Adjusting haptic guidance to idiosyncratic visuo-haptic matching errors improves performance in reaching.

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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 in tele-operation systems. In this study, we investigated whether compensating for visuo-haptic matching errors results in better performance (precision, accuracy and less conflict between the system and user) in a reaching task. Subjects had to reach for visual targets with the handle of a haptic device held in their unseen dominant hand, either without guidance, or with haptic guidance towards the target position, or with haptic guidance towards the position they would reach for according to their idiosyncratic visuo-haptic matching error. The results show that the accuracy was higher for the guidance towards the idiosyncratic matched positions, and the conflict between the subject and the system was smaller, reflected by a lower residual force on the handle at the end position. Overall, adjusting for idiosyncratic visuo-haptic matching errors seems to have benefits over guidance to the veridical visual target position.
Introduction

In human perception, several significant distortions are present, which illustrates discrepancies that can exist between the physical and the perceptual world. Some of these distortions show comparable patterns across people, such as the direction-dependent distortion in force magnitude perception (Van Beek et al., 2013) and the well-known radial-tangential illusion (Gentaz & Hatwell, 2004). 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 (Smeets et al., 2006; Sousa et al., 2010; Rincon-Gonzalez et al., 2011; Kuling et al., 2013; Van der Kooij et al., 2013; Kuling et al., 2014). These visuo-haptic matching errors typically occur when reaching for a visual target, without seeing the hand. The resulting mismatches between the actual target position and the haptically indicated target position have shown to be idiosyncratic (Rincon-Gonzalez et al., 2011), consistent over time (Smeets et al., 2006; Kuling et al., 2016a), and robust under external forces (Kuling et al., 2013, 2015). In this article, the visuo-haptic matching paradigm is used as a proof-of-principle for compensating for subject-specific perceptual differences in haptic guidance.

Haptic guidance is a recently developed tool that can be used to aid humans in interacting with the environment through machines, by providing suggestions about the task objective through forces (Abbink et al., 2012). This technique can be useful in various domains, ranging from the automotive industry to surgical robots. A promising application domain is that of tele-operation systems (Boessenkool et al., 2013). With these systems, users perform actions using tools that are located at a distance and that are operated using a haptic device. Users typically receive visual feedback about the environment and their tools through screens, which can be accompanied by haptic feedback through the haptic device. In tele-operation systems with haptic guidance, the system and the user both contribute to the execution of actions (Mulder et al., 2008a; Abbink et al., 2012; Boessenkool et al., 2013). 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 (Mugge et al., 2016). One of the reasons why the design of haptic guidance is not straightforward could be distortions in human perception. Clearly, both
general and subject-specific distortions form a potential problem in the design of haptic guidance. If the user's perception of the environment is distorted, haptic guidance towards the physical target position might not be directed towards the user's perception of the target position, and if this happens, a conflict between the human and the intelligent controller arises.

Attempts have been made to incorporate general perceptual distortions in human-machine interactions. Pierce and Kuchenbecker (2012) 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. (1995) resulted in the best consistency between human and robot movements. In contrast to general perceptual distortions, subject-specific distortions however, have not been incorporated before. Moreover, Pierce and Kuchenbecker actually used two mappings simultaneously: a visual mapping from the top view on a vertical screen to the horizontal plane in which the subjects performed the movements and, secondly, a mapping from veridical to distorted space. In our study, we provided visual feedback at the same place and in the same plane as where the subjects performed the movements.

In this 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, guidance was provided towards the physical target position or towards the idiosyncratic matched positions (the positions the subject would reach for according to their idiosyncratic matching errors) without the subject knowing. These conditions were compared to assess whether user performance improved when the guidance was adjusted in this user-specific way.
Methods

Subjects

Twelve subjects (8 right-handed, 3 men, 18-42 yrs) 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 of VU University Amsterdam.

Figure 8.1 Experimental set-up. 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.
<table>
<thead>
<tr>
<th>Block</th>
<th>Description</th>
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<tbody>
<tr>
<td>V</td>
<td>Visual targets, no forces, this block was used to measure visuo-haptic matching errors</td>
</tr>
<tr>
<td>H</td>
<td>Haptic guidance to the target position, no visual targets shown, this block was used to measure the force error (F)</td>
</tr>
<tr>
<td>V + H</td>
<td>Visual targets, haptic guidance towards the target position.</td>
</tr>
<tr>
<td>V + HI</td>
<td>Visual targets, haptic guidance towards the idiosyncratic matched positions (measured in V).</td>
</tr>
<tr>
<td>V + HI + F</td>
<td>Visual targets, haptic guidance towards the idiosyncratic matched positions (measured in V), but now corrected for the force error (measured in H).</td>
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**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). 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 (Table 8.1). In the first two blocks, presented counterbalanced over subjects, individual errors were measured. A visual target (dot, d=15 mm) was projected onto a horizontal surface within a mirror set-up (Figure 8.1, similar to Kuling et al. (2013); (2014)).

In the first block, 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 towards 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. We will refer to this block as V. In the second block (H), an attractive (spring-like) guidance force towards the same six target positions with a stiffness of 50 N/m (limited to 3.5N to avoid large forces on the hand) was presented. In each trial, we asked subjects to find the minimum of the force fields without visual cues, and measured the residual force of the guidance on the hand (force error F). 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
towards the target positions (V+H) and in the other block the haptic guidance
was towards the idiosyncratic matched positions (V+HI). In the fifth block 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). The instructions to the subjects in the last three blocks (V+H,
V+HI, and V+HI+F) were identical. They were told that we had three blocks, in
which the two first blocks (V and H) were combined. In each block, each target
was presented 13 times, resulting in 78 trials in each block. Trials were
presented in semi-random sequences of the six targets: each targets was
presented once before a target appeared for a second time and there were
never two identical target positions in a row.

