Short communication

The perception of changes in visual movement feedback delay is biased by visuomotor congruence

Abbreviated title: Delay perception and visuomotor congruence

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Abstract: The Weber-Fechner Laws have been evaluated across a wide variety of modalities and tasks, but not yet in the domain of visuomotor mapping. A prominent manipulation of visuomotor mapping is temporal; i.e., delaying visual movement feedback. Yet, while visuomotor delay detection itself has been extensively studied, it is not known whether the perception of changes in delay depends on the present amount of delay. We developed a virtual reality based, continuous hand movement task, during which participants had to detect changes in visuomotor mapping (delay): Participants (N=40) performed continuous, auditory-paced grasping movements, which were measured with a data glove and transmitted to a virtual hand model. The movements of the virtual hand were periodically delayed between 0-700ms; the delay changed repeatedly in a roving oddball fashion in steps of 100-400ms. Participants had to indicate perceived delay changes by key presses, as fast as possible. This design allowed us to investigate detection accuracy and speed related to the magnitude of the delay change, and to the “baseline” delay present during movement. As expected, larger delay changes were detected more accurately than smaller ones. Surprisingly, delay changes were detected more accurately and faster when participants moved under larger delays. These results suggest that visual movement feedback delay affects the detection of changes in visuomotor mapping, but not as predicted by the Weber-Fechner Laws. Rather, smaller visual movement feedback delays likely increased the tolerance for visuomotor changes via an enhanced subjective embodiment of the virtual hand.

KEYWORDS: Action, Delay, Virtual Reality, Visuomotor Mapping, Weber-Fechner-Law

1. Introduction

For much of our usual sensory input, like sound, light and weight, the perceived magnitude of a change is proportional to the initial stimuli perceived before the change. Thus, the larger an initial stimulus is, the larger the change needs to be, so the resulting stimulus is perceived as different from the initial stimulus. This relationship is described by the Weber-Fechner Laws (Fechner, 1966), which we know hold true across different sensory modalities (Baird, 1997; Gescheider, 1997). Recent empirical evidence suggests that the Weber-Fechner Laws may also be valid for more abstract concepts like time and reward perception (Brannon et al., 2008; Namboodiri et al., 2014; Takahashi, 2005, 2006). Thus, Nieder and Miller (2003) proposed that sensory and certain cognitive representations follow the same neural coding schemes and thus hold true for all similar processes.

However, several studies investigating 'bodily' perception, e.g., concerned with self-motion and proprioception, have yielded notable violations of the Weber-Fechner Laws (Mallery et al., 2010; Nesti et al., 2015; Nouri & Karmali, 2018). Furthermore, it could be shown that the Weber-Fechner Laws are violated for visually guided grasping tasks (Ganel et al., 2008). In their study, Ganel and colleagues show that just noticeable differences depended on object size only in perceptual tasks, not in grasping tasks. Thus, the processing of stimuli related to bodily action and self-motion may follow different perceptual laws than the perception of external stimuli (Carriot et al., 2021).

The flexible control of bodily action by the brain relies on the capacity to adapt internal models for motor control to novel sensory movement feedback (Limanowski, 2022; Shadmehr et al., 2010; Wolpert & Kawato, 1998). Sensorimotor adaptation is necessary in cases where e.g. visual movement feedback is delayed, i.e., a temporal incongruence is introduced between movements and their visual feedback (Foulkes & Miall, 2000; Rohde & Ernst, 2016). Sensorimotor delays are an inherent feature of our nervous system, which the brain overcomes through internal forward modeling (Miall & Wolpert, 1996; Todorov & Jordan, 2002). But sensorimotor delays are also increasingly encountered in new technologies enabling cyber-physical interactions, such as controlling robots remotely or via virtual reality (Peters et al.,

2018; Schulze et al., 2024). In most of these scenarios, sensorimotor delays are to be expected and, more importantly, they can vary unpredictably (Planthaber et al., 2018). Yet, it is crucial that humans are able to experience control and, where possible, a sense of presence and embodiment in such scenarios (Sanchez-Vives & Slater, 2005; Wen & Imamizu, 2022).

