Technical Correspondence

Adjusting Haptic Guidance to Idiosyncratic Visuo-Haptic Matching Errors Improves Perceptual Consistency in Reaching

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***Abstract*—When subjects reach for a visual target with their unseen hand, they make systematic errors (visuo-haptic matching errors). Visuo-haptic matching errors are idiosyncratic and consistent over time. Therefore, it might be useful to compensate for these subject-specific matching errors in the design of haptic guidance to make the guidance perceptually consistent with the visual information. In this study, we investigated whether compensating for visuo-haptic matching errors results in better perceptual consistency in a reaching task. Subjects ($N = 12$) had to reach for visual targets with the handle of a haptic device (PHANToM Premium 3.0/6DoF) held in their unseen dominant hand without guidance, with haptic guidance toward the target position, or with haptic guidance toward the position they would reach for according to their idiosyncratic visuo-haptic matching error. We found that the distance between the aiming point of the guidance and the reached end position was smaller for the guidance toward the idiosyncratic matched positions, suggesting a larger perceptual consistency. Adjusting for idiosyncratic visuo-haptic matching errors seems to have benefits over guidance to the visual target position.**

***Index Terms*—Hand position sense, haptics, multisensory integration, proprioception, visual localization.**

I. Introduction

Haptic guidance is a tool that can be used to aid humans in interacting with the environment through machines, by providing suggestions about the task objective through forces [1]. This technique can be useful in various domains, ranging from the automotive industry to surgical robots. Besides using haptic guidance in direct interaction, it can also be used in teleoperation systems [2]. With these systems, users perform actions using tools that are located at a distance. Users typically receive visual feedback about the environment and their tools through screens, which can be accompanied by haptic feedback through a haptic device. In teleoperation systems with haptic guidance, the system and the user both contribute to the execution of actions [1]–[3]. The user is in charge, but the system helps the user in the form of assisting forces that provide information on the path to follow or the position to reach. The challenge is to design these assistive forces in an understandable and intuitive way [4].

A potential problem in the design of haptic guidance is that human perception is not veridical. There are several considerable distortions between the physical world and how it is perceived. Some of these distortions show comparable patterns across people, such as the direction-dependent distortion in force magnitude perception [5] and the well-known radial-tangential illusion [6]. These consistent distortions can often be explained by general human characteristics, such as the biomechanics of the arm. In addition to these general perceptual distortions, subject-specific distortions exist, such as visuo-haptic matching errors [7]–[14]. Such a distortion of the perception of positions implies that there is a difference between the physical and the perceived position of an object in the environment. If haptic guidance is toward the physical target position, it is not aligned with the user's perception of the target position, and thus, a conflict between the human and the intelligent controller arises.

Attempts have been made to incorporate perceptual distortions in human–machine interactions. Pierce and Kuchenbecker [15] have investigated nontraditional data-driven motion mappings to couple the movements of a robot on a screen with the movements of a human. The task for the human was to follow the robot's motions as precisely as possible. The authors show that a mapping that coincided quite well with general distortions found previously in proprioceptive position tasks by Ghez *et al.* [16] resulted in the best consistency between human and robot movements. In a follow-up study, Khursid and Kuchenbecker [17] show that adjusted spatial mappings based on both population-fits and individual-fits significantly reduced reaching errors. Note that these studies did not include haptic guidance.

In the present study, we used the existence of visuo-haptic matching errors to test for the effectiveness of subject-specific adjustments of haptic guidance, in a task in which participants were asked to localize visually presented targets without seeing their hand. Visuo-haptic matching errors are the resulting mismatches between the visual target position and the haptically indicated target position [7]–[14]. These matching errors are idiosyncratic: they are consistent within, but not between subjects [10]. In general, the matching errors are in the same direction for all positions and can reasonably well be described as a uniform translation [12], but the matching errors are larger when the arm is further away from the body [18], [19] or when the targets are positioned further to the left or right [20]. In previous studies, we have shown that visuo-haptic matching errors are consistent when measured a month later [14], and they are not affected by added forces or torques [12], [21].

