



# Goal-directed aiming under restricted viewing conditions with confirmatory sensory feedback

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## ABSTRACT

A substantial body of research has examined the speed-accuracy tradeoff captured by Fitts' law, demonstrating increases in movement time that occur as aiming tasks are made more difficult by decreasing target width and/or increasing the distance between targets. Yet, serial aiming movements guided by internal spatial representations, rather than by visual views of targets have not been examined in this manner, and the value of confirmatory feedback via different sensory modalities within this paradigm is unknown. Here we examined goal-directed serial aiming movements (tapping back and forth between two targets), wherein targets were visually unavailable during the task. However, confirmatory feedback (auditory, haptic, visual, and bimodal combinations of each) was delivered upon each target acquisition, in a counterbalanced, within-subjects design. Each participant performed the aiming task with their pointer finger, represented within an immersive virtual environment as a 1 cm white sphere, while wearing a head-mounted display. Despite visual target occlusion, movement times increased in accordance with Fitts' law. Though Fitts' law captured performance for each of the sensory feedback conditions, the slopes differed. The effect of increasing difficulty on movement times was least influential in the haptic condition, suggesting more efficient processing of confirmatory haptic feedback during aiming movements guided by internal spatial representations.

## 1. Introduction

For more than a half century, under a wide variety of circumstances, research has established that goal-directed movements are subject to a speed-accuracy tradeoff. That is, when the target of movement is made smaller, or placed farther away, it requires more time to acquire. Fitts (1954), in a series of classic experiments, demonstrated this speed-accuracy tradeoff for reciprocal (or serial) goal-directed aiming tasks. He found that as the difficulty of the task increases via the decrease of target width ( $W$ ) and/or increase of movement amplitude ( $A$ ), so does the movement time ( $MT$ ) required to complete it, and formally characterized this relationship with the following equation:

$$MT = a + b \times \log_2(2A/W),$$

where “ $a$ ” and “ $b$ ” are empirical constants, and  $\log_2(2A/W)$  comprises the index of difficulty (ID) in bits. This speed-accuracy relationship has proven extremely versatile, leading to its designation as “Fitts' law” and its widespread application in the field of motor control and human-computer interaction (for reviews, see Mackenzie, 1992; Plamondon & Alimi, 1997).

Although the importance of visual target and effector feedback to motor control has been recognized following the pioneering

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research of Woodworth (1899), manipulations of these factors have not often been examined with an eye to serial aiming movements and Fitts' law. Macuga and Frey (2014) compared serial aiming performance with and without effector feedback and found that Fitts' law was upheld in both cases, but the effect of ID on MT was not as pronounced when effector feedback was removed. However, to our knowledge, no studies have examined how the absence of a target within the context of a serial, goal-directed aiming task influences performance in terms of speed-accuracy tradeoffs. It is also unknown how different forms of confirmatory feedback (i.e., haptic, auditory, etc.) might improve performance under these restricted visual conditions. In the traditional Fitts (1954) aiming paradigm, auditory (metal-on-metal noise) and haptic (felt sensation) feedback may have facilitated faster movement times by decreasing participants' reliance on visual confirmation for target acquisitions (Glover, 2004; Hatfield, Wyatt, & Shea, 2010). This potentially important confirmatory feedback has been absent in more recent studies on serial aiming, where participants were asked to move a stylus or cursor back and forth on an electronic screen (e.g., Bootsma, Boulard, Fernandez, & Mottet, 2002; Smits-Engelsman, Van Galen, & Duysens, 2002). The present study sought to examine these two neglected areas: 1) representation-guided movement and, 2) confirmatory feedback as conveyed through different sensory modalities, at their confluence within a serial aiming paradigm. Online visual feedback is extremely valuable for tasks requiring target acquisition (for a review, see Elliott, Helsen, & Chua, 2001). However, it has been shown that in the absence of visual feedback, movements can be guided reliably based on internal representations (Graziano, Hu, & Gross, 1997; Heath & Westwood, 2003), though these internal representations tend to degrade over time (in as little as two seconds for discrete aiming tasks; Elliott, 1992; Heath & Binsted, 2007; Ploner, Gaymard, Rivaud, Agid, & Pierrot-Deseilligny, 1998). In serial reaching tasks, visual memory can be used to plan each successive movement but relies more on visual information (if available) once movement execution has begun (Brouwer & Knill, 2007). However, it is unclear how this might play out in an experiment involving rapid aimed movements, particularly with respect to the speed-accuracy tradeoff. In partly addressing this gap, researchers utilized a discrete aiming paradigm to test Fitts' law under conditions of restricted visual feedback (Wu, Yang, & Honda, 2010; Zhang, Yang, Inai, Huang, & Wu, 2015). They showed that Fitts' law could be applied to visually-restricted movements, though these were more error-prone than visually-guided movements. This may have resulted from the lack of information upon which to base corrective movements. It remains to be seen whether the guidance of serial aiming movements under conditions of restricted visual feedback conforms to Fitts' law. While discrete and serial movements have produced similar results in tasks with full vision (Fitts & Peterson, 1964) there are reasons why the consequences of target occlusion for a discrete versus a serial aiming task may differ. For discrete aiming, only one target must be held in memory and only for the duration of that single movement. For serial aiming, two targets must be held in memory for a relatively extended period. Thus, serial aiming tasks under visually restricted conditions differ in that there is more than one target that must be internally represented. In the absence of continuous visual feedback, these representations would likely degrade over time, a problem that could be mitigated by confirmatory feedback (Heath & Westwood, 2003).