Not surprisingly, the corresponding learning and predictive processes are subject to intense study: Many studies have investigated the perceptual thresholds for visuomotor delays, the capacity to adapt to them, and the neuronal underpinnings of these processes (Farrer et al., 2008; Foulkes & Miall, 2000; Krugwasser et al., 2019; Leube et al., 2003; Limanowski, 2017; Miall et al., 1985; Miall & Jackson, 2006; Parvin et al., 2024; Rohde & Ernst, 2016; Tsakiris et al., 2006).

One key question that, to our knowledge, has not yet been addressed is whether the perceptual sensitivity to visuomotor delay changes depends on the amount of delay present during movement; i.e., are identical delay changes detected differently when people currently move under large, compared to small delays? In other words, it is unclear whether the Weber-Fechner Laws hold for visuomotor delay perception. Not last, the aforementioned technological developments that humans face today require this question to be answered. Therefore, here, we tested whether people's sensitivity to *changes* in visual movement feedback delay depends on the amount of delay already present during movement.

We addressed this question through a virtual reality based hand movement task: Participants performed continuous right-hand grasping movements, paced by an auditory rhythm. Their movements were fed to a photorealistic virtual hand model presented on screen, with an experimentally added delay that changed in a roving oddball fashion (Fig. 1). Participants had to report perceived delay changes (i.e., changes in the mapping of their real hand movements to those executed by the virtual hand) by key presses, as fast as possible throughout the movement task. We expected larger delay changes to be detected more accurately and faster; following the Weber-Fechner Laws, we expected that participants would detect delays better and quicker if they were moving under relatively smaller delays.

2. Methods

2.1 Participants:

We recruited 40 healthy, right-handed participants, with normal or corrected-to-normal vision (15 female, mean age = 28.1, range= 22-38). We excluded three participants (one because the data glove could not be adequately fitted and calibrated; one participant was not able to perceive the changes in loudness of the tracking sound; and one did not perceive any delay of the virtual hand, even for a delay of 700ms), leaving us with 37 participants whose data could be analyzed. The experiment was approved by the ethics committee of the Technische Universität Dresden and conducted in accordance with this approval.

