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Perceptual Grouping Affects Haptic Enumeration Over the Fingers

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Abstract
Spatial arrangement is known to influence enumeration times in vision. In haptic enumeration, it has been shown that dividing the total number of items over the two hands can speed up enumeration. Here we investigated how spatial arrangement of items and non-items presented to the individual fingers impacts enumeration times. More specifically, we tested whether grouping by proximity facilitates haptic serial enumeration (counting). Participants were asked to report the number of tangible items, amongst non-items, presented to the finger pads of both hands. In the first experiment, we divided the tangible items in one, two, or three groups that were defined by proximity (i.e., one nonitem in between two groups) and found that number of groups and not number of items were the critical factor in enumeration times. In a second experiment, we found that this grouping even takes place when groups extend across fingers of both hands. These results suggest that grouping by proximity affects haptic serial enumeration and that this grouping takes place on a spatial level possibly in addition to the somatotopic level. Our results support the idea that grouping by proximity, a principle introduced in vision, also greatly affects haptic processing of spatial information.

Keywords
Enumeration, numerosity, haptic perception, perceptual grouping

Introduction

The spatial configuration of items affects the process of enumeration (Allen & McGeorge, 2008; Ginsburg & Pringle, 1988; Van Oeffelen & Vos, 1982b; Wender & Rothkegel, 2000). In some cases, faster enumeration of certain spatial arrangements as compared with others has been explained by pattern recognition (Krajcsi, Szabó, & Mórocz, 2013; Mandler & Shebo, 1982). Moreover, other studies have shown that spatial arrangements like regularity or symmetry can induce perceptual grouping (e.g. Beckwith & Restle, 1966). Perceptual grouping plays a major role in perception, as it is a mechanism to organize the incoming stream of perceptual information (Wagemans, Elder, et al., 2012; Wagemans,

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Feldman, et al., 2012): Information that belongs together is processed more efficiently and thus faster than when it belongs to different perceptual groups (Palmer, 1977; Reed & Johnsen, 1975). This reasoning led us to the question whether perceptual grouping also enhances the process of enumeration. In the current article, we investigate the effects of perceptual grouping by proximity on haptic serial enumeration.

A few studies have shown faster enumeration when participants could segregate the items in multiple groups. These studies suggested that perceptual grouping speeds up enumeration mainly because small (<4) and large sets of items are enumerated using different type of enumeration mechanisms (e.g., Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982; Trick, 2008; Trick & Pylyshyn, 1993, 1994). For numerosities up to *four* items, an efficient process known as *subitizing* is used, while larger sets of items are enumerated using the serial process of *counting*. By dividing a set of items into groups small enough to enable subitizing, the total number of items can be extracted by subitizing each group and adding it to the running total (e.g., Van Oeffelen & Vos, 1982a). This strategy is faster than serially counting all presented items. That is, when the groups contain a number of items that is within the subitizing range and the total number of items is outside this range (in the counting range). However, does perceptual grouping enhance enumeration, even when subitizing is not an option?

Both subitizing and perceptual grouping have recently been demonstrated in the haptic modality. Haptic subitizing has been shown when participants had to report the number of stimulated fingers (Cohen, Naparstek, & Henik, 2014; Plaisier & Smeets, 2011b; Riggs et al., 2006), but also when the number of objects (such as small spheres) grasped in the hand had to be reported (Plaisier, Tiest, & Kappers, 2009). A direct comparison of visual enumeration of dot patterns to haptic enumeration of spheres grasped in the hand showed striking similarities in behavior, and the authors suggested that similar processes underlie visual and haptic numerosity judgment (Plaisier, Tiest, & Kappers, 2010). Furthermore, the subitizing range could be extended by dividing the total number of objects into over the two hands, effectively making groups small enough to subitize (Plaisier et al., 2010). The way in which objects are grasped in the hand and can be freely moved and rearranged in the hand is quite different from a visual enumeration task in which a dot pattern is usually presented which cannot be actively rearranged by the observer. A static set of items presented to the individual fingertips is in that sense more comparable to a visual enumeration task. Therefore, in this study, we will focus on the specific case in which a static pattern is presented to the fingertip.