Though visual feedback (Welch & Warren, 1980) is often dominant, task demands such as target modality (Cameron & López-Moliner, 2015; Sober & Sabes, 2005) or movement direction (van Beers, Wolpert, & Haggard, 2002) can lead to the prioritization of nonvisual feedback. Moreover, recent findings suggest that rapidly accessible, haptic feedback can have a greater influence than visual feedback (Crevecoeur, Munoz, & Scott, 2016). Research on multisensory integration has shown that multimodal cues can improve performance compared to unimodal cues (Angelaki, Gu, & DeAngelis, 2009; Ernst & Banks, 2002). Additionally, augmenting visual information with confirmatory auditory (Hatfield et al., 2010) or haptic (Akamatsu, Mackenzie, & Hasbroucq, 1995; Campbell, Zhai, May, & Maglio, 1999; Forlines & Balakrishnan, 2008; Vercher-Vitense, Jacko, & Emery, 2003) feedback can enhance movement-based task performance. Though the role of nonvisual confirmatory feedback has not received much attention, it could potentially facilitate faster movement times with respect to target acquisition.

In the present study, visual feedback of the target was removed, and this continuous feedback was replaced by multiple forms of confirmatory feedback, delivered through individual and paired sensory modalities. To accomplish this, we used a serial movement paradigm resembling the original Fitts' serial aiming task. The targets of this task were previewed and then removed as each trial began (with no delay between onset of trial and target occlusion), necessitating that participants guide their movements using an internal spatial representation of the targets. Despite this, we hypothesized that each confirmatory feedback condition would conform to the speed-accuracy tradeoff described by Fitts' law. In other words, the movement times should display the characteristic linear increase in accordance with the index of difficulty. Because participants' internal representations of the targets may degrade over time, we expected error rates to be somewhat higher than in previous studies where targets were continuously visible. To investigate the influence of confirmatory feedback via different sensory modalities on Fitts' law, uni- or bi-modal feedback (auditory, haptic, visual, as well as paired combinations of each) was given upon each successful target acquisition. Here, we hypothesized that both visual and nonvisual unimodal confirmatory feedback could be used but that bimodal confirmatory feedback would result in smaller increases in movement times across difficulties (i.e., shallower slopes).

## 2. Method

### 2.1. Participants

Participants included 41 undergraduate Oregon State University students. They were recruited using the SONA online system and were given course credit for their research participation (with alternatives for credit available). Written informed consent was obtained. All participants had normal or corrected-to-normal vision and were fluent in English. The experimental protocol was approved by the local Institutional Review Board. A single participant was removed from the results for failing to adhere to instructions throughout the study.

