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Chapter 3

Perception of force direction

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T.K. Verhoogt, B.G.A. Wolfs & A.M.L. Kappers (2014)
Subject-specific distortions in haptic perception of force direction
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In a previous study, we found that the accuracy of human haptic perception of force direction is not very high. We also found an effect of physical force direction on the error subjects made, resulting in 'error patterns'. In the current study, we assessed the between- and within-subject variation of these patterns. The within-subject variation was assessed by measuring the error patterns repeatedly over time for the same set of subjects. Many of these patterns were correlated, which indicates that they are fairly stable over time and thus subject-specific. The between-subject analysis, conversely, yielded hardly any significant correlations. We also measured general subject parameters that might explain this between-subject variation, but these parameters did not correlate with the error patterns. Concluding, we found that the error patterns of haptic perception of force direction are subject-specific and probably governed by an internal subject parameter that we did not yet discover.

3.1 Introduction

Force feedback is a very important aspect of haptic devices. To understand how force feedback algorithms should be designed, it is useful to gain insight in the human perception of force. In this study, we focussed on the human perception of the direction of a force. Like with all measurements, the terms *precision* and *accuracy* can also be used in relation to perception. Precision (also called discrimination threshold or variability) refers to the random error that subjects make, so it indicates the spread of the data around the perceived mean value. Accuracy (also called bias) refers to the systematic error that subjects make, so it indicates if the perceived mean differs from the physical mean.

Some studies already evaluated the precision of the perception of the direction of a force exerted on the passive index finger in the fronto-parallel plane (Barbagli et al., 2006; Tan et al., 2006; Ho, Tan, Barbagli, Salisbury, & Spence, 2006). They report a precision of 30 degrees, which was the same for all force directions. Switching from a stationary to a moving arm seems to have no influence for forces exerted in the fronto-parallel plane, as the precision stays the same (Yang et al., 2008b). This does not hold for the perception of force direction of a shear-force exerted on the finger tip, as in this case the precision is higher when the arm is stationary (Vitello, Ernst, & Fritschi, 2006). For forces in the horizontal plane, force direction does seem to influence the precision of perception (Elhajj et al., 2006), with the median region showing a higher precision than the left and right lateral areas.

While there is some knowledge of the precision of perception of force direction, work on the accuracy of perception of force direction is very scarce. Toffin et al. (2003) investigated this topic by asking subjects to move the handle of a joystick in the direction of a force presented earlier. However, this only shows the accuracy of the motor output, which could be adjusted for biases in perception. To investigate the accuracy of perception itself, we asked people directly for their perception of force direction in a previous study (Van Beek, Bergmann Tiest, & Kappers, 2013). We found that humans make large errors, and thus are quite inaccurate, in this task. We also found a significant effect of physical force direction on the error humans make in perceiving the direction of the force. This indicates that the errors are not constant nor random, but form a kind of 'error-pattern'. In the current study, an attempt was made to investigate what the basis of these patterns is and how consistent they are over time.

In experiment 1, the within-subject differences in patterns over time were investigated. This was done by measuring the error patterns of a small group of subjects at different moments in time. The aim of this experiment was to investigate if the patterns are stable over time and thus subject-specific. Therefore, a small number of subjects were studied, while many measurements were performed for each subject.