Whether subitizing is possible over the fingertips seems to depend on the stimulus. Riggs et al. (2006) showed subitizing for one, two, or three fingers, while using a setup in which rods actively stimulated the fingertips by shooting up against the finger pads. A similar pattern was suggested in a recent study that used vibrators for stimulation (Cohen et al., 2014; although they did not measure numerosities outside the subitizing range). Subitizing was also found in a study where participants placed some of their fingers on surfaces while other fingers were suspended in the air. However, in the same study, no subitizing was found when participants touched static raised lines (items) amongst empty stimulus elements (non-items; Plaisier & Smeets, 2011b). In the latter case, participants had to enumerate the items while ignoring the non-items. This step of separating items from non-items potentially makes the enumeration process much less efficient and prohibits subitizing. Similarly, enumeration of target items placed among distractor items prohibits subitizing in both vision and touch (Plaisier, van't Woud, & Kappers, 2011; Trick & Pylyshyn, 1993). Taken together, these results suggest that subitizing in haptics is only occurring when the number of items matches the number of fingers that are stimulated. A question that is still unanswered is whether the spatial configuration (grouping) of items presented to the fingers can induce faster enumeration, and this will be investigated in the current study by means of a haptic serial enumeration task.

Processing of input on the fingertips is known to be a serial process within the hand. We have shown in haptic search studies, in which a target had to be localized between distractors that were presented one-to-one to the fingertips, that search time increased with the number of items (Overvliet, Smeets, & Brenner, 2007a, 2007b, 2010). Interestingly, if we used lines as distractors, and placed them in such a way so that they could be grouped by good continuation, search was significantly faster (Overvliet, Mayer, Smeets, & Brenner, 2008). Perceptual grouping has been shown to affect haptic perception in multiple ways. A recent study showed that a pattern recognition mechanism could explain faster enumeration times for grouped items in a haptic serial enumeration task (Verlaers, Wagemans, & Overvliet, 2015). In this study, participants scanned a strip with tangible dots that could be grouped based on their configuration, or on proximity. Grouping by proximity also improved haptic contour detection (Overvliet, Krampe, & Wagemans, 2013). In yet another study, participants scanned strips with tangible items in order to search for a target between distractors that could be grouped by similarity and good continuation. In the grouped conditions, haptic serial search was faster, as compared with the non-grouped conditions (Overvliet, Krampe, & Wagemans, 2012). An additional question we asked in this last study is whether grouping by proximity is operational on a spatial or somatotopic level of processing. However, the results did not show an effect for any of the proximity manipulations. Similarly, Frings and Spence (2013) did not find effects for proximity in a tactile variant of the negative priming paradigm. The results on grouping by proximity in haptics are mixed: Some studies do find effects of grouping by proximity is operational remain and will additionally be addressed in the current study.

In the current study, we investigated whether grouping by proximity facilitates enumeration over the fingers in a condition where subitizing is not possible. Moreover, we investigated whether this grouping is operational in a spatial reference frame: whether grouping can take place over two hands. We presented different numbers of items to the participant' finger pads (one each) and showed empty display elements to their remaining finger pads and asked to enumerate the items as fast and as accurate as possible. In Experiment 1, we created different numbers of groups and by varying the proximity between some of the items. We hypothesized that if grouping by proximity is operational in haptic serial enumeration, enumeration speed will depend on the number of groups.

In Experiment 2, we investigated whether grouping can take place over two hands, that is, whether grouping is in a spatial context, or just based on somatotopic location of the fingers. We hypothesize here that if the spatial context is critical for grouping, a group that is overlaying two hands will be faster as compared with two groups divided over two hands. However, if the somatotopic location of the items is critical, we expect to find no difference between one group overlaying two hands, which will then be interpreted as two groups or two groups divided over two hands.

