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The effect of perceptual grouping on haptic numerosity perception

K. Verlaers · J. Wagemans · K. E. Overvliet

Abstract We used a haptic enumeration task to investigate whether enumeration can be facilitated by perceptual grouping in the haptic modality. Eight participants were asked to count tangible dots as quickly and accurately as possible, while moving their finger pad over a tactile display. In Experiment 1, we manipulated the number and organization of the dots, while keeping the total exploration area constant. The dots were either evenly distributed on a horizontal line (baseline condition) or organized into groups based on either proximity (dots placed in closer proximity to each other) or configural cues (dots placed in a geometric configuration). In Experiment 2, we varied the distance between the subsets of dots. We hypothesized that when subsets of dots can be grouped together, the enumeration time will be shorter and accuracy will be higher than in the baseline condition. The results of both experiments showed faster enumeration for the configural condition than for the baseline condition, indicating that configural grouping also facilitates haptic enumeration. In Experiment 2, faster enumeration was also observed for the proximity condition than for the baseline condition. Thus, perceptual grouping speeds up haptic enumeration by both configural and proximity cues, suggesting that similar mechanisms underlie perceptual grouping in both visual and haptic enumeration.

Keywords Haptics · Enumeration · Perceptual grouping · Gestalt principles · Proximity · Configural cues

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The brain has to organize the incoming stream of perceptual information; an important mechanism in this perceptual organization is perceptual grouping. Koffka (1922) and Wertheimer (1912, 1923) were the first to formulate Gestalt principles, which describe how individual elements in the perceptual field are organized into groups. The first principle of grouping described by Wertheimer is *proximity*, which states that elements that are close to each other will be grouped together. Some other important and commonly used principles are *similarity* and *good continuation*. The Gestalt principle of similarity states that we tend to group items that share the same characteristics—for example, color or orientation. The Gestalt principle of good continuation states that we tend to group lines or curves that follow one another, even if some parts are hidden (Wertheimer, 1912, 1923).

A considerable amount of research has focused on the applicability and underlying mechanisms of these Gestalt principles in visual perception (for an overview, see Wagemans, Elder, et al., 2012; Wagemans, Feldman, et al., 2012). Although research has shown that these Gestalt principles also apply to the auditory modality (e.g., Bozzi & Vicario, 1960; Camos & Tillmann, 2008), it remains relatively unclear how and whether these grouping principles apply to the *haptic* modality. On the basis of the results of his studies with relief copies of the original Wertheimer figures, Scholtz (1957) claimed that the Gestalt principles have no validity in the haptic modality. This is surprising, since haptics and vision are often referred to as the spatial senses, and the spatial resolving power of the skin is better than that of the ears, but poorer than that of the eyes (Sherrick & Cholewiak, 1986). More recently there has been renewed interest in these Gestalt principles, and researchers now suggest that their applicability to the haptic modality is not as invalid as Scholtz first suggested (for a review, see Gallace & Spence, 2011). This is, for

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example, the case for the principle of grouping by similarity (e.g., Chang, Nesbitt, & Wilkins, 2007; Overvliet, Krampe, & Wagemans, 2012).

Interestingly, researchers do not agree on the operationalization of the principle of proximity in the haptic modality. Chang et al. (2007) made a direct comparison between the visual and haptic grouping of elements. They asked participants to explore different layouts in a visual and a haptic condition and to verbally express the numbers of groups that they perceived. They manipulated the spacing between the elements and hypothesized that participants would group elements that were closer together, and found that participants indeed grouped elements using proximity when they perceived unequal spacing between the elements in the layout; Chang et al. thus concluded that the principle of proximity is at work in the haptic grouping of elements. However, it can be reasoned that Chang et al. found an effect because they asked participants explicitly how many groups of items were present in the layout, which may have caused grouping to start with. Frings and Spence (2013) found an unexpected effect of proximity in a tactile negative-priming experiment, in which a larger distance between the hands led to negative-priming effects, whereas a small distance did not lead to any effects.