2.2 Experimental Procedure

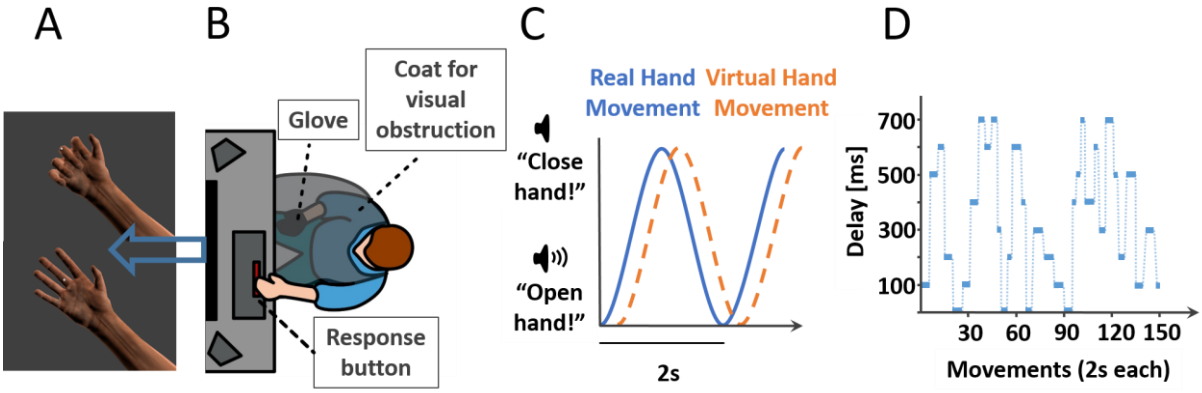

Figure 1. Experimental task and design. A-B: Participants used a data glove, worn on their right hand (occluded from view, **B**) to control a photorealistic virtual hand displayed on a screen in front of them (**A**). **C:** Participants had to execute continuous grasping (close-and-open) movements paced by an auditory cue, a tone changing loudness with a frequency of 0.5 Hz. Flexion data from the glove were fed to the virtual hand model, but with a delay; this altered the temporal congruence between the participants' hand movements and the movements of the virtual hand (i.e., the visuomotor mapping). Shown here is a schematic plot showing a full grasping cycle, i.e. the hand opening on a loud tone and closing on a quiet tone, under an exemplary delay between the virtual and real hand movements. **D:** During the continuous movement task, we repeatedly changed the amount of delay. This plot shows an example roving oddball sequence of delays between 0-700 ms as used in the experiment (i.e., one run of 4.9 min = 147 movements). Participants had to report whenever they perceived these changes, as fast as possible, by pressing the space bar of a computer keyboard (see **B**).

First, participants were briefed about the experimental procedure and completed a demographic questionnaire. Afterwards, they put on a sanitary glove (for hygienic reasons) and the data glove on their right hand (5Dt Data Glove Ultra, 14 sensors, 10 bit flexure resolution per sensor, 60 Hz sampling rate, communication with the PC via USB with approx. 10 ms delay). The data glove allowed our participants to control a photorealistic virtual hand (modelled with python 3 in blender 2.79 [(Blender Foundation, n.d.), Fig. 1B]), by measuring the flexion of the participants' fingers and transmitting these values to the virtual hand model's fingers (Fig. 1A-C). The virtual hand was shown on a monitor in front of the participant (1920 × 1080 pixels resolution, screen distance to eye about 90 cm, 18.92° of visual angle, 13 ms Motion Picture Response Time). Participants placed their right hand on their leg, with the palm facing upward, in a position that allowed for comfortable opening and closing of the hand (see Fig. 1A). Their right hand was occluded from view by a barber coat. The data glove was then calibrated; i.e., the virtual fingers' movement range was dynamically adjusted to the sensor values until it accurately displayed the movements of the real hand.

Participants were instructed to fixate a dot presented centrally on screen, and visible at all times, for the entirety of the experiment (Fig. 1B). The movement task was to execute simple, continuous grasping movements: Participants opened and closed their right hand paced by a rhythmic auditory cue; i.e., a 250 Hz tone that grew louder and quieter following a sine wave function with 0.5 Hz frequency. When the tone was loudest, the physical hand of the participant was supposed to be open and when the tone was quietest, the hand was supposed to be closed (Fig. 1C).

Before the actual experiment, participants practiced to align their real hand grasping movement with the auditory rhythm (without added delay to the virtual hand) until they felt confident that they could open and close their hand continually throughout the main experiment, without falling out of synchrony with the pacing signal.

In the first part of the experiment, participants had to perform 10 auditory paced grasping movements (20 s) while fixating the dot in front of the virtual hand, at each delay level used in the main experiment – and rate the task difficulty (see below). I.e., the virtual hand moved

either synchronously (0 ms delay) or was delayed by 100, 200, 300, 400, 500, 600 or 700 ms. We chose relatively long delays for our experiment compared with previous single-trial delay detection tasks (Leube et al., 2003; Limanowski, 2017; Limanowski et al., 2020), because our pilot experiments indicated that delay perception was more difficult with our task setup, which required simultaneously maintaining a continuous synchronization of the movements with the pacing rhythm. Each delay level was presented three times, resulting in 24 trials in total. After each trial, we asked our participants to indicate how difficult they felt it was to follow the auditory cue, in comparison to the synchronous practice trial, on a 5-point Likert scale from “very easy” to “very difficult”.

