as well as movement kinematic variables associated with the first movement segment included: The primary dependent variables are reaction time (RT), movement time<sub>1</sub> (MT<sub>1</sub>), peak velocity<sub>1</sub> (PV<sub>1</sub>), Time to peak velocity<sub>1</sub> (TTPV<sub>1</sub>), Time after peak velocity<sub>1</sub> (TAPV<sub>1</sub>), constant error<sub>1</sub> (CE<sub>1</sub>), and variable error<sub>1</sub> (VE<sub>1</sub>).

The dependent variables associated with the second segment of the movement included: pause time (PT),

movement time<sub>2</sub> (MT<sub>2</sub>), peak velocity<sub>2</sub> (PV<sub>2</sub>), time to peak velocity<sub>2</sub> (TTPV<sub>2</sub>), time after peak velocity<sub>2</sub> (TAPV<sub>2</sub>), constant error<sub>2</sub> (CE<sub>2</sub>) and variable error<sub>2</sub> (VE<sub>2</sub>).

RT was defined as the time from the visual go-signal to movement initiation. MT was defined as the time from movement onset to movement offset. PV was defined as the highest velocity that the marker reached during movement execution in the resultant. TTPV and TAPV were defined as the duration of time from movement initiation to peak velocity and from peak velocity to movement end, respectively. PT was defined as the duration of time spent at the first target during two-target movement task. VE was calculated as the standard deviation of the differences between actual endpoint and target locations and CE was calculated as the mean of the differences between the actual endpoint and target locations.

### Data Analysis

We utilized E-Prime software to precisely control the presentation of visual targets and to synchronize the onset of the visual go-signal with the initiation of movement recording. This ensured accurate timing between stimulus presentation and data acquisition.

After participants completed the main experimental tasks, we conducted a calibration phase to assess their perceived target centers. In this phase, participants were instructed to place their stylus at the center of each target location. Once positioned, a 5-s stationary trial was recorded for each target. These recordings were subsequently used to calculate endpoint error, providing insights into the accuracy of participants' target localization.

Movement onset was defined as the first frame that the resultant velocity of the IRED reached 30 mm/s and stayed above that velocity for 30 ms. Movement offset was defined as the first frame that the resultant velocity fell below 30 mm/s and stayed below that velocity for 30 ms.

A mixed between-within factorial design was employed to assess the effects of three sensory feedback conditions (auditory, vibrotactile, and no feedback) on movement performance in one- and two-target goal-directed aiming tasks. The between-subjects factor was age group (younger vs. older adults), and the within-subjects factors were sensory condition and target task. Each participant experienced all combinations of sensory condition and target task in a fully counterbalanced design.

For the variables associated with the first movement segment a three-way, 2 Age Group (Younger, Older)  $\times$  3 Sensory Condition (Auditory, Vibrotactile, No feedback)  $\times$  2 Target Task (1 Target, 2 Target) mixed ANOVA, with repeated measures on the last two factors. For the dependent variables associated with the second movement segment, a two-way, 2 Age Group (Younger, Older)  $\times$  3 Sensory Condition (Auditory, Vibrotactile, No Feedback) mixed ANOVA, with repeated measures on the Sensory Condition factor, was used. The raw data was tested for normality and for equality of variances using the Shapiro-Wilk test and Levene's test, respectively. The assumption of normality was met. Lastly, Mauchly's test of sphericity was used to test the assumption of sphericity for the repeated measures variables. Tukey's HSD was used to locate significant differences post hoc. Alpha was set at 0.05 for the omnibus and post-hoc tests. All statistical tests were conducted using SPSS (version 28.0; IBM Corp., Armonk, NY, USA).

The raw position data was filtered using a second-order dual-pass Butterworth 15 Hz low-pass cutoff filter. Moreover, prior to the analyses, data were visually assessed for outlier values that may have resulted from technical or data entry errors. Outliers were identified for each dependent variable separately, including temporal measures (RT, MT1, and MT2) and spatial accuracy measures (CE1, CE2 and VE1, VE2). A trial was excluded from a specific analysis if its value for that dependent variable exceeded  $\pm 2.5$  standard deviations from the participant's mean for that variable. Importantly, trials were not excluded from all analyses

based on a single measure; exclusion was applied on a variable-by-variable basis. Using this approach, approximately 9.72% of data points were excluded across all measures.