General Methods

Participants

A total of 20 volunteers from the university community were paid 8 euros per hour for their participation in this study (Experiment 1: 10 participants, mean age 24.2 ± 6.6 years, 9 right-handed [as measured by the Edinburgh handedness inventory], 9 females; Experiment

2: 10 participants, mean age 21.7 ± 2.9 years, 9 right-handed, 7 females). The study was conducted in line with the ethical principles regarding research with human participants as specified in The Code of Ethics of the World Medical Association (Declaration of Helsinki). The experiment was part of a program that has been approved by the ethics committee of the Faculty of Human Movement Sciences at VU University, and the participants gave written informed consent before starting the experiment.

Stimuli and Apparatus

The stimuli consisted of strips of swell paper (ZY®- TEX2) that either contained a circle with a dot in the middle (one item) or were left empty (one nonitem; see Figure 1). We chose a spatially noninformative stimulus, which does not contain any spatial features that may induce grouping by themselves (e.g., by good continuation: Overvliet et al., 2012; Overvliet et al., 2008). The stimuli and apparatus are shown in Figure 1.

The experimenter placed the stimulus strips underneath the fingers of both hands (the thumbs were not included in the experiment), and on top of pressure-sensitive sensors that were triggered by placing a finger on the stimulus. Response time measurement was started as soon as any of the sensors was triggered, and it was terminated with a vocal response. We had only six pressure sensors available; therefore, two items (and consequently fingers) did not have a sensor underneath. This does not affect reaction time accuracy, as Overvliet et al. (2007b) have shown that there are no significant differences in reaction times between the

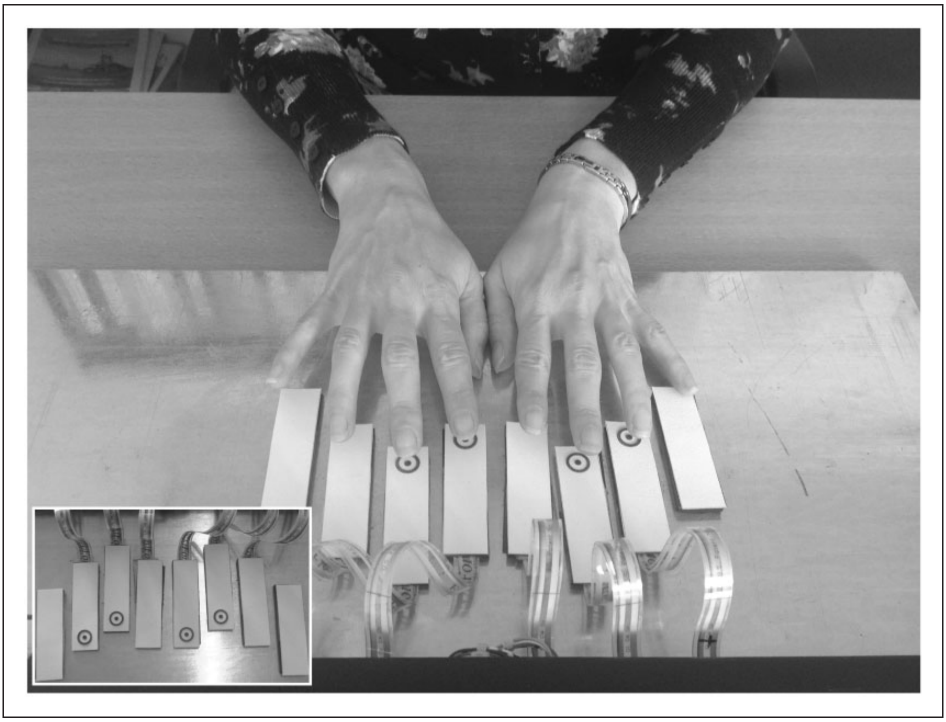

Figure 1. The experimental setup. The inset shows one of the possible grouping conditions (in this case: four items and two groups).

fingers. Response times were measured with an accuracy of 24 (±14 *SD*) ms, which is the average delay between measurement onset and termination by the output of the microphone. Note that the delay and variation on the delay are about a factor hundred smaller than the variation in the response times measured in this study.

