Target contact and exploration strategies in haptic search

Vonne van Polanen* Wouter M. Bergmann Tiest
Astrid M.L. Kappers

MOVE Research Institute, Faculty of Human Movement Sciences,
VU University, Amsterdam, The Netherlands
*v.van.polanen@vu.nl

Supplementary Methods

Apparatus

The hand movements were measured with a 3D Guidance TrakSTAR movement tracking system (Ascension Technology Corporation). The system had an accuracy of ~ 1 mm. Data were sampled with a frequency of 100 Hz and lowpass filtered online. Besides x, y, and z coordinates, the sensors also measured the azimuth, elevation and roll orientations. A total of eight sensors were used, of which six were placed on the hand and the other two were placed inside stimuli (see below). Sensors were placed on the nail of each finger, including the thumb, and one sensor was placed on the back of the hand, approximately in the middle in line with the knuckle of the middle finger. The sensors on the nails were placed with their centres ~ 5 mm from the fingertip. To keep the sensors in place, they were attached with double-sided tape and the wires were taped to the second phalanx. No tape was placed on the inside of the hand, so the cutaneous perception of the skin was not reduced.

Three types of wooden stimuli were used in the experiment: rough spheres, smooth spheres and smooth cubes. The rough spheres were created by gluing small pieces of sandpaper (Bosch, P60) on the spheres (similar method as van Polanen et al.[1]). The spheres had a radius of ~ 7.5 mm and the cubes an edge length of ~ 12 mm. They weighted about a gram.

Practice block and randomisation

Preceding a condition, participants performed a practice block. At least twenty practice trials were performed until 10 were answered correctly in a row or up until a maximum of 35 trials. In the experiment, 50 trials were performed of which half were target-present trials. Target-present trials and target-absent trials were presented in a randomised order. The position of the target in the stimulus bunch was not systematically controlled, but it was made sure that it was located at different positions between the trials.

The order of the conditions was randomised among participants. However, each condition had to follow every other condition at least once and the starting condition was divided approximately evenly among the participants. The experiment was divided in two sessions, with two conditions each, performed on different days. Between the two conditions, the participants took a short break.

Analysis

For all analyses, only correctly answered trials were included. Six trials (0.3%, 3 target-present and 3 target-absent trials) were removed from the analysis due to measurement errors. Furthermore, in the reaction time analysis, outliers ($< 0.5\%$) that differed more than 3 standard deviations from the mean were removed.

The start of a trial was defined as the point in time when the stimuli were first touched. More specifically, it was defined as the moment the velocity of the target stimulus (or one of the distractors in a target-absent trial) reached the criterion of 4 cm/s. The data point that was equal or higher than this criterion was the start point of the trial. The stimulus velocity was calculated as the

derivative from the filtered target position. A 2nd order low-pass Butterworth filter was used, with a cut-off frequency of 10 Hz. The end of the measurement was determined by the participant's vocal response, as measured by the microphone placed on the participants head. This response stopped the data sampling automatically. The time between the start and end of the trial was the reaction time. The reaction times were averaged over the conditions, for target-present and target-absent trials separately.

For the contact analysis, only target-present trials were used in the analysis. Sometimes the target made a quick position 'jump', due to measurement errors. These trials were identified by looking at the acceleration of the target and its height. When the height of the target was 13 mm below the average resting height or had an acceleration above 1 m/s, the position data were interpolated. The acceleration was calculated as the derivative from the target velocity, that was calculated from the filtered position data as described above. The interpolated data were the identified samples + 5 samples before and after. A sample is here one step in time and equal to 10 ms. The maximum interpolated range was 25 samples or at most 14% of the reaction time. A total of 52 (5.2 %) trials were identified with these 'jumps'. Five trials could not be interpolated because the identified samples were at the end of the trial. In these trials the target was assumed not to be in contact with any hand part at these samples.

In many trials, the position of proximal joint could not be calculated for one or more samples, because the assumed triangle between the joints could not be closed. In these situations, the alternative solutions of the model were used.[2] In 24 (2.4 %) trials, the model could not be used for the calculation of the proximal joint due to other reasons. However, this was only for 3 samples (30 ms) or fewer, so in these trials the previous correct sample(s) was (were) repeated. For most of the cases where the alternative solutions were used this was in the thumb and little finger.