Contrary to Chang et al.'s (2007) and Frings and Spence's (2013) findings, Overvliet et al. (2012) found that none of their proximity manipulations speeded up search times in a haptic search experiment, whereas their similarity manipulations did, suggesting that grouping by proximity does not take place in haptic search. In a follow-up experiment (Overvliet, Krampe & Wagemans, 2013), they tested whether spontaneous grouping by proximity has an effect in haptic contour detection. Their results indeed showed higher detection rates and shorter exploration times when the contour elements were placed closer to each other, even when the contour:background ratio was controlled for. This study provided evidence for grouping by proximity in haptic processing. Thus, the results regarding studies on grouping by proximity are mixed, and the question of whether proximity really speeds up contour detection still remains. In the present study, we therefore again aimed to investigate the applicability of grouping by proximity in the haptic modality, by using yet a different paradigm. To do so, we used a haptic enumeration task to test whether spontaneous grouping by proximity occurs in haptic numerosity perception. We chose to focus on haptic numerosity perception because Gallace and Spence (2011) put forward indirect evidence that Gestalt principles can play a role in haptic enumeration processes. This indirect evidence was based on enumeration studies in the visual modality.

Enumeration, which is one of the most elementary numerical processes, can be defined as the determination of the number of elements that are present in a set (van Oeffelen & Vos, 1982). From visual perception research, we know that enumeration processes can be divided into three types of processes (Kaufman, Lord, Reese, & Volkmann, 1949). The first process is *subitizing*, which is the fast (<100 ms/item) and accurate enumeration of a small number of items (less than three). The second enumeration process is *counting*, which is an accurate but much slower process (>200 ms/item) used for larger numbers of items. The third process is *estimation*, which is a rather fast but imprecise process that requires a constant period of time (Kaufman et al., 1949). In visual perception studies, researchers have found that grouping principles can speed up these enumeration processes (e.g., Allen & McGeorge, 2008; Beckwith & Restle, 1966; Krajcsi, Szabó, & Mórocz, 2013; Mandler & Shebo, 1982; van Oeffelen & Vos, 1982; Wender & Rothkegel, 2000).

Beckwith and Restle (1966) were the first to suggest that enumeration can be facilitated by using grouping principles. They asked participants to enumerate visual objects on 40 different cards as quickly as possible. The objects differed in number, arrangement (line, circle, rectangle, or scrambled), and shape (square, circle, triangle, or teardrop). Their results showed that participants were faster and more accurate when they had to enumerate items that were arranged at the corners of a rectangular figure rather than in a linear, circular, or scrambled arrangement. From this observation, they suggested that people use the grouping principles of proximity, similarity, and good continuation to speed up their enumeration process. They also suggested that when people enumerate a set of dots, they count quickly within a group, pause and store this result, and then move to the next group. Mandler and Shebo (1982) went further, suggesting that the process of subitizing is the result of a fast pattern recognition mechanism. In their experiment, participants enumerated faster and were more accurate in response to a familiar, geometric organization of the dots than to a random organization. Mandler and Shebo suggested that when grouping results in geometric cues, these geometric cues can lead to fast pattern recognition and can give access to associated information regarding their numerosity (e.g., a triangle is associated with three, a rectangle with four). Similar performance advantages of configural patterns relative to linear or random patterns were found in studies by Allen and McGeorge (2008), van Oeffelen and Vos (1982), and Wender and Rothkegel (2000), as well as in a recent study by Krajcsi et al. (2013). Krajcsi et al. found a larger subitizing range when the participants had to enumerate configural dot patterns than when they had to enumerate random patterns. They defined configural patterns as special organizations that are symmetrical or are perceived frequently in the same arrangement (e.g., on dice or dominos). They concluded that the pattern recognition model, described by Mandler and Shebo, could account for this larger subitizing range. Taken together, these studies suggest that grouping principles seem to speed up the enumeration process in the visual modality. To find out whether the same grouping principles can speed up the enumeration process in the haptic modality was the aim of this study.

It is well known that subitizing also takes place in the haptic modality, and research has suggested that common processes might underlie visual and haptic numerosity perception. For example, Riggs et al. (2006) observed subitizing in a passive touch experiment in which participants had to count the number of fingers that were stimulated by pins pressed onto the fingers. Although Riggs et al. were the first to demonstrate that subitizing can occur in touch without active exploration, Plaisier and colleagues (Plaisier, Bergmann Tiest, & Kappers, 2009, Plaisier, Bergmann Tiest, & Kappers 2010b; Plaisier, van't Woud, & Kappers, 2011) showed that subitizing also takes place in active exploration. In their studies, participants had to report the number of shapes grasped in their hand. From the results of the studies, Plaisier, Bergmann Tiest, and Kappers (2010a) suggested that common mechanisms might exist behind visual and haptic subitizing and that the same processes underlie haptic and visual numerosity judgments.