## Results

Statistically significant results are reported below. A full statistical summary, including non-significant results can be found in [Appendix Tables 1–4](#). Detailed ANOVA results for one-target performance and spatial measures are presented in [Appendix Tables 1 and 2](#). Corresponding results for two-target performance and spatial measures are summarized in [Appendix Tables 3 and 4](#).

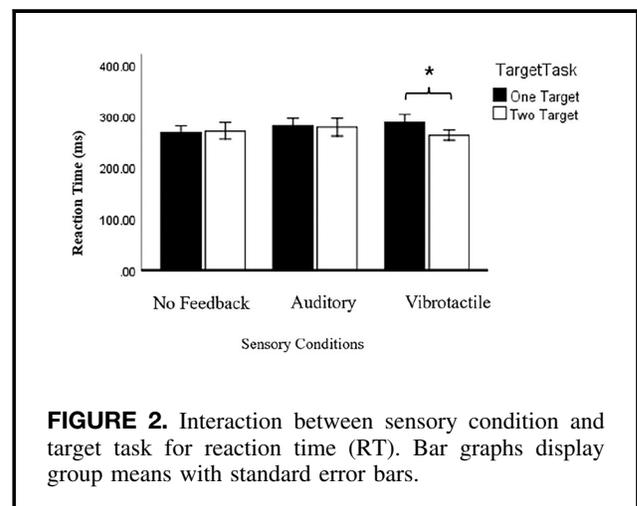
### Temporal Measures: Reaction Time and Movement Time

#### Reaction Time (RT)

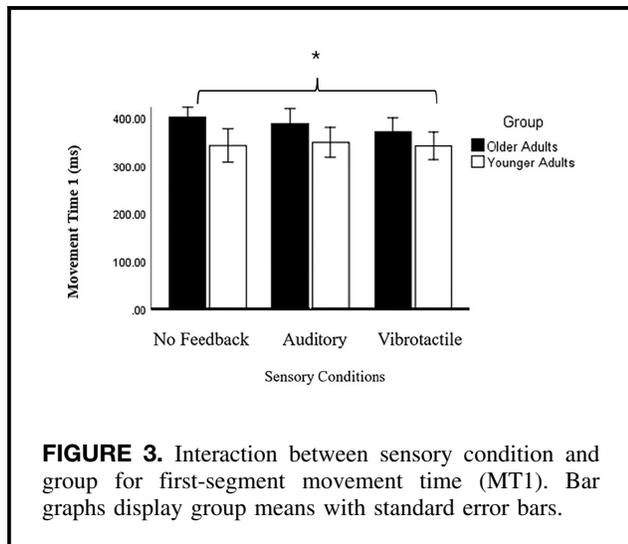
A main effect of group on reaction time (RT) was observed ( $F_{1, 28} = 7.40$ ,  $p = .011$ ,  $\eta_p^2 = .21$ ) with older adults responding slower ( $M = 291$  ms,  $SE = 8$  ms) than younger adults ( $M = 258$  ms,  $SE = 8$  ms). A significant interaction was also found between sensory condition and target task for (RT),  $F_{2, 56} = 4.99$ ,  $p = .010$ ,  $\eta_p^2 = .15$ . As illustrated in [Figure 2](#), post hoc comparisons revealed that under vibrotactile feedback RT was significantly shorter ( $p = .002$ ) in the two-target condition ( $M = 262$  ms,  $SE = 5$  ms) compared to the one-target condition ( $M = 287$  ms,  $SE = 8$  ms).

#### Movement Time 1 (MT1)

For MT1, a Group  $\times$  Sensory Condition interaction was significant,  $F_{2, 56} = 4.16$ ,  $p = .021$ ,  $\eta_p^2 = .12$ . Older adults benefited most from vibrotactile feedback ( $M = 370.51$  ms,  $SE = 14.18$  ms) compared to no-feedback ( $M = 400$  ms,  $SE = 17$  ms), ( $p = .002$ ), whereas



**FIGURE 2.** Interaction between sensory condition and target task for reaction time (RT). Bar graphs display group means with standard error bars.



younger adults showed no significant differences across sensory conditions; no feedback ( $M = 342$  ms,  $SE = 17$  ms), auditory feedback ( $M = 348$  ms,  $SE = 15$  ms), and vibrotactile feedback ( $M = 341$  ms,  $SE = 14$  ms). These effects are illustrated in Figure 3.