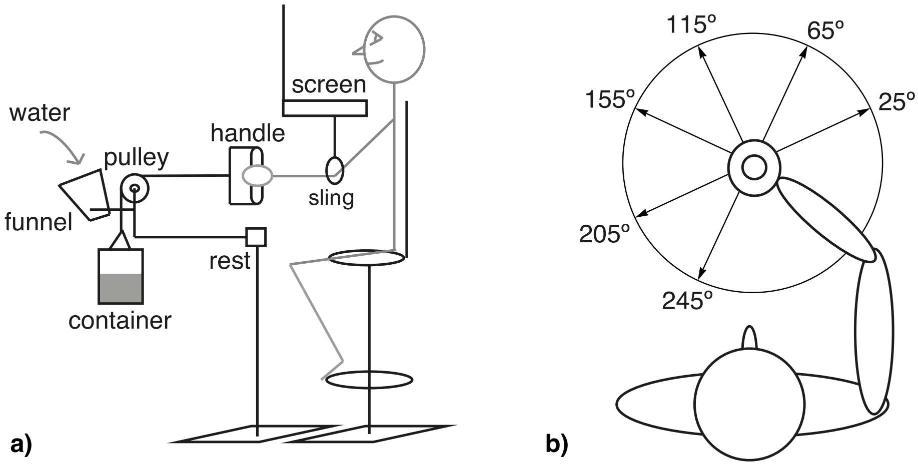

Figure 3.1: Diagrams of the set-up that was used in both experiments. **a)** Side view of the set-up showing the apparatus designed to deliver forces at different directions in the horizontal plane. **b)** Top view of the same set-up, to indicate the force directions that were used in both experiments

In experiment 2, the between-subject differences in error patterns were investigated. In addition to the error patterns, a number of general subject parameters, which might be correlated to the between-subject variation, was measured. The aim of this experiment was to find groups of subjects that show similar patterns and to investigate if general subject parameters might explain the differences between the (hypothetical) groups.

Together, these experiments show the intra- and inter-subject differences in the perception of force direction. This information might be useful in the design of haptic feedback algorithms, because force direction is used to communicate information in this application. To make sure that the user understands the information properly, it might be beneficial to adjust force direction according to the error pattern of the user.

3.2 Material and methods

3.2.1 Subjects

In experiment 1, 8 male subjects participated, aged 22±2 years (mean±s.d.). In experiment 2, 21 male and 4 female subjects participated, aged 21±2 years.

In both experiments participants were naive to the purpose of the experiment. They were all right-handed, which was assessed using a Coren-test for handedness (Coren, 1993). All participants signed an informed consent form. They received no compensation for their time.

3.2.2 Set-up

Subjects were seated in front of the set-up (see Figure 3.1a) on a height-adjustable chair. Their vision was blocked by a black screen. Beneath their faces, in the horizontal plane, the screen of a laptop was placed. Subjects used their right hand to hold a handle and their left hand to control a computer-mouse to provide the answers. Even though they controlled the mouse with their non-dominant hand, they reported that this was not a difficult task. There was also no time limit on answering, so they could take the time they needed to perform the task precisely. At each trial, subjects were prompted via the screen to lift the handle from the resting position and then keep their hand at the same position in the air throughout the trial. At this point, the experimenter gradually increased the force by pouring water in the container, which was connected to the handle. The gradual increase (4 N was reached after 5 seconds) minimized inertial cues and made sure that subjects could keep their hand at the same position. Moreover, the funnel made sure that the force ramp was similar in all trials. During this force-ramp, white noise was played on the headphones, which the subjects were wearing. Once all the water was in the container and thus the force had reached its plateau-level of 4 N, the noise was switched off and the subjects answered the question: which direction do you think the force is coming from? They did this by turning the needle of a gauge shown on the screen, followed by a button-press to confirm their answer. The water was then removed from the container and the handle was returned to the resting position. To provide different force directions — which were 25, 65, 115, 155, 205 and 245 degrees in both experiments, as shown in Figure 3.1b — the set-up was turnable around its vertical base.

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3.2.3 Protocol

In experiment 1, subjects performed at least three experimental sessions of one hour each within one week, on three different days. During each session, every force direction was presented ten times in a random order. After three sessions, the correlation between the mean errors found in these sessions was calculated. When the correlation coefficient was significant (r>0.78, p<0.05), subjects were asked to return to the lab one month later to perform a fourth measurement session. When these criteria were not met, stability of the patterns on a short time scale could not be proven and therefore stability of the patterns on a longer time scale was very unlikely. Therefore, subjects showing patterns that did not meet the criteria were not asked to perform a fourth session.