In the current study, we investigated whether user performance (precision, accuracy, and agreement between the user and the system) improves when haptic guidance is based on known subject-specific perceptual distortions. As a proof of principle, the paradigm of visuo-haptic matching was used. First, the personal visuo-haptic matching errors were measured. Then, without the subject knowing, guidance was provided toward the physical target position or toward the idiosyncratic matched positions (the positions the subject would reach for according to their idiosyncratic matching errors). These conditions were compared to assess whether user performance improved when the guidance was adjusted in this user-specific way. The practical implication of this is that if haptic guidance is directed toward a visual target, subjects do

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TABLE I
EXPERIMENTAL BLOCKS

Block	Description
V	Visual targets, no forces, this block was used to measure visuo-haptic matching errors.
H	Haptic guidance to the target position, no visual targets shown, this block was used to measure the force error (F).
V+H	Visual targets, haptic guidance toward the target position.
V+HI	Visual targets, haptic guidance toward the idiosyncratic matched positions (measured in V).
V+HI+F	Visual targets, haptic guidance toward the idiosyncratic matched positions (measured in V), but now corrected for the force error (measured in H).

not perceive it to be directed to that location. If the matching errors are known, it is possible to correct for them by adjusting the guidance. This way, the visual and haptic information could be made perceptually consistent, rather than physically consistent. The resulting physical inconsistency could be compensated for in the design of a teleoperation system in such a way that the slave moves as the operator intended.

II. METHODS

A. Subjects

Twelve subjects (eight right-handed, three men, 18–42 years) took part in the experiment. All subjects were naive about the purpose of the experiment, were compensated for their time, and gave their written informed consent prior to participation. The experiment is part of an ongoing research program that has been approved by the ethics committee of the Department of Human Movement Sciences, Vrije Universiteit Amsterdam.

B. Experimental Design

Subjects had to reach for targets with their unseen dominant hand, in which they held the handle of a PHANToM Premium 3.0/6DoF (Geomagic) in a power grip. Specialized software was used for the onscreen visualizations and data acquisition at 300 Hz (D-Flow, MotekForce Link). The experiment was divided in five blocks, measured in one session (see Table I). In the first two blocks, presented counterbalanced over subjects, individual errors were measured for all target positions. A visual target (dot, $d = 15$ mm) was projected onto a white see-through projection screen above a horizontal mirror. The mirror reflected the images so that the subjects perceived the targets in a plane below the mirror (see Fig. 1, similar to [12]–[14]).

Subjects were to keep the handle vertical during the experiment (without any guidance to help them keep this orientation) and press the button on the side of the handle with their thumb to confirm the reached position. The color of the visual target provided feedback about the height of the handle to prevent the subjects from hitting the mirror. The dot was green as long as the handle was not more than 30 mm above or below the plane of the targets. Above this range, the visual target turned red, and below this range, it turned blue. Subjects were informed about this color-coding and instructed to keep the target green.

In block V, the visual target could be presented on six different target positions, at which the subjects' idiosyncratic visuo-haptic matching errors were measured (for each position). Subjects had to move toward the visual target position with their unseen hand and press the button on the handle of the PHANToM to confirm the position, after which a new visual target appeared. In block H, an attracting (spring-like) guidance force toward the same six target positions with a stiffness of 50 N/m (limited to 3.5 N to avoid large forces on the hand) was presented. In

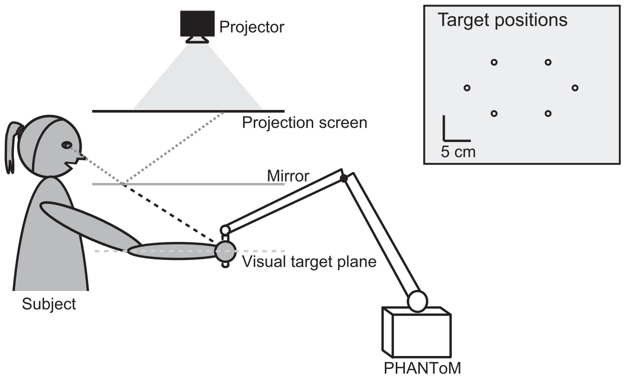


Fig. 1. Experimental setup. The subject saw the reflection of the target projected on the projection screen. The targets were perceived in a virtual plane between the mirror and the table. The subject held the handle of the PHANToM, which was used to exert the forces of the haptic guidance on the hand.