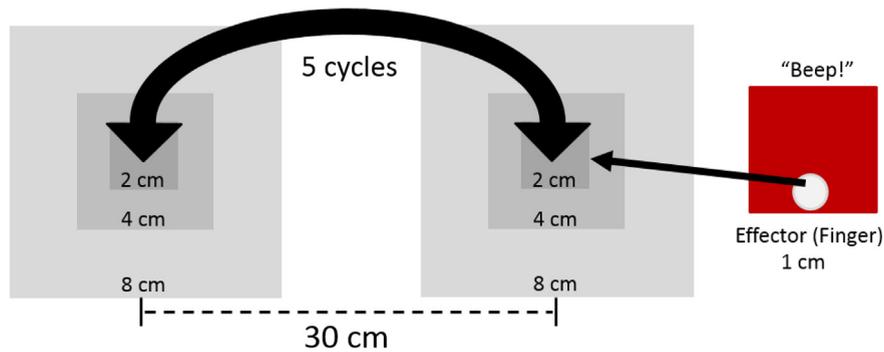


Fig. 1. Serial aiming task.

## 2.2. Materials

Participants completed the experiment in an immersive virtual environment, while wearing a stereoscopic, spatially-tracked head-mounted display (HMD) with dual  $1280 \times 1024$  SXGA OLED displays, one per eye (Sensics zSight). The HMD provided an immersive, 60 degree diagonal field of view with 100% binocular overlap, and the graphics were updated at 60 Hz. The virtual environment and experiment were created and run using WorldViz's Vizard virtual reality development software and rendered by a computer with an Intel Xeon quad-core E5-2603 0 processor clocked at 1.80 GHz and an nVidia GeForce GTX 660 Ti graphics card. The virtual environment was visually unremarkable, containing only the table upon which the serial aiming task was to take place, which was modeled to have the same dimensions as the physical table. An infrared video tracking system (Worldviz PPT-E) and a 3DoF orientation sensor (Inertial Labs OS3D) mounted on the HMD tracked the participant's position and orientation, allowing their movements to be updated and displayed in real time. The effector (the participant's finger) was represented within the virtual environment as a 1 cm white sphere (Fig. 1). Targets appeared as green squares when present, and were represented in code as proximity sensors, with confirmatory feedback (and target acquisition) occurring as the finger-affixed tracker entered the programmed boundaries. Confirmatory feedback was delivered in a manner congruent with the sensory modality condition. For the auditory condition, participants heard a sound delivered through headphones (Koss KSC75 Portable Stereophone Headphones) upon target acquisition. For the haptic condition, participants felt the target square's surface, which had a vertically-oriented corrugated texture, upon target acquisition. For the visual condition, the target reappeared upon target acquisition. Bimodal conditions were paired versions of the unimodal forms of feedback: Target acquisition in the visual-auditory condition provided participants with a reappearance of the target and a sound; the auditory-haptic condition provided participants with a sound and a textured square; the visual-haptic condition provided participants with a reappearance of the target and a textured square.

## 2.3. Design and procedure

The study used a 3 (ID; low, medium and high)  $\times$  6 (Sensory condition; auditory, haptic, visual, auditory-visual, auditory-haptic, visual-haptic) within-subjects design. The ID values in the low, medium and high conditions were 2.91, 3.91, and 4.91, respectively. These values were derived from target widths of 8, 4 and 2 cm, with a fixed distance of 30 cm separating the centers of these targets (Fig. 1).

Following receipt of informed consent, participants were seated at a table on which the aiming movements would take place. The procedure was explained and the task was demonstrated to participants. Participants were told to complete five cycles (left-right tapping sequences) as quickly as possible while maintaining accuracy. Participants were then introduced to and equipped with the HMD and finger tracking apparatus. Participants were notified that targets would be disappearing during the task and were instructed to look at them very closely prior to the start. They were also notified of the nature of the sensory feedback that would be received upon a successful target acquisition for each of the sensory conditions.

The beginning of each trial was marked by an auditory beep, with the target removal occurring simultaneously. Participants were given several practice sessions, with the experimenter giving feedback, to become familiar with the reciprocal aiming task under each unimodal condition in blocks of 6 trials (2 repetitions of the 3 IDs delivered in a randomized order). Following these practice trials, participants received blocks of 18 trials (6 repetitions of the 3 IDs delivered in a randomized order) for every sensory feedback condition. The blocked conditions were counterbalanced using a Latin square design to account for order effects. Each trial consisted of five cycles, where one cycle involved moving over to tap the left box and then back to tap the right box. After completing five cycles, participants ended the trial by moving their finger to a 6 cm red box which appeared 25 cm to the right of the targets (Fig. 1). Participants received a break after the practice sets, and after every pair of experimental trials.