In experiment 2, subjects performed one experimental session of one hour. Each force direction was presented ten times in a random order. In addition to the perception measurements, general subject parameters were recorded, which were: age, height, length of

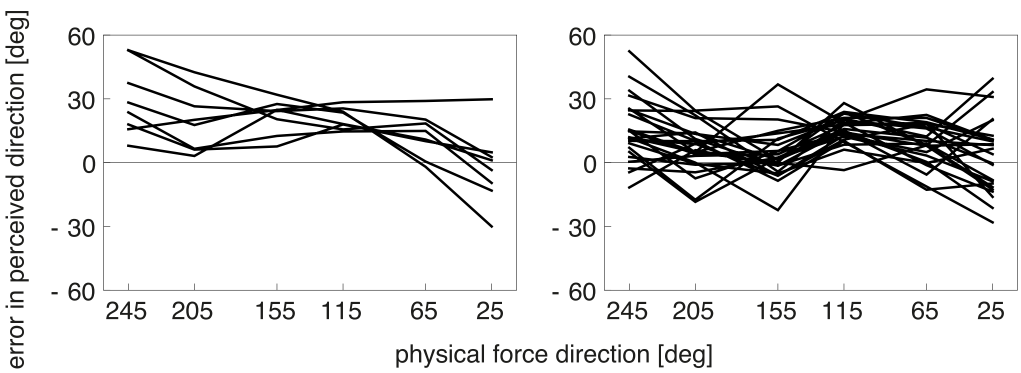

Figure 3.2: Mean errors per physical force direction, as found in experiment 1 (left) and 2 (right). The means are based on 30 trials (3 sessions) per physical direction for experiment 1 and on 10 trials (1 session) per physical direction for experiment 2. The lines connect the errors per subject.

upper and lower arm, arm span, hand size, and Maximum Voluntary Contraction (MVC). MVC is a measure of hand strength.

In both experiments, subjects performed 3 practice trials to familiarize with the procedure.

3.2.4 Statistics

To assess whether subjects were veridical in their perception of force direction, *t*-tests were performed on the results per physical force direction for each subject, which showed whether the mean errors differed from 0. The influence of physical force direction on the error that subjects made in judging that direction was investigated using a repeated measured ANOVA with physical force direction as within-subject factor. In all ANOVAs, Greenhouse-Geisser correction was used when the sphericity criterion was not met. The similarities between and within subjects were assessed in more detail by calculating the correlation between the error patterns with Pearson's correlation tests. When the correlation coefficient was significant, it was deemed 'high'.

For experiment 1, the main effect of session on the error patterns was also assessed in the repeated measures ANOVA, which was performed on the data of the first three sessions only. To obtain a more detailed view of the similarities between the different sessions of single subjects, the correlations between the error patterns of the different sessions were calculated for each subject.

For experiment 2, the correlation of the error patterns between the subjects was tested. The significance of the general subject parameters as a predictor of the differences between subjects was measured by introducing these parameters as covariates in the repeated measures ANOVA and then testing their significance.

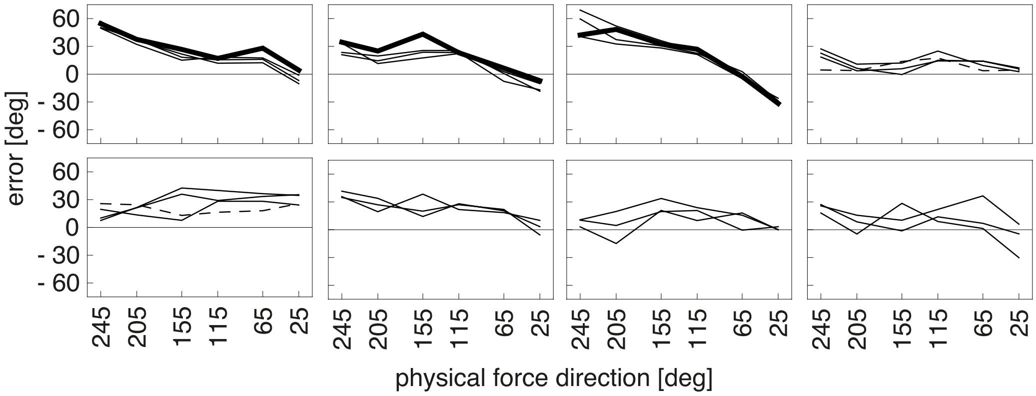

Figure 3.3: Mean errors per physical force direction per subject, arranged from left to right in order of descending correlation between sessions. Thick solid lines indicate a fourth session with a high correlation with the first three sessions, while thin dashed lines indicate a low correlation. When only thin solid lines are plotted, subjects performed only three sessions.