each trial, we asked subjects to find the minimum of the force fields without visual cues (the design of the Phantom ensures that subjects had to actively find this minimum) and measured the residual force of the guidance on the hand (force error F). Finding a matching error here would mean that subjects perceive a nonzero force as no force. The order in which the blocks V and H were presented was counterbalanced over subjects.

In both the third and the fourth block, visual targets and haptic guidance were presented together. The order of these two blocks was counterbalanced over subjects. In one block, the haptic guidance was toward the target positions (V+H), and in the other block, the haptic guidance was toward the idiosyncratic matched positions as determined in block V (V+HI).

The fifth block was an additional block, in which we combined the matching errors from blocks V and H, to see whether adjusting for both the visuo-haptic matching error and the force error would increase precision and accuracy further (V+HI+F). To do this, the center of the haptic guidance was shifted in such a manner that the force on the idiosyncratic matched positions was identical to the subject's idiosyncratic force error (measured in H). As this block was additional, it was always presented last to make sure that possible effects in this block could not have been transferred to the others.

The instructions to the subjects in the last three blocks (V+H, V+HI, and V+HI+F) were identical. They were told that there were three blocks, in which both a visual target and haptic guidance were present. Trials were presented as 13 semirandom sequences of the six targets; therefore, all targets were presented once before a target appeared for a second time and we ensured that there were never two identical target positions in a row (as in that case the hand would already be at the target). Each block consisted thus of 78 trials.

C. Analysis

From each block, we discarded the first sequence of targets, resulting in 12 repetitions for each target in each block. The mean end position and the 95% confidence ellipse were calculated for each subject, block, and target. With the mean end position, we calculated the visuo-haptic matching error for each target. One subject showed very low accuracy in V+H ($>5\sigma$ larger than the mean across subjects). We, therefore, excluded this subject from further analyses.

In the blocks in which both visual position information and haptic position information were presented, we expected to find an integration of the two [22], [23], leading to a higher precision than when only visual or haptic information is available. To test this, we used the area of the