To help quantify the importance of continuous target presence, an additional full vision control experiment was conducted in our lab with a different sample of 42 undergraduate participants (21 women, 21 men,  $M_{age} = 21.7$  years). It was identical to the visual condition in terms of the stimulus and procedure, except the targets were continuously visible, as in the standard Fitts' paradigm. The data from this full vision appears alongside the primary experiment conditions in the tables and figures, as a source of comparison.

## 2.4. Analysis

All Analyses were conducted using R 3.5.2 (R Core Team, 2018) and RStudio (RStudio Team, 2015). Assumptions for all analyses were tested using visual methods (e.g., q-q plots for normality of residuals) or quantitative methods (e.g., Mauchly's sphericity test). Unless otherwise stated, the assumptions requisite within each analysis were judged to be satisfied.

To evaluate whether Fitts' law would hold under conditions of restricted vision, and whether bimodal feedback conditions would produce relatively superior performance to unimodal feedback conditions, we conducted a linear mixed model analysis using *lme4* and *afex* with type 3 sums of squares tests, the Kenward-Roger method of approximating degrees of freedom, and an unstructured covariance matrix (Bates, Maechler, Bolker, & Walker, 2015; Singmann, Bolker, Westfall, & Aust, 2018). In the model, feedback condition and index of difficulty were inserted as fixed factors, the latter acting as a continuous covariate and interacting with the former, while intercepts and slopes were allowed to vary by participant, reflecting the possibility for participants to differ in their performance across various conditions. The linear trends of movement time across ID for each feedback condition were extracted for comparison using the "emtrends" and "contrast" functions of the R package *emmeans* (Lenth, 2018). Bimodal conditions were contrasted with unimodal, and post-hoc pairwise comparisons were conducted to determine whether any of the feedback conditions demonstrated stronger relative performance. For the 15 pairwise comparisons, *p*-values were adjusted using the Bonferroni-Holm correction. The focus of these analyses was on the linear trends rather than the movement times due to our use of Fitts' law in interpreting the results. The slope is often used within a Fitts paradigm to judge performance, beginning with Fitts's own calculation of the index of performance (IP), the inverse of the slope, in his seminal experiment (Fitts, 1954).

Mean error rates for each sensory feedback condition were also analyzed with a one-way repeated-measures ANOVA. Sphericity was found to be violated, thus Greenhouse-Geisser corrected values presented for this analysis ( $\epsilon = 0.381$ ). Pairwise comparisons were conducted to compare the feedback conditions individually resulting in 15 tests, with the *p*-values again adjusted using a Bonferroni-Holm procedure.

## 3. Results

### 3.1. Fitts' law

For all conditions, movement times increased as a function of task difficulty. The linear mixed model regression analysis confirmed that there was a speed-accuracy tradeoff for each sensory feedback condition, suggesting that Fitts' law applies even under restricted vision (see Fig. 2). The simple regression slopes (*b*) and index of performance (IP) values for each condition are listed in Table 1. However, the appearance of the data in some of the conditions (most prominently auditory) suggests the potential for a nonlinear relationship, with the MTs for the high IDs being somewhat larger than expected. To explore this, we used a power law equation, based on Meyer, Abrams, Kornblum, Wright, and Keith Smith (1988) stochastic optimized-submovement model:

$$MT = a + b(A/W)^{1/2}$$

The  $R^2$  values for both Fitts' law and Meyer et al.'s formulation of the power law are reported in Table 1.  $R^2$  values were high for both equations, though the power law fit the data slightly better, suggesting that the relationship between movement time and task difficulty might be better described by a power law. In fact, a reanalysis of Fitts' original data also suggested that a power law may