In the second, main part of the experiment, participants also executed continuous, paced grasping movements – but now with an added delay to the virtual hand movements that changed repeatedly, following a roving oddball paradigm (Fig. 1D). Participants put their left index finger on the space bar of a computer keyboard, and were instructed to press it as fast as possible every time they detected a change in the visual movement delay (i.e., a change in the mapping of the virtual hand movements to their actually executed movements). Participants were specifically instructed, and trained to maintain stable grasping rhythm with their real hand; i.e., to not alter their movements in response to the delays or delay changes.

During the experiment, each of 8 “baseline” delay levels (ranging from 0-700 ms in steps of 100 ms, see above) was presented for 3 to 6 movement cycles (i.e., 6-12 s), before changing to a larger or smaller delay. The delays changed gradually between ±100-400 ms (in steps of 100 ms); i.e., over the course of 0.5 s to prevent sudden jumps in the visual movement. The delays were presented in runs of 147 movements (4.9 mins); each run contained a predefined, pseudorandomized sequence of 32 delay changes. Thus, we ensured that every run contained 8 delays with each length (3, 4, 5, and 6 movement cycles); and that, within each run, each baseline delay level was presented once in combination with each absolute delay change (i.e., ±100-400 ms; 8 delays x 4 changes = 32 delay changes). Note that, due to the nature of the design, it was not possible to include all relative i.e., directional combinations of delay changes with all initial delays (e.g., 700 ms was the largest delay, so there was no change of 700+100

ms, only 700-100 ms). An example of a delay sequence can be seen in Figure 1D. Overall, eight such sequences were generated, and presented to each participant in randomized order; resulting in 256 delay changes in total. After every run, participants could take a break until they felt ready for the next one. After every break, the data glove was calibrated again.

2.4 Data analysis

To analyze detection performance, we defined a correct delay detection ("hit") as a button press within two movement cycles (4 s) of a delay change. We chose to include the second movement cycle, because each delay change was gradually introduced (see above), leaving only a partial movement cycle for "detection" otherwise. Button presses outside of this window were categorized as false alarms. If multiple button presses were recorded within 250 ms of a hit or a false alarm (which we took as a proxy for 'visual' reaction time, following Jain et al., 2015), they were counted as a single button press. To quantify the overall delay change detection accuracy, the *False Alarm Ratio* was calculated as the number of false alarms per number of total alarms (i.e., button presses) (Barnes et al., 2007). Note that this is different from the often used False Alarm *Rate* (also called False Positive Rate), which is defined as the number of false alarms per total number of "non-events". In our case, we could not clearly define "non-events", as this would apply to any time point not corresponding to a delay change, i.e., to most of the actual movement period. Thus, for our study we used the False Alarm Ratio. Furthermore, we calculated a "detection score" as a more conservative index of detection performance, punishing the percentage of hits by the False Alarm Ratio. Thus, participants who were more hesitant and thus more accurate, but had lower hits overall, would still receive an adequate score as compared to participants that hit the button at a near random rate. We calculated the detection score as follows:

$$detection\ score\ = \frac{Percentage\ of\ Hits}{1 + FAR}$$

Detection scores were calculated for each of the 32 delay changes (see above). We then inserted the detection scores into a 4 x 8 repeated measures ANOVA, with the factors *Delay Change* (100, 200, 300, 400 ms) and *Baseline Delay* (0, 100, 200, 300, 400, 500, 600, 700, 800 ms). To test for non-normal properties, we used the Shapiro test. Since our data showed non-normal properties, we used an aligned ranks transformation ANOVA for our analysis. The degrees of freedom were calculated using the Kenward-Roger approximation. Post-hoc, we used a linear regression model (method of least squares) to visualize the direction of the main effects.

As an index of tracking error, we calculated the absolute phase shift in time between the normalized mean movement of the participant and the target movement. To test whether tracking performance (i.e., how well participants were able to maintain an accurate and stable grasping rhythm) was influenced by detection performance, we calculated the Spearman's rank correlation coefficients for tracking error vs. the detection score and the reaction times, respectively, averaged over delay levels.