The task for the participants was to report the number of items presented. We opted for an indirect measurement of grouping, by not asking participants to count the number of groups but the number of items. The number of groups was irrelevant to the task, and the existence of groups was never mentioned in the instructions. By doing so, we could measure the effects of spontaneous grouping without artificially induce grouping effects. We instructed the participants explicitly to lower all their fingers onto the stimulus strips simultaneously after the experimenter indicated that they could start a trial. They were not allowed to move the fingers between the different stimulus strips, but there were no other restrictions on exploratory movements. Participants tended to make small finger movements over the stimulus strips during a trial. A screen was placed between the participant and the setup, in order to hide the stimuli from the field of view of the participants.

In Experiment 1, our main question was whether grouping by proximity could facilitate enumeration in a simultaneous enumeration task. Therefore, we created stimulus patterns in which there could be three, four, or five items, which could be presented in one, two, or three "groups." These groups were defined as a set of adjacent items separated from another set of adjacent items by a single nonitem in between them. There was never more than one empty piece of swell paper in between two groups. All numerosities were presented 10 times in groups of one, two, or three items. The configurations were randomly generated such that the fingers, to which the items were presented to, were randomized across numerosities and the number of groups.

In Experiment 2, we tested whether grouping takes place in a somatotopic or spatial reference frame, or in other words: whether items that are divided over two hands but are spatially near can still be grouped to increase enumeration speed. To do so, we presented one, two, three, or four items. The one-item trials were included to establish a baseline reaction time (RT) value for the detection of a single item. The other numerosities were presented in one or two groups. Also here we used the definition of a group being adjacent items separated from another group by a single nonitem. The items were either presented in a single group to a single hand (one hand all items and the other all non-items), a single group divided over two hands or two groups divided over two hands (see Figure 2 for examples of stimuli). Again, each numerosity was presented 10 times in each grouping condition and configurations were generated randomly. Thus, the major difference with Experiment 1 is the introduction of one group divided over two hands versus two groups divided over two hands.

We never presented more than five items, because one of our previous studies revealed that response times decreased with numerosities above five items, indicating that participants counted the non-items, instead of the items, for larger numerosities (Plaisier & Smeets, 2011a).

Procedure

After placing the fingers on the stimulus strips, participants were instructed to call out the correct number of items as quickly as possible. After each trial, the subjects received feedback on whether the answer was correct. To ensure the same number of correct trials for each numerosity, error trials were repeated at the end of the experiment. The error rate was 9% in Experiment 1 and 7% in Experiment 2, indicating that the participants were quite good at the task. In Appendix A, we show the confusion matrices for both Experiments 1 and 2. We analysed the reaction times of the correctly answered trials only.