There was also a main effect of target task for MT1,  $F_{1, 28} = 4.75$ ,  $p = .038$ ,  $\eta_p^2 = .15$ , with faster performance in the one-target task ( $M = 355$  ms,  $SE = 11$  ms) compared to the two-target task ( $M = 374$  ms,  $SE = 11$  ms). Additionally, there was a main effect of sensory condition,  $F_{2, 56} = 4.84$ ,  $p = .011$ ,  $\eta_p^2 = .14$ , with significantly shorter MT1 in the vibrotactile condition than in the no-feedback condition ( $p = .028$ ).

### Movement Time 2 (MT2)

For movement time to the second target (MT2), the effect of sensory condition was significant,  $F_{2, 56} = 3.67$ ,  $p = .032$ ,  $\eta_p^2 = .11$ . Post-hoc results indicated that MT2 was significantly faster ( $p = .022$ ) in the vibrotactile condition ( $M = 358$  ms,  $SE = 11$  ms) compared to the no-feedback condition ( $M = 378$  ms,  $SE = 14$  ms) and the auditory condition ( $M = 375$  ms,  $SE = 12$  ms).

### Spatial Accuracy

#### Constant Error (CE1)

For constant error at the first target (CE1), a significant interaction between sensory condition and target task emerged,  $F_{2, 56} = 9.11$ ,  $p < .001$ ,  $\eta_p^2 = .25$ . Tukey's HSD showed that, in the no-feedback condition, participants undershot more in the two-target task ( $M = -0.7$  mm,  $SE = 0.52$  mm) compared to the one-target task ( $M = 0.7$  mm,  $SE = 0.41$  mm;  $p = .011$ ).

A significant three-way interaction (Group  $\times$  Sensory  $\times$  Task) was also found,  $F_{2, 56} = 5.14$ ,  $p = .009$ ,  $\eta_p^2 = .16$ . This was driven by older adults, who showed greater undershooting  $p = .005$  in the two-target/no-feedback

condition ( $M = -1.6$  mm,  $SE = .74$  mm), but not in Auditory (A) or Vibrotactile (VT) conditions. In contrast, their performance across target tasks was similar in the auditory ( $M = -0.5$  mm vs.  $-0.9$  mm) and vibrotactile ( $M = -.1$  mm vs.  $-.6$  mm) conditions. Younger adults showed no significant differences across sensory conditions or target tasks (see Appendix Table 1).

#### Variable Error 2 (VE2)

A significant main effect of group was found for VE2,  $F_{1, 28} = 5.61$ ,  $p = .025$ ,  $\eta_p^2 = .17$ , with younger adults showing greater endpoint variability ( $M = 4.00$  mm,  $SE = .26$  mm) than older adults ( $M = 3.13$  mm,  $SE = .26$  mm), indicating more consistent performance in older adults.

### Kinematic Control

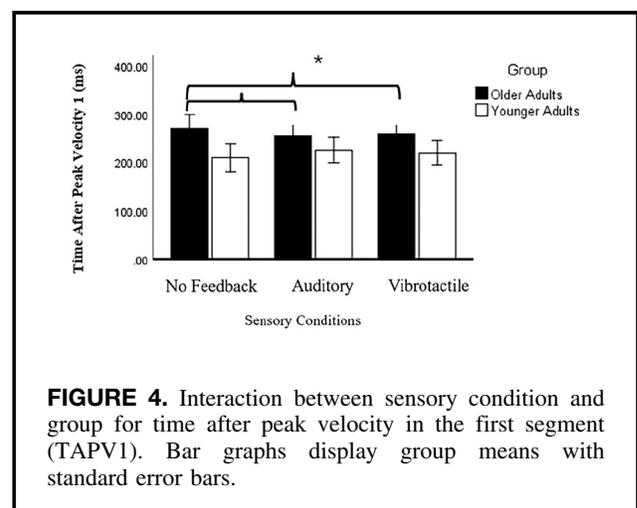
#### Time After Peak Velocity 1 (TAPV1)

For TAPV1, a Group  $\times$  Sensory Condition interaction was significant,  $F_{2, 56} = 3.79$ ,  $p = .029$ ,  $\eta_p^2 = .12$ . Examination of sensory effects within each group showed that older adults exhibited shorter time after peak velocity under Auditory feedback (A) ( $M = 256$  ms,  $SE = 13$  ms) and Vibrotactile feedback (VT) ( $M = 259$  ms,  $SE = 12$  ms) compared to No Feedback (NF) ( $M = 270$  ms,  $SE = 14$  ms), with the most reliable pairwise effect emerging in VT versus NF ( $p = .036$ ). Younger adults showed no reliable sensory-related modulation of TAPV1 (all comparisons were non-significant).