For the movement classification analysis, both target-present and target-absent trials were included. Another trial was removed from this analysis, because the model yielded an impossible ring finger angle (i.e. the assumed triangle could not be closed). The speed of the thumb was calculated with respect to the hand sensor by subtracting the hand sensor position from that of the thumb. Then, the speed was calculated and the median was taken to diminish the influence of short fast movements. Similarly, the median ring finger speed was calculated with respect to the hand palm.

The volume in which the thumb moved was the volume of the convex hull that enveloped the positions of the thumb over the course of the trial, with the hand sensor positions subtracted.

The last variable, the number of turning points, reflected the bending and stretching of the ring finger. To estimate this, the angle between the middle and proximal phalanx of the ring finger was calculated. The angles were filtered with a 4th order low-pass Butterworth filter with a cut-off frequency of 5 Hz and then differentiated to obtain the angular velocity. Because only large changes in the angles are interesting and not the small movements, a criterion of 50°/s was used. Once the angular velocity got above this value or below −50°/s, a turning point was counted.

To get an indication of how well the algorithm was able to classify the strategies, 100 (5% of total) randomly chosen trials were judged by the first author by looking at video recordings of the trials. A total of 64% of the trials were

classified the same by the algorithm and the human observer. Particularly grasp and manipulate strategies were in good agreement, whereas shuffle and thumb strategies were classified more differently. When 50 trials were classified by two human observers, 70% of the trials were classified similar. The algorithm was not completely in agreement with visual observation. Especially the percentage of shuffle and thumb strategies might have been underestimated. However, the video classification of the human observer should not be seen as the standard, because this is subject to the observer's interpretation of the strategies and some movements might not fit into any of the categories. This is also seen in the by the differences between the two human observers.

Supplementary Results

Reaction times

The reaction times were analysed with a 4 (condition) $\times$ 2 (target presence) repeated measures Analysis of Variance (ANOVA). Effects of condition ($F(1,9) = 93, p < 0.001, \eta_p^2 = 0.91$), target presence ($F(1.6,14) = 49, p < 0.001, \eta_p^2 = 0.84$) and an interaction effect ($F(1.8,16) = 29, p < 0.001, \eta_p^2 = 0.76$) were found. The condition with a cube as target had shorter reaction times than both the sphere and smooth conditions, in both target-present and absent trials (ps < 0.001), although differences were larger in target-absent trials as indicated by the interaction effect. Also the condition with the rough target had shorter reaction times than the sphere and smooth conditions in target-present and absent trials (ps < 0.01). Target present trials were performed faster than target-absent trials in all conditions (ps < 0.01), but these differences seemed to be larger when the target was a sphere or smooth.

Contact with the target

Different ANOVAs were performed on the contact data. A 4 (segment group) $\times$ 4 (condition) repeated measures ANOVA was conducted to evaluate the differences between the different segment groups. Next, separate 5 (finger) $\times$ 4 (condition) repeated measures ANOVAs were performed on the distal, middle and proximal phalanx segments. The hand palm segment was evaluated in a repeated measures ANOVA with only the condition as a factor. Furthermore, a 5 (finger) $\times$ 4 (condition) $\times$ (time step) repeated measures ANOVA was performed on the data of the distal segment to examine differences in time. The significant results are shown in Tables S1-3.

References

[1] Van Polanen, V., Bergmann Tiest, W. M. & Kappers, A. M. L. Integration and disruption effects of shape and texture in haptic search. *PLoS ONE* **8**, e70255 (2013).

[2] Van Polanen, V. *Findings in haptic (re)search.* PhD dissertation, VU University Amsterdam, Faculty of Human Movement Sciences (2014), http://dare.ubvu.vu.nl/handle/1871/51344.

Table S1: Statistical results of the comparisons of the different segments (distal, middle, proximal and hand). Only significant differences are listed.

effect			p
segment		$F(2, 27) = 9.5$	$p < 0.001, \eta_p^2 = 0.51$
		distal-middle	0.004
		middle-hand	0.033
condition		$F(3, 27) = 12$	$p < 0.001, \eta_p^2 = 0.57$
		smooth-cube	0.018
		smooth-rough	0.001
interaction		$F(3.7, 34) = 7.3$	$p < 0.001, \eta_p^2 = 0.45$
	cube	middle-hand	0.013
	smooth	distal-middle	0.002
		distal-proximal	0.035
	distal	cube-sphere	0.010
		cube-smooth	0.002
		rough-smooth	< 0.001
	middle	cube-sphere	0.004
		cube-smooth	0.003
		rough-smooth	0.023