In the present study, we investigated whether perceptual grouping speeds up haptic enumeration. Since grouping principles can speed up the enumeration process in the visual modality, especially by enlarging the subitizing range, and since subitizing is also observed in the haptic modality, we expected to find haptic grouping effects. We investigated whether grouping facilitates the enumeration process by testing a baseline condition against two grouping conditions: grouping by proximity and grouping by configurality. In the *baseline* condition, we placed dots evenly on a straight line, without using any grouping cues. In the *proximity* condition, we enlarged the spacing between some of the dots to create groups. In the *configural* condition, we placed dots in configural patterns to create groups, while a larger spacing between the groups remained. If spontaneous grouping by proximity occurs in the haptic modality, we would expect to find an effect of the proximity manipulation on the speed and accuracy of enumeration. In addition, we expected to find a higher enumeration speed and higher accuracy in the configural condition. This would suggest that the same subitizing processes are operational in the haptic and visual modalities, and the latter finding would give evidence for the validity of the pattern recognition model in both modalities.

Experiment 1

Method

Participants Eight participants (M_{age} = 21.9, SD_{age} = 0.99; one left-handed; seven female, one male) took part in the study. We tested their moving and static two-point discrimination by using the Touch-Test Two-Point Discriminator (North Coast Medical, Inc., USA). We also measured their tactile sensitivity by using the Touch-Test Tactile Sensitivity (North Coast Medical, Inc., USA). None of the participants scored below normal according to the manufacturer, and all were naive to the purpose of the experiment and signed informed consent. The study was approved by the local ethical committee.

Stimuli and setup The stimuli consisted of strips of ZY-TEX2 swell paper. These were made using the ZY-FUSE heater (Zychem Ltd., Cheshire, England). The stimuli consisted of tangible dots with a diameter of 1.4 mm that protruded about 1 mm from the surface of the swell paper. The dots were placed in the center of each strip of paper between two vertical tangible lines. The tangible lines, which had a length of 10 mm and a thickness of 0.3 mm, served as indicators for the starting and ending points of the stimulus. The distance between the two vertical lines was 100 mm, and we placed the dots between the two lines. We manipulated the organization of the dots: Dots were organized on a straight horizontal line (baseline condition; Fig. 1B) or into groups of two, three, or four dots. We used 5-mm spacing between the dots within a group and 10-mm spacing between groups. The groups were based either on proximity or on configurality (Figs. 1C and D, respectively). In the *proximity 10-mm* condition, we used a larger spacing between some of the dots in the display to create subsets of dots. In the *configural 10-mm* condition, besides having a larger spacing between the groups, we placed the subsets of dots in a geometric configuration. In a stimulus with groups of two dots, the dots in a pair were organized horizontally (proximity 10-mm condition) or vertically (configural 10-mm condition; see Fig. 1). Dots within a triplet were organized horizontally (proximity 10-mm condition) or in triangles (configural 10-mm condition). In groups of four dots, the dots in a group were organized horizontally (proximity 10-mm condition) or in squares (configural 10-mm condition). The dots in the baseline condition had a spacing of 5 mm between the dots (similar to the spacing between the dots within a group, making them possibly interpretable as one group of dots) or a spacing of 10 mm between the dots (similar to the spacing between groups, making them possibly interpretable as multiple instances of one dot). We varied the distance to be able to check that dot distance itself did not influence exploration times and/or error rates. This resulted in two baseline conditions—baseline 10-mm and baseline 5-mm—and two grouping conditions—proximity 10-mm and configural 10-mm.

We further manipulated the number of dots in a stimulus: The total number of dots could be one, two, three, four, six, eight, or nine. We did not include stimuli with five or seven dots