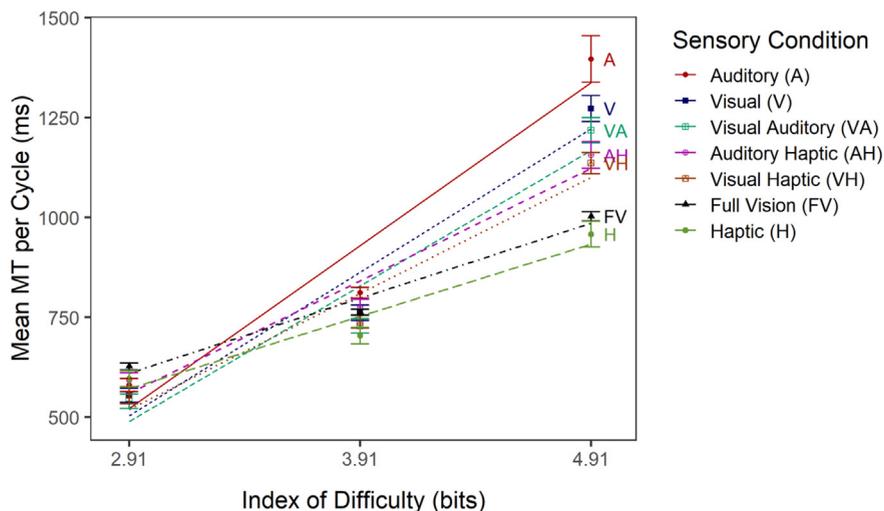


Fig. 2. Mean MT regressed against ID for each sensory feedback condition. Note: Data points at each ID are the empirical MT means for each condition. Lines for each sensory condition are the best-fitting lines as calculated by ordinary least squares regression. Error bars represent the within-subject standard errors calculated according to methods described by Cousineau (2005) and Morey (2008).

**Table 1**  
Slope estimates of sensory feedback conditions.

Sensory Condition	b	SE	95% CI		IP	$R^2_{Fitts}$	$R^2_{Power}$
			Lower	Upper			
Haptic	180.92	17.62	145.31	216.53	5.53	0.95	0.98
Auditory	408.16	34.17	339.11	477.22	2.45	0.94	0.98
Auditory Haptic	281.58	20.53	240.08	323.07	3.55	0.96	0.99
Visual	359.11	19.74	319.21	399.01	2.78	0.94	0.98
Visual Auditory	339.44	20.23	298.56	380.33	2.95	0.94	0.98
Visual Haptic	290.71	18.22	253.89	327.54	3.44	0.96	0.99
Full Vision	187.89	12.85	161.93	213.85	5.32	0.97	0.99

*Note.* Linear trends extracted using the “emtrends” function of emmeans. Slope coefficients based on single cycle in milliseconds. IP corresponds to the index of performance, the inverse of the slope for the full task (reported in bits/s).  $R^2$  values computed using simple linear regressions, where values of the IV are computed using the Fitts Law (Fitts, 1954) and Power Law (Meyer et al., 1988) equations, respectively. Full Vision condition was part of a separate control experiment, added to provide context for the other conditions.

provide better fits (Kvalseth, 1980).

### 3.2. Performance

In our linear mixed model, ID produced a significant conditional effect on MT,  $F(1, 40) = 439.60$ ,  $p < .001$ . As evidenced by Fig. 2, this manifested as the characteristic linear increase of MT across ID levels, supporting the hypothesis that movements under restricted vision conform to Fitts' law. The model also suggested a significant conditional effect of feedback condition, such that the conditions differed in movement time,  $F(5, 36) = 10.88$ ,  $p < .001$ . Most relevantly, the interaction term between feedback condition and index of difficulty was significant,  $F(5, 36) = 13.16$ ,  $p < .001$ , suggesting that the increases in movement time brought about by changes in ID differed between sensory feedback conditions. The contrast of unimodal vs. bimodal linear trends was nonsignificant,  $p = .385$ . Taken together, this suggests that there was no added benefit to confirmatory feedback given in two modalities and fails to support our hypothesis that bimodal conditions would result in more efficient performance.

Pairwise comparisons between the slopes, however, revealed significant differences in performance between sensory feedback conditions. The haptic condition was less affected by increases in difficulty than all other conditions,  $p < 0.001$ , such that the increase in movement time associated with higher levels of difficulty was reduced. Conversely, the auditory-only condition was more affected by increases in difficulty than the haptic, visual-haptic, and auditory-haptic conditions,  $p < 0.002$ . The visual-only condition was also more affected by increases in difficulty than the haptic, visual-haptic, and auditory-haptic conditions,  $p < 0.05$ . Thus, the speed of movements guided by haptic confirmatory feedback was more robust to small targets than movements guided by auditory or visual confirmatory feedback. For all pairwise comparison results with confidence interval estimates, see Table 2.

