The Haptic Perception of Spatial Orientations studied with an Haptic Display

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Abstract. Blindfolded adults explored the orientation of a "virtual rod" generated by an haptic display in the frontal plane and reproduced it in the 2D (movements constrained to the frontal plane) or in the 3D (movements free in space) reproduction conditions. We found that the haptic perception of orientations in the frontal plane was similar in both conditions, indicating that the haptic perception of orientations generated by an haptic display is similar to the results of classical haptic studies.

1 Introduction

The vertical and horizontal orientations are perceived more accurately than the oblique orientations. Appelle called this anisotropy the "oblique effect"[1]. In most studies of the oblique effect in the haptic modality, the set of possible orientations was limited to a plane by the experimental apparatus (i.e., a metallic rod that rotated around a fixed axis in space) [2,3,4]. The orientation of a stimulus in a plane is defined by a single parameter such as the angle with the horizontal or vertical axis. In contrast, an orientation in space is defined by two parameters such as its azimuth and elevation. The objective of this study is to find out whether the oblique effect is still present in the absence of any spatial constraint when the participant needs to focus only on more than a single parameter to perform the task.

In this study, we used a haptic display to present the stimulus and record the response in space. In the exploration phase, the haptic display constrained the participant's fingertip's to-and-fro movements along a "virtual rod" in space. In the reproduction phase, the participant reproduced the same movements in two different conditions. In the 2D reproduction condition, the finger movements were constrained to the frontal plane. Like in the previous studies, we expected to find an oblique effect in this condition. In the 3D reproduction condition, the movements of the finger were unconstrained in space. Because the participant needed to pay attention to the orientation of his or her movements inside as well as outside the frontal plane to perform the task in this condition, we did not know whether the oblique effect would still be present.

2 Method

Ten right-handed undergraduate students participated in the study. Each participant was blindfolded and wore a brace that immobilized the wrist joint. The participant sat in front of the haptic display (PHANTOM 1.5) and put the right index finger into a thimble that was mounted on the extremity of the haptic device. At the beginning of each trial, the haptic device produced a central force field that guided the participant's finger to the center of the workspace 35 cm in front of the sternum. A beep indicated the beginning of the exploration phase. During this phase, the haptic device allowed the participant to move the fingertip freely during 7.5 seconds along a 14 cm-long line segment which defined the target orientation. Then, a central force field brought the fingertip back to the center of the workspace (5 s). Finally, a second beep indicated the beginning of the reproduction phase during which the participant had to reproduce the exploratory to-and-fro movements as accurately as possible during 7.5 seconds.

In the *2D condition*, the movements were constrained to the frontal plane during the reproduction phase (Fig. 1). In the *3D condition*, the participant could move his or her finger freely in space. The experiment included four orientations which all intersected in the workspace center. Inside each condition, each orientation was presented six times in a random order. Both reproduction conditions were presented in two successive blocks of 24 trials. Their order of presentation was reversed for half the participants. Participants rehearsed the procedure until proficient before starting the experiment. The position of the fingertip was recorded by the haptic device every 50 ms during both phases.

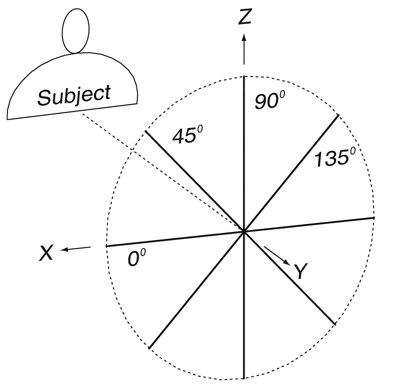

Fig. 1. The four target orientations positioned in the participant's fronto-parallel plane.

To compute the orientation of the movement recorded during the reproduction phase, we fitted a straight line to the trajectory by computing the main eigenvector of the covariance matrix:

$$S = \frac{1}{n-1} \sum_{i=1}^{n} \left(X - \bar{x}\right)' \left(X - \bar{x}\right)$$

where X is an n x 3 matrix with the coordinates of the trajectory in space, n is the number of samples, and $\bar{x}$ is the mean position. The direction of the main eigenvector constituted the response of the subject to a trial.

The *angular error* in the 3D reproduction condition, i.e. the angular difference between the orientation of the stimulus and of the response in space, was split into two components: the in-plane and out-of-plane error. The *in-plane* error corresponds to the angle between the target orientation and the projection of the response in the frontal plane while the *out-of-plane* error corresponds to the angle between the response and the frontal plane. In the 2D reproduction condition, the out-of-plane error is null by definition.

For each participant, target and reproduction condition, we computed the mean and standard deviation (SD) of the in- and out-of-plane errors. Then, we computed the systematic error (across-subject signed average), the between-subject variability (SD of the subject means), and the within-subject variability (mean of the participants' SDs).