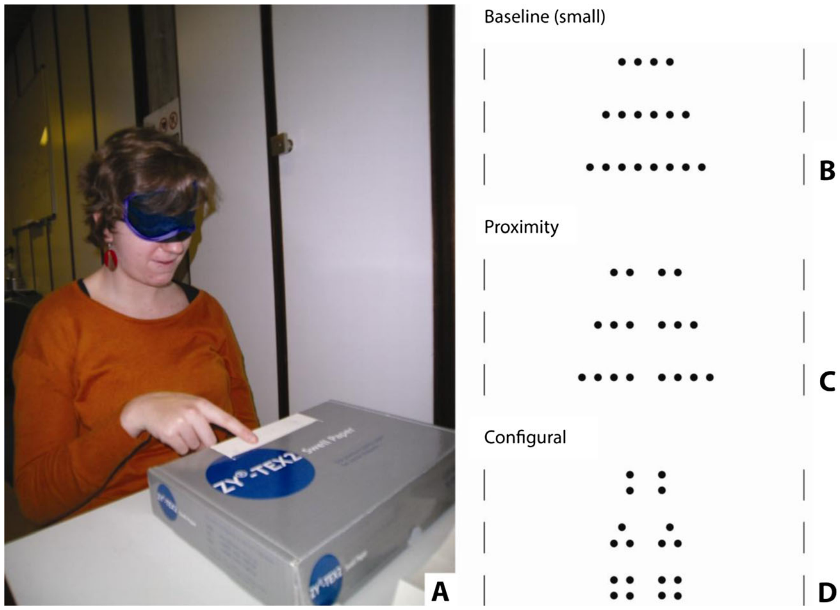

Fig. 1 Stimuli and setup of Experiment 1. (A) Participant performing the task. (B–D) Visual representations of the stimuli in the baseline, proximity, and configural conditions

because it was not possible to divide these numbers into equal groups of two, three, or four dots. This resulted in a total of 28 different stimuli, with six stimuli belonging to the baseline 10-mm condition, six to the baseline 5-mm condition, six to the proximity 10-mm condition, and nine to the configural 10-mm condition. A stimulus with one dot was also included in both the baseline 5-mm and baseline 10-mm conditions. We organized the grouped stimuli (both the proximity 10-mm and configural 10-mm conditions) in subsets according to the number of dots in one group. The possibilities here were groups of two dots (pair), groups of three dots (triangle), and groups of four dots (square). In the further analysis, this division into subsets will be referred to as *group size*. For a visual representation of all of the stimuli, see Appendix A.

Procedure In the instructions, we informed the participants that there were no more than ten dots in a stimulus. We did so because we reasoned that participants would find out about a maximum number of dots during the experiment, anyway, and we wanted to keep this knowledge constant during the course of the experiment and over participants. We also informed them that the different numbers of dots would not have equal numbers of trials. By doing this, we kept participants unaware that there were no trials with five or seven dots. Participants were blindfolded and seated in front of a table with a cardboard box placed on top of it. The stimuli could easily be attached to the box by inserting the two ends of the strip of paper into the slots on top of the box (see Fig. 1A). We instructed the participants to use the index finger of their dominant hand. At the start of each trial, the experimenter placed the finger on the left tangible vertical line and hit a button on the keyboard. When the experimenter pressed the button, the participants could hear a starting signal and had to move their index finger to the right, without making backward movements, until they reached the second vertical line. While moving from the left to the right vertical line, the participants had to enumerate the tangible dots as quickly and accurately as possible. When reaching the second vertical line, they had to press a foot pedal and give a vocal response of the number of dots perceived. At the end of each trial, the participant received feedback on whether or not the answer was correct. We repeated all stimuli five times and presented them in random order. This resulted in a total of 140 trials. Prior to the start of the experiment, participants performed five training trials. Exploration times and accuracy were recorded.

Analysis First, we analyzed whether there were any differences in accuracy between the baseline conditions (baseline 5-mm and baseline 10-mm) and the two grouping conditions (proximity 10-mm and configural 10-mm). To analyze accuracy, we calculated an averaged proportion correct score for each condition and each participant. To compare accuracies between the two grouping conditions, we calculated an averaged proportion score for each group size (groups of two, three, or four) separately for the two grouping conditions and for each participant.

To analyze enumeration speed, we removed the incorrect trials (11.74 %) and the trials with an enumeration time above or below two standard deviations from the mean (1.6 % of the correct trials). We calculated these outliers for each group size, separately for the four grouping conditions and for each participant. The enumeration time, as measured by the computer, also included fixed amounts of time to start moving and to press the foot pedal when reaching the second vertical line.