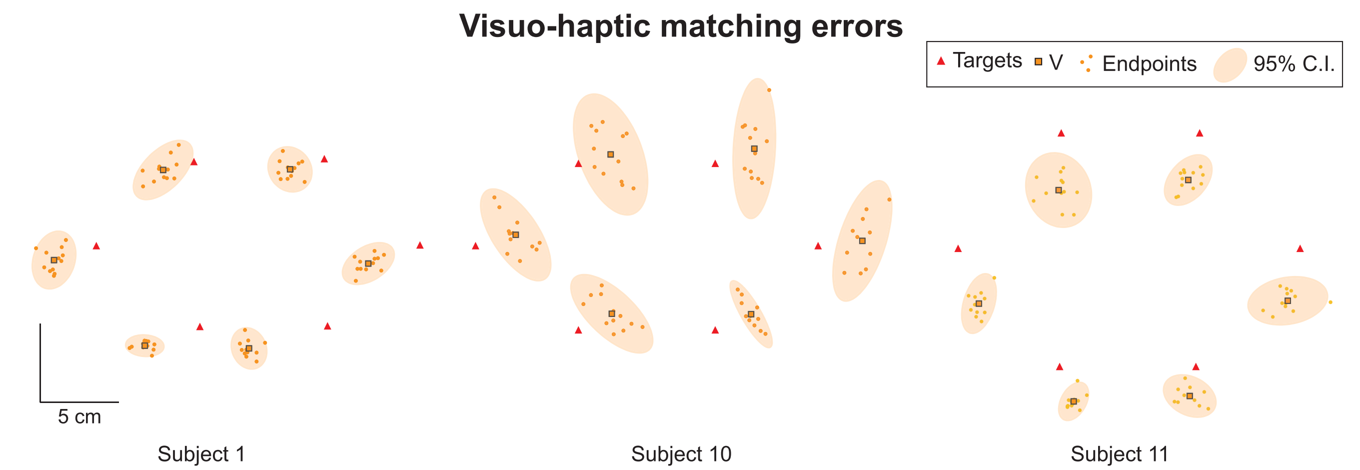


Fig. 2. Top view (with the subjects at the bottom of the figures) of the visuo-haptic matching errors for three subjects. The red triangles indicate the target positions. The individual dots (orange) show the reached end positions of the hand in each trial. The orange squares show the means of the distribution and the shaded ellipses are the 95% confidence ellipses. Both the matching errors and the precision are different for each subject.

95% confidence ellipse as a measure of precision and compared the precision between blocks with an one-way repeated measures (RM) analysis of variance (ANOVA).

As we were specifically interested whether changing the position of the guidance could improve perceptual consistency of the guidance with the visual target position, we calculated the distance between the minimum of the force field and the reached end position for the blocks involving guidance (H, V+H and V+HI) and compared them with an one-way RM ANOVA. Note that these distances also reflect the amount of residual force left on the handle at the reached end position for distances below 70 mm (or 3.5-N residual force). Therefore, this measure can be seen both as accuracy measure and as measure of conflict between the system and the user. A zero distance and residual force would mean that the system and the user fully agree on the end position, while a large distance and residual force indicate that the user is in conflict with the system.

For both ANOVAs, Greenhouse–Geisser corrections were used if sphericity was violated and Bonferroni corrections were used in all posthoc comparisons.

Force correction: To see whether the additional force correction improved the perceptual consistency, we used three measures. First, we compared the precision of V+HI and V+HI+F. Second, we compared the distance between the reached end position and the position of the initial matching error. Third, we compared the residual force of the guidance on the hand at the end position as a measure of conflict between the system and the user. Note that for V+HI, the residual force is directly related to the distance between the matching error and the reached end position for distances below 70 mm (or 3.5-N residual force). At larger distances from the center of the force field, the force is limited to 3.5 N, which breaks the relation between the residual force and the accuracy.

In V+HI+F, the residual force and the distance between the position of the initial matching error and the reached end position are not directly related because of the correction for the force error F. All comparisons were statistically tested with pairwise t-tests.

III. Results

Fig. 2 shows the visuo-haptic matching errors and the 95% confidence ellipses of the visuo-haptic matching errors for three example subjects. In congruence with previous studies [7]–[14], there are quite large visuo-haptic matching errors (orange), as the target position (red squares) is clearly not in the 95% confidence ellipses of these matching errors. There are also large individual differences in these visuo-haptic matching errors.

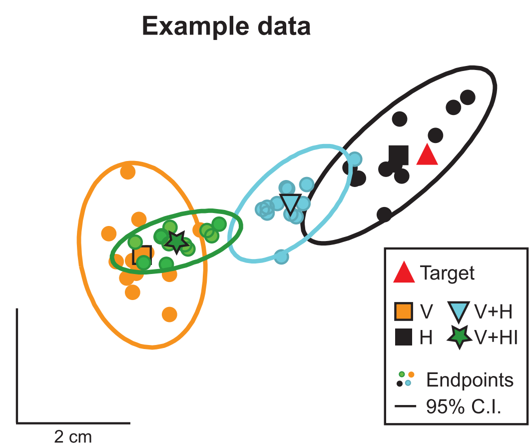


Fig. 3. Results of an example subject when reaching to a visual target (V) without haptic guidance, the minimum of a haptic guidance force field (H), a visual target with haptic guidance toward the physical target location (V+H), and a visual target with haptic guidance toward the position of the individual visuo-haptic matching error (V+HI). The individual dots show the end points of the trials. The squares show the means of the distribution and the ellipses are the 95% confidence areas.