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 distribution 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
from the mean across subjects). We therefore excluded this subject from
further analyses.

Precision. We used area of the 95% confidence ellipse as a measure of
precision.

Accuracy. To assess the amount of accuracy between the predicted end
position (by the system) and the reached end position we calculated the
distance between them. For the V block the predicted position is the position of
the visual target. For H, V+H and V+HI the predicted position is the minimum
of the force field. For V+HI+F, the predicted position is the position of the
visuo-haptic matching error. This is the same position as in V+HI.

Conflict. We used the residual force of the guidance on the hand at the end
position as a measure of conflict between the system and the user. A zero
residual force would mean that the system and the user fully agree on the end position, while a high residual force indicates that the user is in conflict with the system. Note that for H, V+H and V+HI the residual force is directly related to the accuracy for distances below 70mm (or 3.5N residual force). At larger distances from the center of the force field, the force is limited to 3.5N, which breaks the relation between the residual force and the accuracy. In V+HI+F, the residual force and the accuracy are not directly related because of the correction for the force error F. The aim of this study is to investigate possible benefits of individualizing haptic guidance in a reaching task. Therefore, we focus our analyses on this question and only compare V+H with V+HI to see the effect of individualizing guidance, and V+HI with V+HI+F to see whether correcting for a force error would be effective. We used pairwise t-tests (with Bonferroni correction for multiple comparisons) to make these two comparisons for precision, accuracy and conflict.

**Figure 8.2** Top view (with the subjects at the bottom of the figures) of the visuo-haptic matching errors for three subjects. 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 ellipses. Both the matching errors and the precision are different for each subject.
Results

Figure 8.2 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 (Smeets et al., 2006; Sousa et al., 2010; Rincon-Gonzalez et al., 2011; Kuling et al., 2013; Van der Kooij et al., 2013; Kuling et al., 2014), there are quite large visuo-haptic matching errors (yellow), as the target position (grey squares) are clearly not in the 95% confidence ellipses of these matching errors. There are also large individual differences in these visuo-haptic matching errors.

The results of an example subject can be seen in Figure 8.3. Again, the visuo-haptic matching errors are shown in yellow, and the target positions are grey squares. The ellipses of the blocks V+H (cyan) and V+HI (green) are smaller than ellipses in both V (yellow) and H (black). The end points in V+HI (green) are close to the visuo-haptic matching errors (yellow), while the end points in V+H (cyan) are somewhere in between the target and the visuo-haptic matching errors.

![Example subject](Figure 8.3: 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 towards the physical target location (V+H), and a visual target with haptic guidance towards 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 ellipses.)
**Precision.** The precision is better (smaller area of the ellipses) for all blocks in which visual targets and haptic guidance were combined (Figure 8.4A). Although the precision seems to be best in the V+HI condition, the differences with the other combined blocks were not significant (V+H and V+HI: $t_{10} = -1.23, p = .496$, and V+HI and V+HI+F: $t_{10} = -1.92, p = .168$).

**Accuracy.** The accuracy is better (smaller distances) for all blocks involving guidance (Figure 8.4B). The pairwise t-tests shows that the distance between the predicted position and the end position of the handle was significantly smaller for V+HI compared to V+H ($t_{10} = -3.14, p = .020$), which means that the subject’s end positions were closer to the expected position with the individualized haptic guidance than with veridical guidance. There was no significant difference between V+HI and V+HI+F ($t_{10} = -.96, p = .722$), suggesting that correcting for the force error did not help the subject further.

![Figure 8.4 Results. A) Mean area of the 95% confidence ellipses. B) Mean distance between the predicted position 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. The horizontal brackets show the statistical comparisons and their results; * indicates a significant result with $p < 0.05$.](image-url)
Conflict. The pairwise t-tests show significantly lower residual forces for V+HI compared to V+H ($t_{10} = -2.91, p = .032$, Figure 8.4C), which means that the subject agreed more with the system when the guidance was individualized. Note that this comparison is similar to that for the accuracy since there were no trials in which the force was limited to 3.5N (due to the cap) at the reached end position. Correcting for the force error on top of the individualized guidance (V+HI vs. V+HI+F) lead to a significantly higher residual force in V+HI+F than in V+HI ($t_{10} = -3.17, p = .020$).

Discussion

In this study we compared traditional haptic guidance towards visual targets with subject-specific haptic guidance towards 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 accuracy improves compared to when the haptic guidance is exclusively based on the original target position. The amount of conflict also decreases between the subject and the system, reflected in 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 tele-operation systems the position and movement of the user, the master and the slave are related but most of the times not identical (Niemeyer et al., 2008; Pierce & Kuchenbecker, 2012). 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. 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 this.

With the individualization of haptic guidance we expect that not only the objective performance increases, but also the intuitiveness of the guidance and the trust of the user in the tele-operated 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 (Mugge et al., 2016).

Individualization of haptic guidance does not have to be a continuous process or something that the user has to do every time he uses the tele-operation system, because it has been found in an earlier study that visuo-haptic matching errors are consistent over time (Kuling et al., 2016a). We argue that the individualized guidance should be measured and set only once, and can be part of the individual user settings. 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 very 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.

Conclusion

In this study we investigated whether guidance towards individual visuo-haptic matching errors improves performance compared to guidance towards the veridical target positions. Our results show significant improvements on the accuracy and on the residual force on the handle at the end position and a non-significant tendency to a better precision. Overall, we showed, as a proof-of-principle, that individualization of haptic guidance could be beneficial in tele-operation systems.