Because we randomized all of the stimuli (different numbers of dots and different grouping conditions), we should expect no differences in how participants would prepare themselves for each trial. We therefore determined a fixed start and response time for each participant, so that we could make a sound comparison between the slopes of the regression functions for the different grouping conditions. This was done by fitting a regression line through all of the data points for each participant, with enumeration time as a function of the number of dots. We used the intercepts of these regression lines as fixed intercepts in the following regressions to determine enumeration speed. To do this, we calculated for each participant a regression slope for the two baseline and the two grouping conditions while using the participant's fixed intercept. This slope represented the enumeration speed (in seconds per item), with lower values indicating higher enumeration speed and higher values indicating lower enumeration speed. Because we did not find differences in exploration speeds between the two baseline conditions, we collapsed those into one baseline condition. We then looked at the differences in enumeration speed between the baseline and the two grouping conditions.

Results

Accuracy Participants made on average 11.74 % errors (SD = 10.43). Most errors were underestimations of the dots in the trial (84.4 % of the total number of errors). Confusion matrices with the raw data for all conditions separately are shown in Appendix B. A one-way repeated measures analysis of variance (ANOVA) on the proportions correct with Condition as the within-subjects factor showed a significant effect for condition (using the Greenhouse–Geisser procedure, because the sphericity assumption was violated), $F(1.291,\ 9.037) = 5.84$, $p = .033$, $\eta_p^2 = .46$. However, Bonferroni-corrected (five tests: $\alpha = .01$) post-hoc comparisons showed no significant differences for the five comparisons (i.e., baseline 5-mm vs. baseline 10-mm, baseline 5-mm vs. proximity 10-mm, baseline 5-mm vs. configural 10-mm, baseline 10-mm vs. proximity 10-mm, and baseline 10-mm vs. configural 10-mm). A repeated measures ANOVA with Grouping Condition (proximity 10-mm vs. configural 10-mm) and Group Size (groups of two, three, or four) as within-subjects factors showed no significant effects. This lack of effects in accuracy allowed us to compare the enumeration speeds in the different conditions.

Enumeration speed

We conducted a paired-sample $t$test on the slopes of the two baseline conditions (baseline 5-mm vs. baseline 10-mm). This showed no significant difference, $t(7) = -0.63$, $p = .552$, and allowed us to average over the two baseline conditions to create one baseline condition, which we then compared with the two grouping conditions. The average regression lines over participants for each condition are shown in Fig. 2. We

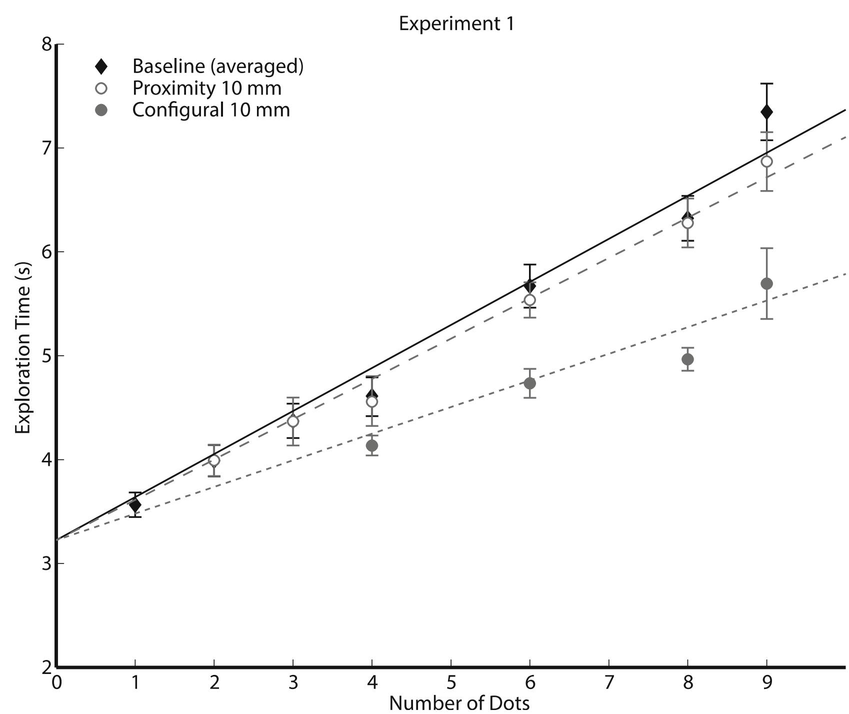

Fig. 2 Results of Experiment 1: Mean regression lines for the baseline (averaged) condition and the two grouping conditions (proximity 10-mm and configural 10-mm) through the mean enumeration times for each number of dots, averaged over participants. Error bars indicate the standard errors of the means over participants