The results of an example subject in the four main conditions can be seen in Fig. 3. The visuo-haptic matching errors for one target are shown in orange; the target position is the red square. The ellipses of the blocks V+H (cyan) and V+HI (green) seem to be smaller than ellipses in both V (orange) and H (black). The end points in V+HI (green) are close to the visuo-haptic matching errors (orange), while the end points in V+H (cyan) are somewhere in between the target and the visuo-haptic matching errors.

The ANOVA on the precision shows significant differences between the blocks ($F_{3,30} = 16.23$, $p < 0.001$). Posthoc comparisons show that the precision is better (smaller area of the ellipses) in V+H and V+HI compared with V ($p = 0.006$, $p = 0.003$, respectively), but only for V+HI when compared with H ($p = 0.002$, for V+H: $p = 0.207$; see Fig. 4).

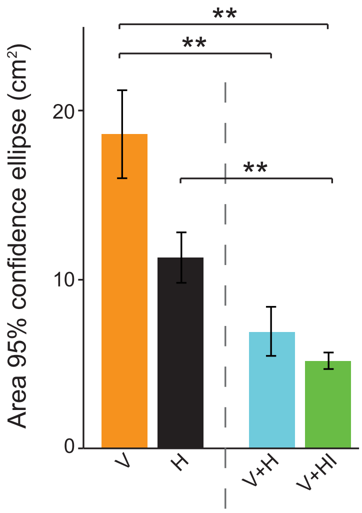


Fig. 4. Mean area of the 95% confidence ellipses. The blocks left of the dashed line are unimodal; those on the right are combined blocks. All error bars show SEM across subjects. The horizontal brackets show the significant statistical comparisons; ** indicates $p < 0.01$.

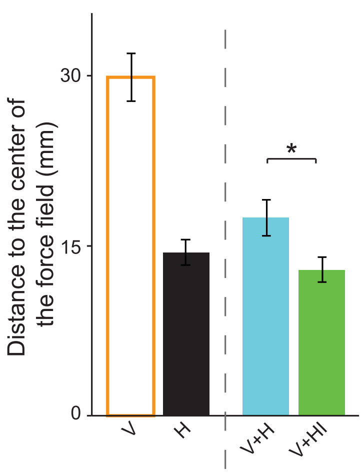
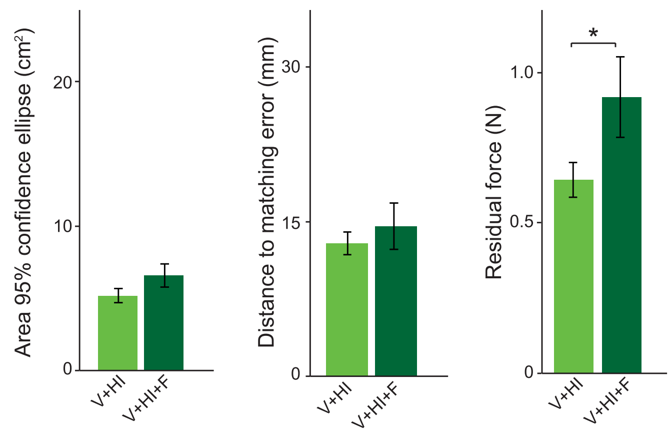


Fig. 5. Mean distance between the center of the force field and the end position of the hand. The bar for V is presented as a reference, showing the magnitude of the initial visuo-haptic matching errors. All error bars show SEM across subjects. * indicates a significant result with $p < 0.05$.

The ANOVA on the distance between the minimum of the guiding force field and the reached end position shows a significant effect ($F_{2,20} = 4.95, p = 0.018$). Posthoc comparisons show only one significant difference: the distance is smaller for V+HI than V+H ($p = 0.031$; see Fig. 5).