3. Results

A repeated measures aligned ranks transformation ANOVA on the difficulty ratings given in the first part of the experiment (i.e., the reported difficulty of tracking the auditory target phase with the grasping movements) showed no significant effect of delay on tracking difficulty ($F_{(7,885)}$=0.64, p=.72), the average difficulty ratings of each delay level, with associated standard deviations, were: 2.58±1.15, 2.51±1.20, 2.44±1.08, 2.51±1.17, 2.53±1.01, 2.33±1.04, 2.50±1.17, 2.59±1.12. This means that participants found the movement task itself comparably difficult across all delay levels.

In the main experiment, participants were well able to maintain regular and comparable grasping across delay levels (Fig. 2). On average, they slightly lead the phase of the auditory cue, with an average absolute tracking error of 0.24±0.15 s. Importantly, however, tracking error did not significantly depend on the amount of visual movement feedback delay

($F_{(7,295)}$=0.23, p=.98; the average tracking errors of each delay level, in seconds, with associated standard errors, were: 0.23±.017, 0.22±0.18, 0.24±0.18, 0.23±0.18, 0.23±0.18, 0.27±0.18, 0.27±0.18, 0.24±0.18). Together, these results suggest that our participants were well able to comply with the task instructions; and that the delay of the virtual hand itself did not significantly influence tracking (grasping) behavior, or the perceived task difficulty.

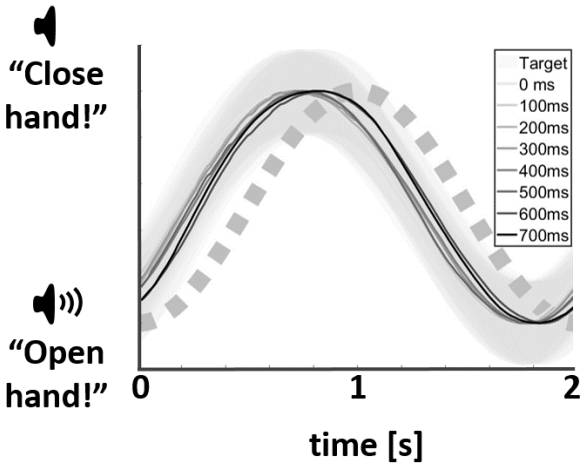

Figure 2. Participants' average hand movements per delay level (with standard deviations in gray shading), relative to the instructed grasping rhythm prescribed by the auditory cue. Participants tracked the auditory target rhythm comparably over all delay levels (see Results for statistical comparison of tracking errors), albeit overall leading slightly. Thus, delay per se did not bias tracking performance.

To validate the overall detection accuracy of our participants in the main experiment, we first tested whether delay change detection was above chance level. The average False Alarm Ratio of our participants was 0.45±0.10, which was significantly lower than the ratio that would have resulted from random button pressing (i.e., >0.67; $t_{(36)}$=13.13, p<.001). This suggests that the participants were able to notice the delay changes and pressed the button accordingly.

An aligned ranks transformation ANOVA on the detection scores showed a main effect of Delay Change; i.e., the magnitude of change in lag of the visual movement feedback ($F_{(3,1116)}$=19.48, p<.001, η^2=.05). A post-hoc linear regression confirmed that these effects could be linearly approximated (Fig.3A, R^2=.067, Slope= $2.58 \cdot 10^{-4}$, df= 35, p<.05; the average detection scores, with standard deviations, in order from lowest to highest delay change were: 0.10±0.03, 0.11±0.03, 0.15±0.06, 0.16±0.04). However, there was no significant effect of Delay Change on the corresponding reaction times (Fig. 3B), while the interaction effect was significant ($F_{(21,1116)}$= 3.505, p<.001, η^2=.06). In sum, as expected, larger delay changes were consistently detected better (albeit not faster) than smaller ones.