Figure 4 illustrates the significant main effect of group on TAPV1,  $F_{1, 28} = 6.03$ ,  $p = .021$ ,  $\eta_p^2 = .18$ , confirming that older adults had longer TAPV1 timing overall, independent of sensory condition.

#### Time After Peak Velocity 2 (TAPV2)

For TAPV2, a main effect of sensory condition was found,  $F_{2, 56} = 8.57$ ,  $p = .001$ ,  $\eta_p^2 = .23$ . Post-hoc analysis



revealed that participants had significantly shorter TAPV2 in the vibration condition ( $M = 222$  ms,  $SE = 9$  ms) compared to both the no-feedback ( $M = 248$  ms,  $SE = 12$  ms;  $p = .038$ ) and auditory feedback conditions ( $M = 238.84$  ms,  $SE = 11$  ms;  $p < .001$ ), suggesting that vibrotactile feedback facilitated faster movement completion (see [Appendix Table 4](#)).

## Discussion

This study examined how augmented sensory feedback (vibrotactile and auditory) influences goal-directed aiming in both younger and older adults using the one-target advantage (OTA) paradigm. Collectively, the results indicate that augmented feedback was associated with improvements in select temporal and spatial kinematic variables, with vibrotactile feedback demonstrating the most consistent and pronounced changes, particularly in older adults and under higher planning complexity.

### Temporal Measures: Reaction and Movement Time

Our results align with previous findings on the OTA (Adam et al., 2000; Khan et al., 2010; Lawrence et al., 2016), showing that reaction times (RT) were generally longer in the two-target condition. However, the facilitative effect linked to vibrotactile feedback reversed this trend, with significantly shorter RTs for the two-target task compared to the one-target condition under VT feedback. This interaction suggests that predictable vibrotactile feedback may help older adults prepare and initiate more complex movements despite the additional planning demands.

The above findings are consistent with research showing that tactile stimuli can reduce RT under high cognitive load. For example, Scott and Gray (2008) found that drivers responded significantly faster when provided with a vibrotactile rear-end collision warning, and Raveh et al. (2018) demonstrated that prosthesis users completed grasping tasks faster with vibrotactile cues while managing a simultaneous driving task. Similarly, Rosa et al. (2020) reported that tactile warning signals remained effective even under increased pilot workload. Taken together, these findings are consistent with the present results in that tactile alerts appear to remain effective when cognitive load is increased. Thus, performance gains for the older adults may be linked with increased preparedness that is most effective with augmented vibrotactile feedback specifically.

Movement times (MT1 and MT2) were also significantly affected by sensory feedback, particularly VT, which led to faster execution compared to no feedback. These findings could indicate compensation for longer planning intervals or reduced endpoint uncertainty, but this explanation remains tentative given that planning processes were not manipulated or measured directly.

This finding aligns with prior research by Lieberman and Breazeal (2007), who showed that VT guidance enhanced motor precision and speed by offering continuous, body-integrated feedback that facilitated more direct motor corrections. The results of the current study are consistent with these findings by showing that older adults especially benefited from tactile feedback, which significantly reduced their movement time in the first segment (MT1).

Overall, the temporal results support the two major theoretical accounts of the OTA. The movement integration hypothesis (Adam et al., 2000; Bested et al., 2018) posits that planning both segments in advance leads to longer MT1 due to cognitive load. In contrast, the movement constraint hypothesis (Lawrence et al., 2016) argues that increased motor variability in two-target tasks leads to slower, more cautious execution. Our finding that vibrotactile feedback shortened both RT and MT, particularly under higher task complexity, suggests that vibrotactile feedback may reduce some of the demands associated with either pre-planning multiple segments or managing increased movement variability.