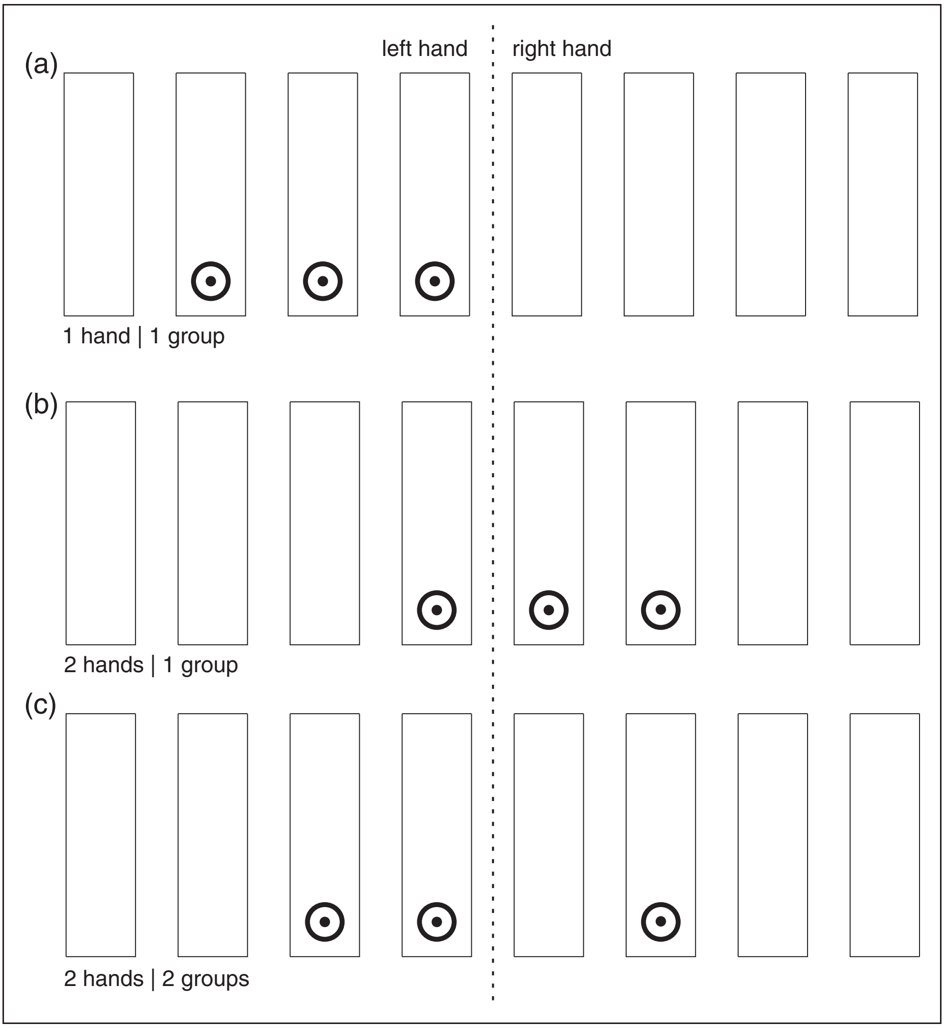

Figure 2. Examples of the different conditions of Experiment 2: (a) 1 hand, 1 group, (b) 2 hands, 1 group, and (c) 2 hands, 2 groups.

Results

Experiment 1

In the first experiment, we investigated whether grouping by proximity increases enumeration speed in a haptic serial enumeration task. The average median enumeration times as a function of the number of groups are shown in Figure 3 for all numerosities. It can be seen that the enumeration times increase with the number of groups for all numerosities. A 3×3 repeated measures analysis of variance with factors *number of items* and *number of groups*, revealed a main effect for number of groups ($F(2, 26) = 11.48$, $p < .01$, $\eta^2_p = .47$), but not for number of items and no interaction. These results indicate that the number of groups is critical for enumeration times as opposed to number of items, suggesting that grouping by proximity indeed increases haptic enumeration speed.