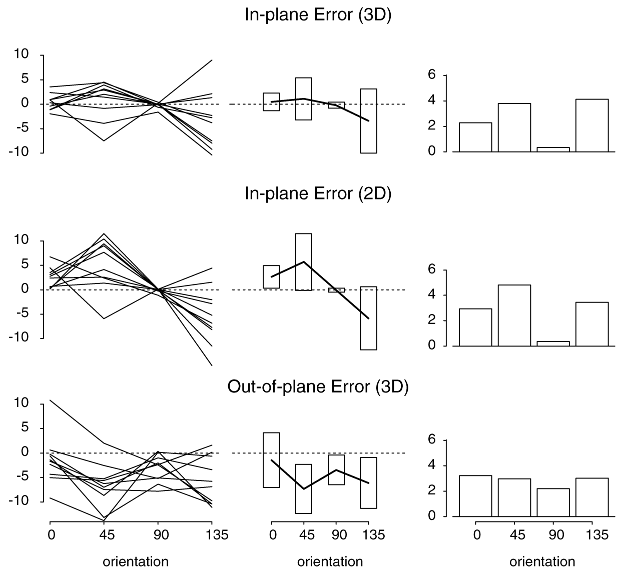

Fig. 2. In-plane and out-of-plane angular error. *Left column*: Mean error for each subject and orientation. Each line corresponds to a different participant. *Middle column:* Grand mean across all subjects (*solid line*). The bars denote the between-subject variability for each orientations. *Right column:* Each bar denotes the across- subject average of the standard deviations computed for each orientation and subject separately.

3 Results

Errors inside the frontal plane were very similar in the 2D and 3D reproduction conditions (Fig. 2). The vertical orientation was reproduced very accurately by all participants in both conditions (mean ± between-subject variability of the in-plane error: -0.1° ± 0.4° and -0.2° ± 0.6° in the 2D and 3D reproduction conditions respectively). The within-subject variability was also the smallest for the vertical orientation (0.4° and 0.3° for the 2D and 3D conditions, respectively). The second best orientation was the horizontal orientation . The between-subject as well as within-subject variability was the largest for the two obliques (>4.0°). These results show the presence of an oblique effect in both conditions and are similar to those observed in previous studies.

In the 3D reproduction condition, the out-of-plane error was on average smaller for the vertical and horizontal than for the two oblique orientations. The differences across orientations were however less marked than for the in-plane errors. In particular, there was almost no difference across orientations with respect to the within-subject variability of the out-of-plane error. Participants reproduced the vertical orientation slightly less accurately outside than inside the frontal plane . The within-subject variability was also the larger outside than inside the frontal plane (2.2° vs. 0.3°). In other words, this pattern of errors indicates that the variability of the responses is larger in the sagittal plane than in the frontal plane for the vertical orientation.

A two-way repeated-measure ANOVA of the in-plane error with the reproduction condition and the orientation as within-subject revealed that the orientation factor as well as the interaction were statistically significant (orientation: $F(3,27)=6.07$, $\varepsilon=.407$, $P=0.027$, interaction: $F(3,27)=11.4$, $P<0.001$). Figure 2 shows indeed that errors are larger in the 2D than in the 3D reproduction condition for the two oblique orientations. In order to test whether the variability of the responses depended on the orientation, we analyzed the SDs computed for each participant, orientation and reproduction condition in a similar manner. The results of the two-way repeated measure ANOVA indicated the orientation factor was the only statistically significant effect ($F(3,27)=33.11$, $\varepsilon = .915$, $P \approx 0$). Finally, one-way repeated-measure ANOVAs of the out-of-plane errors in the 3D reproduction condition indicated that the orientation factor was not statistically significant ($P>.05$).

4 Discussion

Like in the classical studies, we found an oblique effect inside the frontal plane in both reproduction conditions. However, unlike previous studies, the vertical orientation was better reproduced than the horizontal orientation. A possible explanation may be that the haptic display permitted the participants to make exactly the same movements in the exploratory and reproduction phases. Thus, it is possible that the need in the classical haptic studies to grasp the rod in order to rotate it back to its initial orientation interfered with the perception of the vertical. The relative size of the in-plane and the out-plane errors in the 3D reproduction condition depended on the orientation of the stimulus. While the participants very accurately and consistently reproduced the vertical orientation inside the frontal plane, they produced out-of-plane errors of the same order of magnitude for all other orientations. In particular, we did not find any significant oblique effect.

The similarity of the in-plane errors in both conditions and the uniformity of the out-of-plane errors across orientations in the 3D condition suggest that the participants focused their attention on the orientation of the stimulus inside the frontal plane in the 3D and 2D reproduction conditions alike. Thus, the processes involved in reproducing the orientation in the frontal plane could be different from those that permitted the participants to keep their response close to the frontal plane in the 3D reproduction condition.

References

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