conducted a one-way repeated measures ANOVA with Condition (baseline [averaged], proximity 10-mm, and configural 10-mm) as the within-subjects factor. The effect of condition was significant, $F(2, 14) = 10.30$, $p = .002$, $\eta_p^2 = .60$, and Bonferroni-corrected (two tests: $\alpha = .025$) post-hoc comparisons showed that only the configural 10-mm condition had a significantly higher enumeration speed than the baseline condition, $t(7) = 3.87$, $p = .006$. A repeated measures ANOVA on the slopes with Group Size (groups of two, three, or four) and Grouping Condition (proximity 10-mm vs. configural 10-mm) as within-subjects factors showed a main effect of grouping condition, $F(1, 7) = 7.47$, $p = .029$, $\eta_p^2 = .52$, with the configural condition having a higher enumeration speed than the proximity condition. There was no significant effect for group size, nor an interaction.

Experiment 2

Experiment 1 showed an effect of the configural manipulation on the enumeration speed, which was higher for the configural 10-mm condition than for the baseline (averaged) and proximity 10-mm conditions. We did not observe any effects of our proximity 10-mm manipulation on enumeration speed and accuracy. However, we expected to find a higher enumeration speed and accuracy when the grouping principle of proximity enhanced haptic enumeration. A possible explanation for the lack of effect could be that the spacing between the subsets of dots was not large enough to allow participants to discriminate between the different groups. With a 10-mm spacing between the subsets of dots, the participant's finger was always in contact with a dot while moving the finger between the groups. Related to this, Overvliet, Smeets, and Brenner (2007a) manipulated the distance between tangible circles and observed that when the distance between two circles was the same size as the participant's fingertip, this resulted in a constant speed over the items. When they used a distance that was larger than the participant's fingertip, participants observed a clear spacing between the dots. In our second experiment, we included stimuli with a 20-mm spacing, which is definitely larger than a fingertip. By including grouping conditions with a small (10-mm) and a large (20-mm) spacing, we were able to investigate whether a larger spacing could increase the awareness of groups and introduce an effect of grouping by proximity.

Another, perhaps even more plausible, explanation for the lack of effect for the proximity manipulation was that the two baseline conditions with different distances between the single dots might have caused confusion. The distance within a group of the proximity 10-mm condition was the same as the interdot distance in the baseline 5-mm condition, and the distance between the groups was similar to the interdot distance in the baseline 10-mm condition. The proximity 10-mm condition could therefore be interpreted as a mix between the baseline 5-mm and baseline 10-mm conditions, instead of as groups of items. In Experiment 2, we used only the baseline 5-mm condition.

Method

Participants The same eight participants as in Experiment 1 participated in Experiment 2. All of the participants were naive to the purpose of the experiment. To avoid learning effects, the time interval between the two experiments was at least four months.

Stimuli and setup We used stimuli similar to those in Experiment 1. Because we found no differences in enumeration speeds and accuracies between the baseline conditions (baseline 5-mm and baseline 10-mm) from Experiment 1, we chose to use only the baseline 5-mm condition in this experiment. Furthermore, we manipulated the distance between the groups for the grouping conditions (proximity and configural): The distance was either 10 or 20 mm (small or large). This resulted in 34 stimuli and five conditions, with six stimuli belonging to the baseline 5-mm condition, six to the proximity 10-mm condition, six to the proximity 20-mm condition, nine to the configural 10-mm condition, and nine to the configural 20-mm condition. One stimulus with one dot was also included in the baseline 5-mm condition; see Appendix C for a visual representation of the stimuli.

Procedure We used the same procedure as in Experiment 1. We presented the 34 stimuli five times, which resulted in a total set of 170 trials. Prior to the start of the experiment, participants performed the same five training trials as in Experiment 1.

Analysis We analyzed the data in the same way as in Experiment 1. We now removed 11.32 % incorrect trials and 1.58 % outliers. We also tested whether the intercepts of Experiments 1 and 2 differed from each other.