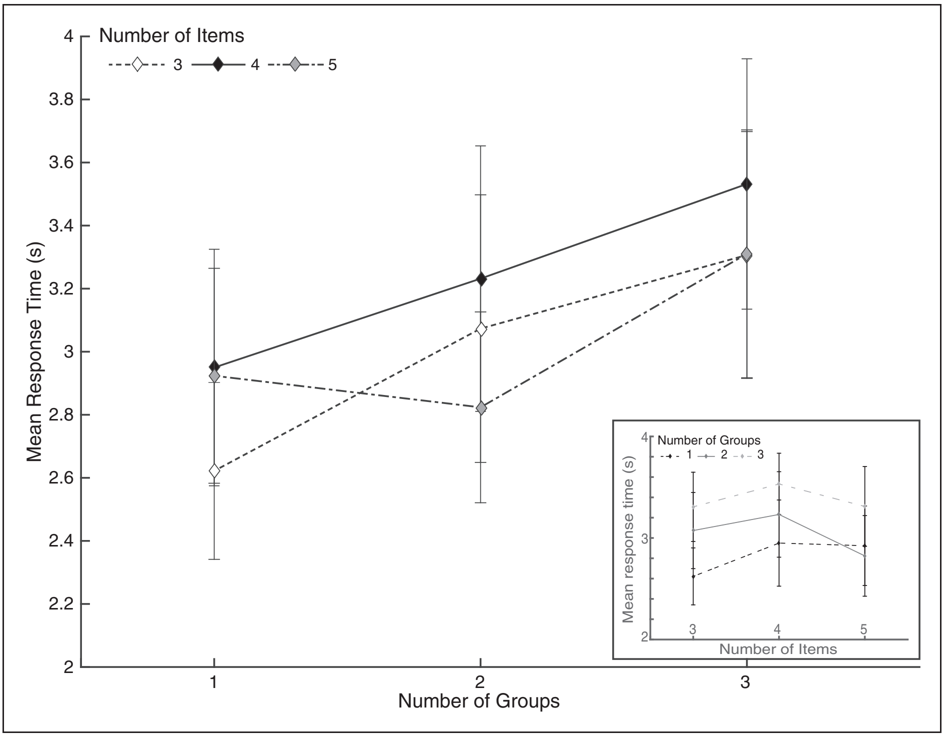

Figure 3. Results of Experiment 1. Average median exploration time for the different numbers of items. Error bars represent standard error of the mean. The insert shows the same data (plotted with the number of groups as separate data series).

These results also confirm that there was indeed no subitizing possible in this experiment: The response times were relatively large and also the error rates for the lower numbers (3 and 4) were not zero (see Appendix A). However, the current study does not have an optimal design to test whether subitizing occured, since we only measured a very limited range of numerosities. A previous study already showed that this type of stimulus cannot be subitized (Plaisier & Smeets, 2011).

Experiment 2

In the second experiment, we investigated whether grouping by proximity is operational on a spatial level, by testing whether adjacent sets items that extend across fingers of both hands are perceptually grouped. The average median enumeration times as a function of the number of items are shown in Figure 4 for each of the three types of item configurations. A repeated measures analysis of variance on the enumeration times revealed a significant main effect for item configuration ($F(2, 18) = 13.79$, $p < .001$, $\eta_p^2 = .61$) "one group one hand," "two groups two hands," "one group two hands") and an interaction between item configuration and number of items ($F(4, 36) = 5.17$, $p < .05$, $\eta_p^2 = .37$). Preplanned Helmert contrast showed a significant difference between "two groups two hands" and "one group two hands" ($F(1, 9) = 21.88$, $p < .001$, $\eta_p^2 = .71$), and a significant interaction for "one group one hand" versus "'two groups two hands' & 'one group two hands'" and number of items ($F(1, 9) = 13.92$, $p < .01$, $\eta_p^2 = .61$). Post hoc paired samples t tests (with a Bonferroni