Table S2: Statistical results of the separate analyses of the different segments (distal, middle, proximal). p-values are listed for significant differences only.

effect			distal	middle	proximal
finger			$F(4, 36) = 17$	$F(4, 36) = 13$	F(1.6,14)=16
			$p < 0.001$	$p < 0.001$	$p < 0.001$
			$\eta_p^2 = 0.66$	$\eta_p^2 = 0.59$	$\eta_p^2 = 0.63$
		thumb-index	0.047	–	< 0.001
		thumb-middle	–	–	0.002
		thumb-ring	–	0.015	0.031
		thumb-little	0.003	–	–
		index-middle	0.021	0.007	–
		index-ring	–	< 0.001	–
		index-little	0.008	–	–
		middle-little	< 0.001	–	< 0.001
		ring-little	< 0.001	< 0.001	0.018
condition			$F(3, 27) = 36$	$F(3, 27) = 24$	
			$p < 0.001$	$p < 0.001$	–
			$\eta_p^2 = 0.80$	$\eta_p^2 = 0.73$	–
		cube-sphere	0.001	< 0.001	–
		cube-smooth	< 0.001	< 0.001	–
		rough-sphere	0.013	0.045	–
		rough-smooth	< 0.001	0.003	–
interaction			$F(12, 108) = 8.6$	$F(12, 108) = 3.9$	
			$p < 0.001$	$p < 0.001$	–
			$\eta_p^2 = 0.49$	$\eta_p^2 = 0.30$	–
	thumb	cube-sphere	0.014	–	–
		cube-smooth	< 0.001	–	–
		rough-smooth	0.001	–	–
	index	sphere-smooth	0.018	–	–
	middle	rough-smooth	–	0.044	–
	little	cube-sphere	–	0.016	–
		cube-smooth	–	0.033	–
		rough-smooth	0.010	0.021	–
	cube	middle-little	0.009	–	–
	sphere	thumb-index	0.014	–	–
		thumb-ring	–	0.024	–
		thumb-little	0.027	–	–
		index-ring	–	0.002	–
		ring-little	0.018	0.019	–
	rough	middle-little	0.001	–	–
	smooth	thumb-ring	0.042	0.016	–
		thumb-little	< 0.001	–	–
		index-middle	–	0.004	–
		index-little	0.024	–	–
		middle-little	0.002	–	–
		ring-little	0.009	0.027	–

Table S3: Statistical results for the analysis of the time steps (1^{st} and 20^{th} interval) for the distal segments. For the interaction effects, only the post-hoc tests for the three-way interaction are shown. Only significant differences are listed.

effect				p
finger			$F(4, 36) = 12$	$p < 0.001, \eta_p^2 = 0.58$
			thumb-little	0.003
			index-little	0.002
			middle-little	0.002
			ring-little	0.002
time step			$F(1, 9) = 296$	$p < 0.001, \eta_p^2 = 0.97$
condition			$F(3, 27) = 25$	$p < 0.001, \eta_p^2 = 0.74$
			cube-sphere	0.001
			cube-smooth	0.001
			rough-sphere	0.008
			rough-smooth	< 0.001
finger × time step			$F(1.9, 17) = 18$	$p < 0.001, \eta_p^2 = 0.66$
finger × condition			$F(12, 108) = 6.7$	$p < 0.001, \eta_p^2 = 0.43$
time step × condition			$F(3, 27) = 16$	$p < 0.001, \eta_p^2 = 0.64$
finger × time step × condition			$F(12, 108) = 9.0$	$p < 0.001, \eta_p^2 = 0.50$
	20^{th}	cube	middle-little	0.048
		rough	index-little	0.012
		smooth	thumb-little	0.004
	cube	thumb	1^{st}-20^{th}	0.029
		middle	1^{st}-20^{th}	0.011
	sphere	thumb	1^{st}-20^{th}	0.004
		index	1^{st}-20^{th}	0.012
	rough	index	1^{st}-20^{th}	0.004
	smooth	thumb	1^{st}-20^{th}	0.001
		index	1^{st}-20^{th}	0.024
	thumb	20^{th}	cube-smooth	0.004
			rough-smooth	0.002