Force correction: For the precision, there was no significant difference between V+HI and V+HI+F ($t_{10} = -1.9, p = 0.084$), suggesting that correcting for the force error did not improve the precision further [and even shows a tendency in the opposite direction; see Fig. 6(a)]. There was also no improvement in the distance between the reached end positions and the position of the matching errors [$t_{10} = -9.58$, $p = 0.361$; see Fig. 6(b)]. Furthermore, correcting for the force error on top of the individualized guidance (V+HI versus V+HI+F) led to a significantly higher residual force in V+HI+F than in V+HI [$t_{10} = -3.17$, $p = 0.010$; see Fig. 6(c)], which is an effect in the direction opposite to what we predicted.



(a) (b) (c)

Fig. 6. Force correction. (a) Mean area of the 95% confidence ellipses. (b) Mean distance between the position of the matching error and the end position of the hand. (c) Mean residual force on the handle at the end positions. All error bars show SEM across subjects. * indicates a significant result with $p < 0.05$.

IV. Discussion

In this study, we compared traditional haptic guidance toward visual targets with subject-specific haptic guidance toward the haptically perceived position of the visual target (visuo-haptic matching error). Our results show that when haptic guidance is based on known perceptual subject-specific distortions, the perceptual consistency improves compared with when the haptic guidance is exclusively based on the original target position. The mismatch between the subject and the system decreases, reflected in smaller distances between the aiming point of the guidance and the reached and position, and lower residual forces on the handle at the moment the subject decides that the target position has been reached.

Besides compensating for the visuo-haptic matching error, we also tried to compensate for the force error (F, measured in the H block). Comparing the accuracy results of V+HI and V+HI+F shows that there is no significant difference, which suggests that compensating for the force error does not help the subject. The results of the residual force showed a larger value for the V+HI+F, which is in line with the correction that we made (the center of the guidance is not on the position of the visuo-haptic matching error, but corrected for the force error F found in the H block). Overall, correcting for the force error does not seem to be additionally beneficial with respect to individualization of haptic guidance alone.

One could argue that, by correcting for the individual visuo-haptic matching errors, the subject does not end at the correct (visually presented) position. However, in teleoperation systems, the relation between the position and movement of the master and those of the slave can be chosen by designer of the system. Therefore, these positions and movements are related, but most of the times not identical (see, e.g., [15] and [24]). Therefore, we argue that theoretically it does not matter whether you correct the movement or position on the side of the user or at the side of the slave and environment, as long as individual perceptual characteristics are taken into account. Therefore, changing the visual position to create perceptual consistency should lead to similar results, which it does [25]. This study, therefore, serves as a proof of principle of the individualization of haptic guidance and does not aim to make any claims about the most practical way to do so.

With the individualization of haptic guidance, we expect that not only the perceptual consistency increases, but also the intuitiveness of the guidance and the trust of the user in the teleoperated system. Speculatively, conflicts between the user and the system reduce the trust of the user in the system, while intuitiveness increases this trust as the user instantly understands the system's intentions. In an earlier study, we found results confirming that intuitiveness rather than the information content is essential in the effectiveness of haptic guidance [4].

Individualization of haptic guidance does not have to be a continuous process or something that the user has to do every time he or she uses the teleoperation system, because visuo-haptic matching errors are consistent over time periods up to at least a month [14]. As it is common that users log onto a system before they start using it, we think that an individualization of haptic guidance can be beneficial for a long time without a lot of effort.

Further research could focus on the implementation of the individualization, expansion of the factors that can be individualized, and more detailed information about the long term benefits of the individualization. A computational model predicting the results of the individualization for different types of haptic guidance could be useful to design the optimal guidance for each application.

V. Conclusion

In this study, we investigated whether guidance toward individual visuo-haptic matching errors improves perceptual consistency compared with guidance toward the visual target positions. Our results show significant improvements on the distance between the aiming point of the guidance and the reached end position of the hand, resulting in less residual force on the handle at the end position. Overall, we showed, as a proof of principle, that individualization of haptic guidance could be beneficial in teleoperation systems.

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