**Table 2**  
Pairwise comparisons of the sensory feedback condition slope coefficients.

Comparison	Difference	SE	t	p	95% CI	
					Lower	Upper
Haptic – Auditory	–227.24	34.00	–6.68	< 0.001	–293.89	–160.60
Haptic – Auditory Haptic	–100.66	21.42	–4.70	< 0.001	–142.64	–58.67
Haptic – Visual	–178.19	23.86	–7.47	< 0.001	–224.96	–131.42
Haptic – Visual Auditory	–158.52	22.83	–6.94	< 0.001	–203.26	–113.78
Haptic – Visual Haptic	–109.79	21.49	–5.11	< 0.001	–151.92	–67.66
Auditory – Auditory Haptic	126.59	30.91	4.09	0.002	66.00	187.18
Auditory – Visual	49.05	29.82	1.64	0.323	–9.40	107.51
Auditory – Visual Auditory	68.72	28.02	2.45	0.112	13.80	123.65
Auditory – Visual Haptic	117.45	32.58	3.60	0.008	53.59	181.31
Auditory Haptic – Visual	–77.53	26.52	–2.92	0.040	–129.51	–25.56
Auditory Haptic – Visual Auditory	–57.87	24.36	–2.38	0.112	–105.62	–10.11
Auditory Haptic – Visual Haptic	–9.14	22.87	–0.40	0.773	–53.96	35.68
Visual – Visual Auditory	19.67	22.46	0.88	0.773	–24.35	63.68
Visual – Visual Haptic	68.40	22.21	3.08	0.030	24.85	111.94
Visual Auditory – Visual Haptic	48.73	22.11	2.20	0.133	5.39	92.07

*Note.* Slope coefficients based on single movements in milliseconds. Difference corresponds to the difference in slope coefficients for the given comparison.  $df = 40$ .  $p$ -values were adjusted using the Bonferroni-Holm method.

**Table 3**  
Error rates of sensory feedback conditions.

Feedback Condition	M	SD
Auditory	9.07	5.74
Auditory Haptic	7.46	5.16
Haptic	12.90	11.10
Visual	5.65	4.69
Visual Auditory	5.85	4.59
Visual Haptic	5.24	3.88

Note. Error rates given as percentage value. M and SD values collapsed across ID levels.

### 3.3. Error rate

We had no specific hypotheses regarding error rate, but an examination of accuracy is pertinent to discussions of performance in the feedback conditions. Because of the lack of continuous target visibility, all conditions generated error rates (see Table 3) considerably higher than those of the original Fitts (1954) aiming tasks, which were below 4.1%. Indeed, in our full vision control experiment with the targets visually present, the mean error rate in the visual feedback condition was 2.75%. A one-way repeated-measures ANOVA was performed on the mean percentage of errors for each sensory feedback condition, collapsed across ID. The analysis revealed that the mean error rates between sensory feedback conditions differed,  $F(1.90, 76.11) = 10.98$ ,  $p < .001$ ,  $\eta^2 = 0.22$ . Pairwise comparisons showed that the error rate for the haptic condition was significantly higher than the error rate for all other conditions except for the auditory condition, whose error rate was higher than the visual, visual-auditory, and visual-haptic conditions ( $p < .01$ ).

## 4. Discussion

The present study sought to expand insight into the importance of continuous target presence on the speed-accuracy trade-off described by Fitts' law. In support of our first hypothesis, Fitts' law proved robust to visual target removal. The Fitts' model was able to characterize movements guided by internal spatial representations of the targets, albeit in some instances not perfectly, with some conditions performing substantially worse in the jump to the highest difficulty. A possible reason for this may have been that the feedback in certain conditions was too ambiguous to support the guidance of rapid movements at the highest difficulty. The auditory feedback, for example, provided only a cue to confirm target acquisition and provided no spatial information regarding the boundaries of the target. This ambiguity may have introduced additional noise in the planning of the next movement, leading to longer movement times, or may have simply failed to adequately support the maintenance of an internal spatial representation of the targets. Meyer et al. (1988) power law improved fit to the data, as is often the case, even for Fitts' original data (for a meta-analysis, see Plamondon & Alimi, 1997). However, given the substantial literature behind Fitts' law and its resilience to target removal in discrete tasks (Wu et al., 2010; Zhang et al., 2015), we suggest that the Fitts (1954) formulation is more appropriate here. Its parameters also directly and conceptually reflect movement task performance, allowing for comparisons between conditions as well as comparisons with other studies.