Secondly, there was a significant main effect of Baseline Delay on detection scores ($F_{(7,1116)}$= 11.76, p<.001, η^2=.07) and reaction times ($F_{(7,1116)}$=6.56, p<.001, η^2=.04); as well as a significant interaction ($F_{(21,1116)}$=2.09, p<.05, η^2=.04 Fig.3B). Post-hoc linear regression analyses showed, again, that these effects could be linearly approximated (detection scores, Fig.3A: R^2=.55, Slope= $1.18 \cdot 10^{-4}$, df= 35, p<.001; reaction times, Fig.3B: R^2=.181, Slope= $4.05 \cdot 10^{-4}$, df= 35, p<.05, means in order from lowest to highest delay: 0.08±0.04, 0.1±0.03, 0.12±0.04, 0.12±0.06, 0.17±0.08, 0.14±0.02, 0.16±0.05, 0.17±0.04; means for reaction times: 2.14±0.18, 2.04±0.19, 2.11±0.27, 2.06±0.20, 2.02±0.14, 1.97±0.30, 1.82±0.20, 1.85±0.30). In sum, delay change detection was overall better and faster, the higher the amount of visual movement feedback delay present during movement at the time of the change.

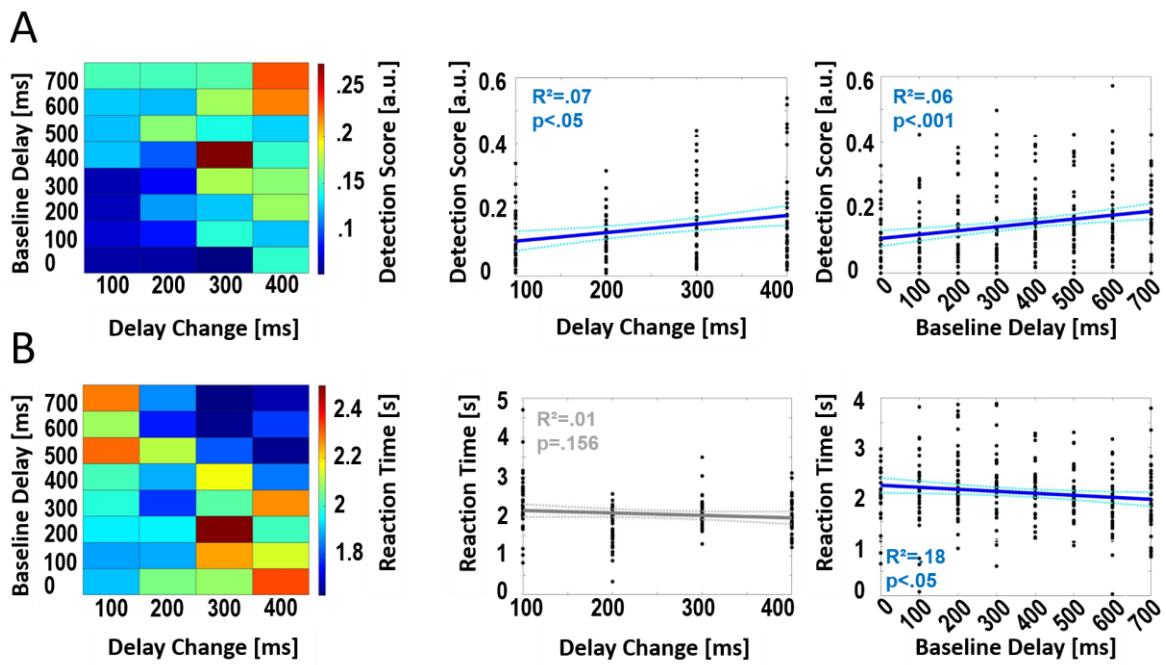

Figure 3. Accuracy and speed of detecting changes in visual movement feedback delay during continuous grasping. The plots show the average detection scores (**A**, in arbitrary units) and reaction times (**B**) for each of the 32 delay change combinations; and the results of the post-hoc linear regression analyses on the respective main effects detected by ANOVA (see Results for details). Overall, larger delay changes were detected more accurately (and slightly but not significantly faster) than smaller magnitude changes; change detection was better and faster when participants were moving at larger, compared to smaller, delays.