Results

Accuracy Participants made on average 11.32 % errors (SD = 15.05). Most errors were underestimations of the dots in the trial (77.3 % of the total number of errors). Confusion matrices with the raw data for all conditions separately are shown in Appendix D. A one-way repeated measures ANOVA on the proportions correct averaged over participants with Condition as the within-subjects factor showed a significant effect of condition, $F(4, 28) = 9.02$, $p < .001$, $\eta_p^2 = .56$. Bonferroni-corrected (four tests: $\alpha = .0125$) post-hoc comparisons showed significantly lower proportions correct for the baseline 5-mm condition than for the proximity 20-mm condition, $t(7) = 4.56$, $p = .003$, the configural 10-mm condition, $t(7) = 4.80$, $p = .002$, and the configural 20-mm condition, $t(7) = 6.60$, $p < .001$. To check for differences between the grouping conditions, we performed a repeated measures ANOVA with Grouping Condition (proximity vs. configural), Group Size (groups of two, three, or four), and Distance (10 vs. 20 mm) as the within-subjects factors. This showed a significant effect of group size (using the Greenhouse–Geisser procedure because the sphericity assumption was violated), $F(1.158, 8.109) = 5.19$, $p = .048$, $\eta_p^2 = .43$, but no effects of grouping condition, distance, or interactions. Bonferroni-corrected (three tests: $\alpha = .0167$) post-hoc comparisons for group size showed no significant differences.

Enumeration speed

A paired-sample *t* test showed no differences between the intercepts of Experiments 1 and 2, $t(7) = -1.45$, $p = .190$, suggesting that there were no learning effects or different enumeration strategies in these experiments. The average regression lines for the conditions are shown in Fig. 3. We conducted a one-way repeated measures ANOVA on the slopes of the regression lines with fixed intercepts, using Condition as the within-subjects factor. This showed a significant effect of condition, $F(4, 28) = 40.22$, $p < .001$, $\eta_p^2 = .852$. We used Bonferroni-corrected (four tests: $\alpha = .0125$) post-hoc comparisons to compare the baseline 5-mm condition with the four grouping conditions. This showed significant differences for all comparisons [proximity 10-mm, $t(7) = 6.93$, $p < .001$; proximity 20-mm, $t(7) = 5.42$, $p = .001$; configural 10-mm, $t(7) = 7.46$, $p < .001$; configural 20-mm, $t(7) = 8.64$, $p < .001$]. To check for differences in enumeration speed between the four grouping conditions, we performed a repeated measures ANOVA with Grouping Condition (proximity vs. configural), Group Size (groups of two, three, or four), and Distance (small vs. large) as within-subjects factors. We found a significant effect for grouping condition, $F(1, 7) = 41.39$, $p < .001$, $\eta_p^2 = .86$, in which the configural condition had a significantly higher enumeration speed than the proximity condition. There were no significant effects for group size, distance, or any interactions.

General discussion

In the present study, we investigated whether perceptual grouping is operational in the haptic modality. We used a haptic enumeration task in which participants had to enumerate tangible dots as quickly and accurately as possible. We hypothesized that when subsets of dots could be grouped, this would lead to a higher enumeration speed and accuracy than in a baseline condition. We manipulated grouping by proximity and by configural cues.