Within the present serial movement task, participants received confirmatory feedback upon successful target acquisition through auditory, haptic and visual modalities (as well as paired combinations). Though the movement times for all of these sensory feedback conditions can be characterized by Fitts' law, differences emerged with respect to the speed and accuracy of movements in each condition. Pairwise comparisons revealed movement times in the haptic condition were the least influenced by increases in ID. The differences may be attributed to haptic processing speed, as these results are consistent with studies, which have shown that haptic stimuli produced the fastest response times in tasks involving hand movements (Akamatsu et al., 1995; Cockburn & Brewster, 2005; Crevecoeur et al., 2016; Ng & Chan, 2012). Our results also support the idea that the haptic modality is specialized for rapid, reliable recognition in target acquisition (Lederman & Abbott, 1981). Though in general, bimodal feedback did not confer any additional benefits, the bimodal visual-haptic and auditory-haptic conditions produced shallower slopes than the unimodal visual and auditory conditions, suggesting that haptic augmentation was beneficial.

Our results are in line with some of the work on applied real-world tasks, particularly in the domain of transportation (Gray, 2008). Haptic foot pedal feedback has been shown to assist with car following performance, even without visual feedback (Abbink, Mulder, van der Helm, & Boer, 2011). In a driving simulator study that investigated rear-end collision warnings, haptic feedback led to faster responses than visual feedback (Scott & Gray, 2008). In another simulator study that examined driving under low visibility, where the visual feedback was reduced, haptic feedback via rumble strips improved driving performance (Ziat, Savord, & Frissen, 2015). As in the present study, haptic feedback in these low-or-no vision contexts produced a more rapid motoric response, suggesting the inclusion of haptic feedback in such scenarios might be advantageous.

Participants were most accurate in the visual feedback conditions (visual, visual-haptic, visual-auditory). The auditory-only condition had a higher error rate than the visual conditions, and the haptic-only condition had the highest error rate. Thus, despite its superiority in movement time, errors were more frequent in the haptic condition. The visual-haptic condition saw a confluence of shallow slope (shallower than the visual-only condition) and low error rate (lower than the haptic-only condition). Thus, the visual-

haptic condition may reflect the best compromise between speed and accuracy in this context.

#### 4.1. Potential limitations and future directions

MT was only assessed across three levels of ID, though prior research on implementations of Fitts' law has similarly included a limited number of ID values (e.g., Bootsma et al., 2002; Smits-Engelsman et al., 2002; Grosjean, Shiffrar, & Knoblich, 2007; Yoxon, Tremblay, & Welsh, 2015). In our case, some practical limitations were imposed by the VR environment. Reducing width would have resulted in target occlusion by the virtual finger representation, while increasing amplitude would have exceeded the field of view of the HMD. Measuring the kinematic patterns of movement that occur throughout the task (as in Hatfield et al., 2010) would allow for more conclusive interpretations regarding the influence of the different feedback forms on movement characteristics. For example, such measurements would allow an examination of differences in controlled sub-movements (e.g., Meyer et al., 1988). It may be that the haptic condition lacked these, leading to rapid but more error-prone movements.

Our finding that haptic cues can be effectively employed as confirmatory feedback in movements guided by internal spatial representations is relevant with respect to the design of virtual environments. VR gaming and training applications can involve guiding movements to targets that are out of the user's current field of view. Examples of this include moving a virtual tool to a visually occluded target in a surgical training simulation, or reloading a bow by moving a controller to a specific over-the-shoulder position and "grabbing" an arrow in an archery game. The results of the present study suggest that these experiences could make use of haptic cues to inform users about target acquisition.

#### 4.2. Conclusions

While research has generalized Fitts' law to a wide variety of situations, there has been a relative shortage of studies examining the performance of aiming movements in visually restricted conditions. Here, we found Fitts' law to be robust to the visual occlusion of targets during the execution of a serial goal-directed aiming task. Movement times increased with task difficulty for all of the confirmatory sensory feedback conditions. Haptic information proved to be the most efficient source of confirmatory feedback, as it enabled faster movement times across increasing IDs. This came at the cost of accuracy, however, with the haptic condition also producing the highest error rates. On the other hand, at the cost of speed, the visual conditions facilitated greater accuracy. Bimodal conditions mostly reflected a balance between speed and accuracy, which suggests that redundancy in confirmatory feedback can be somewhat beneficial. In terms of application, it appears that targeted movements guided by spatial representations would benefit from haptic confirmatory feedback, provided that the errors are not too costly.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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