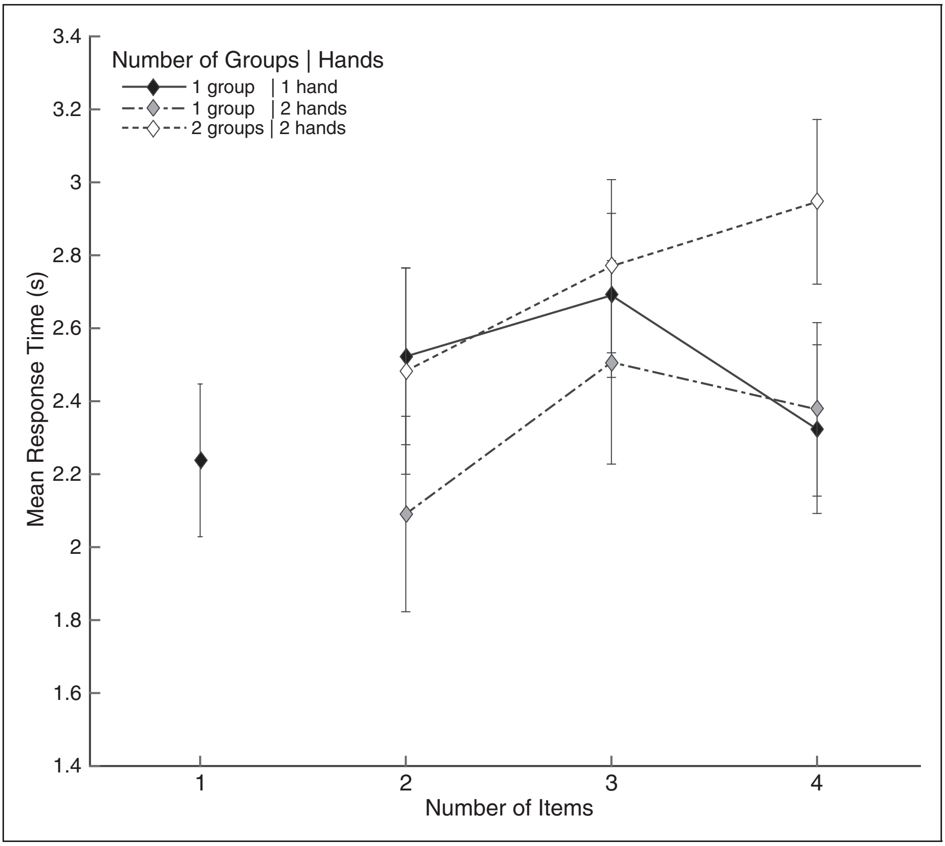

Figure 4. Results of Experiment 2. Average median exploration time as a function of the number of items for the different configural conditions. Error bars represent standard error of the mean.

corrected alpha level of .005) revealed a difference between "one group two hands" and both "one group one hand" and "two groups two hands," when two items had to be enumerated. ($t(9) = 5.56$, $p < .001$) and $t(9) = 4.74$, $p < .001$, respectively). However, when four items had to be enumerated, "two groups two hands" was the slowest condition and differed from the other two ("one group two hands" and "one group one hand"; ($t(9) = 3.73$, $p < .005$ and $t(9) = 4.04$, $p < .005$, respectively). The faster enumeration in the "four items, one group, one hand" condition can easily be explained by the saliency of "all fingers of one hand stimulated." These results show that a group that is spatially overlaying two hands is enumerated faster as compared with a condition in which the same number of items is divided over two hands, but could *not* spatially be grouped, suggesting that grouping by proximity is operational on a spatial level in haptic serial enumeration.

We additionally tested from which other conditions the single item trials differed significantly. We found that the single item was significantly faster than "one hand one group": three items and "two hands two groups": three and four items (all $t > 3.92$, all $p < .003$, tested against a Bonferroni corrected alpha of .0056). This shows that the larger numbers of items in the "one hand, one group" and "two hands, two groups" conditions are slower compared with the single item condition, but the single item was never significantly different in the "two hands one group" condition, which is again suggesting that spatially grouping over two hands leads to enhanced enumeration speed.

Discussion

The results from Experiment 1 clearly show that grouping by proximity is an important factor in haptic serial enumeration. The number of groups and not the number of items is the critical factor for enumeration speed. In Experiment 2, we showed that spatial proximity is inducing grouping effects.

Our results suggest that perceptual grouping by proximity is a general mechanism in haptic enumeration, it cannot only induce subitizing, but it can also enhance the speed of serial enumeration. These findings are in accordance with earlier findings on perceptual grouping in haptics, in which grouping by good continuation enhanced serial search speed in the same setup (Overvliet et al., 2008). Moreover, grouping by proximity also enhanced haptic contour detection (Overvliet et al., 2013) and speeded up haptic enumeration when participants had to serially scan the display (Verlaers et al., 2015).