Finally, we tested whether the participants' average detection performance covaried with how well they were able to maintain stable tracking. With this, we aimed to detect a possible general relationship between delay detection and tracking error; despite the fact that tracking performance on average was comparable across delay levels (cf. Fig. 1). Indeed, we found a negative correlation between detection accuracy and tracking error: Participants who tracked the target rhythm overall better (i.e., had a smaller average tracking error) detected less of the delay changes (Fig. 4, ρ=.40, p<.05). The correlation between reaction times and tracking error showed a similar directionality, but was not significant (smaller tracking error ~ longer reaction times to delay changes; ρ=-.05, p=.78).

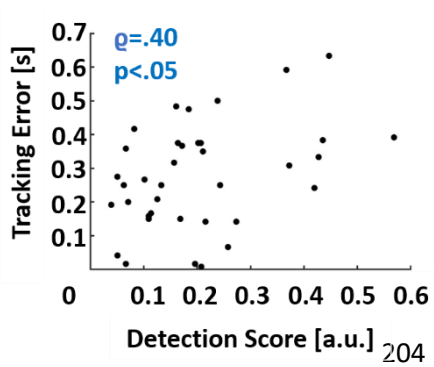

Figure 4. Spearman correlation between detection score and tracking error of the individual participants. The more accurately participants tracked the auditory cue with their real hand (i.e., smaller average tracking error), the less of the delay changes they detected.

4. Discussion

Using a virtual reality based continuous hand movement task, we tested whether the detection of changes in visuomotor temporal mapping (i.e., delay) depends on the amount of delay currently present during movement. As expected, we found that larger delay changes were detected significantly more accurately than smaller ones. Somewhat surprisingly, however, delay changes were detected more accurately and faster when participants moved under larger > smaller delays. In other words, our results suggest that the sensitivity to changes in visual movement feedback delay is better when there already is a substantial amount of delay present during movement. This result seems to indicate that the Weber-Fechner Laws do not

apply to the perception of (temporal) visuomotor mapping; as the laws would predict the opposite finding, i.e., better sensitivity to changes in delay when delay itself is low.

Results inconsistent with the Weber-Fechner Laws have been reported in other domains before, where they have been interpreted as indicating, for instance, saturation effects (Augustin, 2008; Augustin & Tanja, 2008; Carriot et al., 2021; Doble et al., 2003). We propose that, in our case, there is another intriguing explanation of the effect we found; which highlights the importance of embodiment and cognitive-attentional control in settings where a conflict is introduced between multiple sources of bodily movement feedback:

Firstly, increasing visuomotor delay reliably reduces the self-attribution of the observed movements (also called a loss of “agency” over those movements) and reduced the subjective embodiement of the seen moving body part (also called a loss of “ownership”; see Dummer et al., 2009; Farrer et al., 2008; Leube et al., 2003; Tsakiris et al., 2006). Thus, it is reasonable to assume that participants experienced more control over the virtual hand under small delays (Krugwasser et al., 2019; Wen & Imamizu, 2022)—which could have led to a relatively stronger subjective embodiment of the virtual limb.