### Spatial and Kinematic Control Findings

Although main effect of sensory condition did not significantly affect spatial accuracy overall, a key interaction between sensory condition and target task was observed for constant error (CE1). In the absence of augmented feedback, participants undershot more in the two-target task, especially older adults. This is in line with the understanding that increased task complexity impairs accuracy when reliable sensory input is unavailable (Konczak et al., 2007; Seidler et al., 2010). The inclusion of auditory or vibrotactile feedback mitigated these errors, particularly in older adults, supporting prior findings that real-time augmented feedback can assist with endpoint control when proprioception is diminished (Lieberman & Breazeal, 2007).

The finding that older adults exhibited lower variable error in the second movement segment (VE2) compared to younger adults is particularly noteworthy. Rather than reflecting superior overall performance, this movement pattern could reflect a speed-accuracy tradeoff in which older adults adopt more conservative, consistent trajectories at the expense of movement speed. This interpretation is consistent with previous work suggesting that older adults prioritize stability and accuracy, especially in later movement phases, by prolonging phase after peak velocity and relying more heavily on feedback-based corrections (Elliott et al., 2020; Welsh et al., 2007). In this context, lower VE2 could represent a compensatory strategy to maintain endpoint control rather than a performance advantage in spatial consistency per se.

Kinematic analyses revealed no significant differences in peak velocity (PV1 or PV2) or time to peak velocity (TTPV1 or TTPV2) across sensory conditions, indicating that feedback primarily affected the later phase of movement. Instead, feedback effects were observed in the limb-target control phase. Specifically, time after peak velocity in the first movement segment (TAPV1) was shorter when Vibrotactile and Auditory feedback were provided, whereas TAPV2 in the second segment was selectively shorter with vibrotactile feedback, with this association being particularly evident in older adults.

Although auditory feedback was linked to shorter TAPV1, its influence may reflect increased temporal alerting rather than enhanced spatially precise target acquisition. Moreover, the brief (200 ms) auditory tone used in the current design may have competed with visually-driven endpoint corrections due to its weaker body-limb coupling compared to vibrotactile guidance. The different feedback locations could partly explain why auditory input did not show the same association as Vibrotactile feedback in TAPV2, a segment more dependent on spatially localized limb control as the target is approached.

Together these findings are consistent with studies showing that tactile cues can support smoother and faster movements during the phase after peak velocity by supplying real-time updates that assist online limb-target regulation (e.g., Sigrist et al., 2013; Tzorakoleftherakis et al., 2015).

### Limitations and Future Directions

Despite the promising findings, several limitations should be acknowledged. First, non-linear or direction-changing target arrangements may influence the expression of the OTA and the effectiveness of vibrotactile or auditory feedback. Future studies should incorporate multi-directional trajectories to evaluate generalization to everyday reaching tasks. Second, the stylus-on-touchscreen task used in this study does not fully replicate free-space reaching or many activities of daily living. Although this setup allowed precise kinematic and endpoint measurement of a movement controlled in a 2D plane, future research should examine whether similar vibrotactile and auditory feedback effects generalize to more naturalistic 3D reaching tasks that include multiple directions or object manipulation. In addition, the present study only assessed immediate, single-session performance; longer-term practice and retention were not evaluated. Future work should incorporate

multi-session training and follow-up assessments to determine whether the benefits of the augmented feedback persist, accumulate over time, or transfer to untrained functional tasks.

### Conclusion

The present investigation provides evidence that augmented sensory feedback was associated with improvements in select aspects of movement initiation, execution speed, and spatial consistency, with stronger and more reliable associations linked to vibrotactile feedback and the most pronounced correlations emerging in older adults, specifically during the deceleration/endpoint homing-in phase, where feedback plays a key role.

These results do not demonstrate a unique or exclusive advantage for tactile feedback, nor direct evidence of feedforward versus feedback control separation. The findings are however consistent with a meaningful benefit for supporting terminal limb-target movement control, especially in older adults as sequence complexity increases.

Auditory feedback yielded comparatively weaker associations but may still represent a valuable augmentation avenue when cues are more salient, rhythmic, or spatially integrated, where the risk of visual or attentional competition is reduced.

Importantly, this study supports the broader potential of sensory augmentation in aging-focused motor research, rehabilitation science, and assistive technology.

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