In a previous study into haptic numerosity judgment of objects grasped in the hand, it was found that enumeration was faster when items were divided over the two hands (Plaisier et al., 2010). Also haptic search has been shown to be more efficient for fingers across the two hands than fingers of the same hand (Overvliet et al., 2010). In Experiment 2, we also found that dividing items over the two hands can make enumeration more efficient, but only when one group is overlaying two hands: Enumerating two groups over two hands is not faster in the current experiment. It may well be that, in stead of purely spatial grouping, grouping takes place in two stages: First, grouping within the hands on a somatotopic level, and if these groups are spatially next to each other, they may be grouped again on a spatial level. One of the major differences between this experiment and the Overvliet et al. (2007b, 2008, 2010) search studies with the same setup is that both index fingers were always touching an item in those studies, while in the current "two hands, two groups" condition this is by definition not the case. We, therefore, speculate that grouping by proximity might also have influenced search times in those studies.

The "two hands one group" condition of Experiment 2 tended to be faster than in the other item arrangements. We explained above that this is likely to be caused by a two-step grouping process, first by somatotopic and then by spatial proximity. However, an additional explanation could be found in an added effect of (mirror) symmetry. When the group is divided over two hands, in the two items condition, this means the items are placed under both index fingers. When there were four items in the display, in some of the cases, this was on both index and middle fingers of both hands. In visual perception, it is well known that grouping by symmetry enhances performance in a wide variety of tasks: for example, enumeration (Van Oeffelen & Vos, 1982a), contour detection (Field, Hayes, & Hess, 2000), and figure ground segregation (Machilsen, Pauwels, & Wagemans, 2009). However, in haptics, the importance of symmetry does not seem to have received a lot of attention. The few studies that are available do not seem to point to similar mechanisms for vision and haptics, for example, symmetry did not improve performance in shape perception (Ballesteros, Millar, & Reales, 1998) and only partly in shape tracing (Locher & Simmons, 1978). Indeed, preliminary comparison of the trials within the "one group two hands" condition of three items on one hand (ring, middle, and index fingers) and one on the other (index finger) versus two items on both middle and index fingers did not yield a significant effect, but this may well have been due to a lack of power. More research will be needed to investigate this issue.

When four items were presented to a single hand RTs dropped considerably. This is most likely due to the fact that four were the maximum number of items per hand, and all fingers were in contact with a target item in that case. It is a common finding in visual as well as haptic numerosity judgment that at the end of the range of the presented numerosities RTs decrease (e.g., Plaisier & Smeets, 2011a; Trick & Pylyshyn, 1994).

Taken together, our results clearly indicate that grouping by proximity occurs across the fingers and enhances the speed of haptic numerosity judgment. Moreover, perceptual grouping by proximity is even operational over the two hands and seems to be encoded spatially. Thus, our results support the idea that grouping by proximity, a principle introduced in vision, also greatly affects haptic processing of spatial information.

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Author Note

Overvliet and Plaisier contributed equally to this work.

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Appendix A

Due to our design, in which we ask participants to try to be correct, error rates are generally low. Here, we show the confusion matrices for both Experiments 1 and 2. In these, it can be seen that error rates tended to increase with the number of items, while item arrangement (i.e., number of groups) did not appear to affect error rates. Moreover, participants tended to underestimate the number of items. This outcome needs to be interpreted with caution; participants were aware of the range of numerosities used, they would never respond with numbers outside of the range.

Experiment 1

presented / reported	1 group			2 groups			3 groups		
	3	4	5	3	4	5	3	4	5
3	100	7	0	100	11	1	100	11	1
4	2	100	13	2	100	15	3	100	15
5	0	1	100	0	2	100	0	1	100
total	102	108	113	102	113	116	103	112	116

Experiment 2

presented / reported	1 group | 1 hand			2 groups | 2 hands			2 groups | 2 hands		
	2	3	4	2	3	4	2	3	4
2	100	4	0	100	9	0	100	9	0
3	0	100	3	0	100	9	0	100	9
4	0	2	100	0	0	100	0	0	100
total	100	106	103	100	109	109	100	109	109