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3.3 Results

A general overview of mean errors per physical force direction of both experiments can be found in Figure 3.2. Note that the errors are quite large, even up to 60 degrees. Moreover, the figure suggests that the patterns differ between subjects.

In the first experiment, 41 out of the 48 force direction-subject combinations had a mean that differed significantly from 0, which corresponds to 85% of the combinations. A significant effect of physical force direction on the error in perceived force direction was found ($F_{1.5,10}$=7.8, p=0.012). No main effect of session on the error patterns was found ($F_{2,35}$=0.24, p=0.79). In Figure 3.3, the error patterns at different sessions for all eight subjects are shown. In the first three sessions, six of the eight subjects showed high correlations between the sessions. For practical reasons, only five subjects performed a fourth session. In the fourth session, three of the five subjects showed an error pattern that was correlated to the patterns measured in the first three sessions. Overall, the correlation analysis revealed that 50% of the correlations between the first three sessions was high.

In the second experiment, 79 out of the 150 force direction-subject combinations had a mean that differed significantly from 0, which corresponds to 53% of the combinations. A significant effect of physical force direction on the error in perceived force direction was found ($F_{2.7,65}$=4.5, p=0.0079). The between-subject correlation revealed that only 7% of the error patterns showed a high correlation with patterns of other subjects. Figure 3.2 also visualizes the differences between subjects. None of the general subject parameters were significant when used as a covariate (all $F_{2.4,40}\leq$1.9, all $p\geq$0.15).

3.4 Discussion and conclusion

In both experiments, we found that humans make substantial errors in judging the direction of a force, as more than half of the mean errors were non-zero. Moreover, these errors were different for different physical force directions, as shown by the significant effect of physical force direction on error. These results are congruent with our previous results (Van Beek et al., 2013), in which we found errors of similar magnitudes (also up to 60°).

In the previous study (Van Beek et al., 2013), we assessed perception of direction using forces of 2, 3, 4, 5 and 6 N. We found no influence of force magnitude on the error patterns. Therefore, we chose to use only a force magnitude of 4 N in the current study. This is not a very large force magnitude, but it is far above the threshold of 0.1 N for feeling the difference between a right- and leftward force direction (Baud-Bovy & Gatti, 2010).

The results of experiment 1, based on 8 subjects, show that for half of the sessions, the patterns correlated within subjects over time. This suggests that the patterns are caused by internal subject parameters, rather than external ones that probably vary over time. For some subjects the patterns did not correlate so well over time, so external parameters might play some role, but internal parameters seem to be the most important ones.

The results of experiment 2, based on 25 subjects, show that only 8% of the error patterns were significantly correlated to patterns of other subjects. We first hypothesized that there might be groups of subjects with similar error patterns, but because of the poor correlation between subjects this does not seem likely. We then hypothesized that there is a general subject parameter that differs between subjects and that might explain these differences in error patterns. The absence of significance of any of the measured parameters (which were: age, height, length of upper and lower arm, arm span, hand size, and MVC) as a covariate in the model indicates that these parameters are not the ones that explain these differences.

Concluding, the correlation between the patterns within subjects (exp. 1) was much higher than the correlation between subjects (exp. 2). This seems to suggest that an internal parameter is the most important governing parameter for the errors in haptic perception of force direction. What this parameter is, remains to be investigated.

The knowledge that humans make errors in perceiving force direction should be considered in the design of force feedback algorithms. An application could, for instance, be the user-specific adjustment of force direction.