Experienced embodiment can affect attentional control and task performance in virtual reality based movement tasks, as shown e.g. by Iwasaki and colleagues (2022). In our case, specifically, an increased embodiment of the virtual hand could have influenced our results twofold: Firstly, an increased subjective sense of embodying the virtual hand could have increased the tolerance for visuomotor mismatches, and thus, delay detection performance. It is well known that the embodiment of an alternative (fake or virtual) limb biases the subjective perception of visuoproprioceptive mismatches between real and fake limbs, resolving intersensory conflict through updates to the corresponding neuronal representations; as demonstrated e.g. in the ‘rubber hand illusion’ (Botvinick & Cohen, 1998; Limanowski, 2022). Since visuomotor delays are, effectively, also visuoproprioceptive mismatches, we speculate that a similar conflict attenuation could occur at smaller, compared with larger delays. Interestingly, seven of our participants spontaneously reported, after the experiment, that they

had perceived up to half of all virtual movements as synchronous to their own movement (i.e., much more than actually were synchronous) – and several of those participants reported a feeling of ownership over the virtual hand in those synchronously perceived periods. While this were only spontaneous post-hoc reports, they tentatively support the above interpretation. An increased embodiment of the virtual hand under small > large delays could also have distorted the perception of movement timing (Desantis et al., 2016; Haering & Kiesel, 2015; Rohde & Ernst, 2016). This would likely also influence the detection of delay changes.

Another possible effect of a potentially increased embodiment of the virtual hand under small delays pertains to visuomotor interference. Visual body movements that are incongruent with one's actual movements and movement goals can capture attention and lead to behavioral deficits—this is sometimes also referred to as visuomotor interference (Blakemore & Frith, 2005; Brass et al., 2001; Kilner et al., 2003; Metral & Guerraz, 2019). In line with this, when moving under visuomotor delay, visual movement feedback is processed differently depending on whether vision is currently task-relevant or a distractor (Limanowski et al., 2020; Limanowski & Friston, 2020). Interestingly, it has been suggested that the distracting effect of incongruent visual stimuli may be particularly strong when they depict one's own, delayed movements (Salomon et al., 2013). Note that our task design implied a continued focus on the real hand movements, to track the auditory rhythm, while the virtual hand moved incongruently. Thus, the inferior detection performance under smaller delays could hint at an increasingly distracting effect of the virtual hand movements on the actual movements—potentially caused by a relatively stronger embodiment of the virtual hand under small>large delays—despite tracking performance itself not differing between delay levels. In other words, participants may have used more cognitive-attentional resources to maintain stable tracking under small delays, because the virtual hand was more distracting; and those resources could have been now lacking for the detection task. This interpretation is supported by the fact that, overall, participants who tracked the auditory rhythm better showed poorer detection performance (as indicated by the positive correlation between overall tracking error and change detection performance). It may also explain the relatively low overall detection performance we

observed, in contrast to other studies using single-movement designs (Farrer et al., 2008; Leube et al., 2003).

Both effects, the increased tolerance for delays and the increased distraction by vision, are not mutually exclusive; and both align with an increased subjective embodiment of the virtual hand at smaller>larger delays. However, as we did not explicitly assess subjective embodiment, both of the above interpretations have to be explicitly tested in future experiments.

Our study raised further questions that should be followed up by future work. One is whether visuomotor delay changes are processed differently depending on whether they are task-relevant or -irrelevant. Another question that our design cannot answer properly is whether delay changes are perceived differently depending on whether delay is increased or decreased. Due to the nature of our design (i.e., limiting delays between 0-700 ms), not all directions of delay changes were presented equally often (e.g., from the 700 ms delay level, delay was only reduced not increased). Furthermore, visuomotor temporal incongruence can in principle also be implemented by leading, not lagging, vision; in the context of self-initiated hand movements, however, this is associated with a number of problems related to the predictability of the visual trajectories before actual movement. This could be an exciting avenue for research using brain activity decoding, for example. Finally, visual feedback delay is only one kind of visuomotor incongruence; future work should test whether other manipulations, such as spatial offset or gain scaling, produce similar results.

In sum, we have shown that the current degree of visuomotor congruence can bias the perception of changes in the visuomotor mapping during movement. Our results tentatively suggest that movement under relatively small delays entails some degree of tolerance for, or inattentiveness to delay changes; thus, they underline the general importance of embodiment in the perception of, and movement under visuomotor conflicts.

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