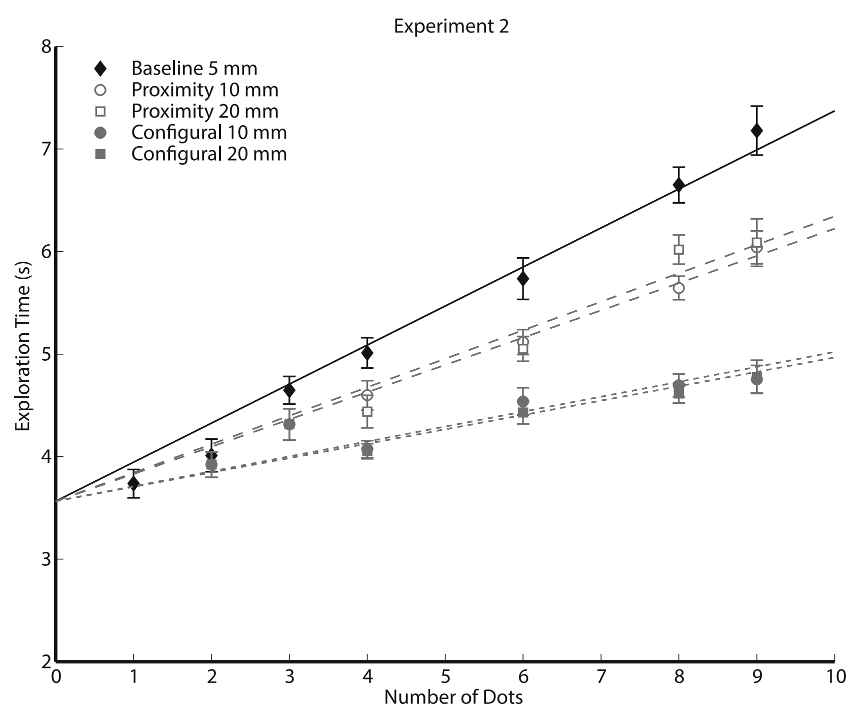

Fig. 3 Results of Experiment 2: Mean regression lines for the baseline 5-mm condition and four grouping conditions through the mean enumeration times for each number of dots, averaged over participants. Error bars indicate the standard errors of the means over participants

As predicted, grouping by configural cues led to a higher enumeration speed than in the baseline condition, and this was the case in both experiments. This is in line with the pattern recognition model, which assumes that simple patterns (e.g., triangles, squares) can be recognized quickly and easily. This fast recognition can result in subitizing, and therefore can speed up the enumeration process (Mandler & Shebo, 1982). This is in contrast with Riggs et al. (2006), who suggested that the pattern recognition model is not suitable to explain subitizing in the haptic modality. They concluded that their results posed a problem for the pattern recognition model, because they did not include canonical patterns in their setup and still observed a subitizing effect. Our results suggest that the pattern recognition model cannot be rejected in haptic numerosity perception and that it can be used as a valid model for subitizing in the haptic modality. Moreover, our results are very similar to the configural grouping effects observed in vision (Krajcsi et al., 2013) and could be interpreted as evidence for the validity of the pattern recognition model in haptic numerosity perception.

In Experiment 2, we observed a higher enumeration speed for the two proximity conditions (10- and 20-mm spacing). A plausible explanation of why we observed an effect of the proximity 10-mm manipulation in Experiment 2, but not in Experiment 1, could be the randomized presentation of the baseline 5-mm and baseline 10-mm trials in Experiment 1. This randomization could have confused participants when detecting the subsets of dots in the proximity condition. When we took out the baseline 10-mm condition in Experiment 2, this confusion was probably reduced. It therefore seems very plausible that grouping by proximity is operational in haptic enumeration, independent of the distance between the groups.

Our results show that the configural manipulation had a stronger effect on enumeration speed than did the proximity manipulation in both experiments. Although in Experiment 1 configural grouping was the only effect that we found, in Experiment 2 we actually may have detected a combined effect of configural and proximity cues, since we manipulated not only the configural organization but also the proximity of the subsets. The reason why our configural manipulation had a larger effect can be explained by the additive effect of the two grouping principles on enumeration speed. In visual perception research, it has been suggested that the conjoint effect of two grouping principles is equal to the sum of their separate effects (e.g., proximity and similarity: Kubovy & van den Berg, 2008; similarity, proximity, and common region: Luna & Montoro, 2011). Hence, our results suggest the existence of additive effects of two grouping cues in the haptic modality. However, future research in which configural conditions without proximity manipulations are tested would give us more evidence for this suggestion.

In the present study, participants had to touch the dots sequentially by moving an index finger over the surface. This resulted in serial input of the dots. However, when we organized the subsets of dots into configural cues, this allowed the fingertip to touch more than one dot at the same time. However, this was not possible for all of the proximity subsets, since they sometimes were wider than the width the fingertip. This could be another explanation why the configural condition had a larger effect on enumeration speed than did the proximity condition. The configural manipulation allowed the participants to process the configural cues in parallel underneath the fingertip. Such parallel input was not always possible in the proximity condition. Subitizing theories refer to a parallel input in which items can be processed simultaneously (e.g., Plaisier & Smeets, 2011). Future research should test whether perceptual grouping also affects enumeration speed when the dots are touched simultaneously instead of one by one. One possible way to investigate this would be to use a more static enumeration task, following the design used by Riggs et al. (2006), Plaisier and Smeets (2011a), Overvliet, Mayer, Smeets, and Brenner (2008), and Overvliet, Smeets, and Brenner (2007b), who used stimulation of multiple fingertips at once. Using this method would allow us to investigate whether configural cues can be processed in parallel and enable us to gain further insight into whether the same enumeration processes are operational in the haptic and visual modalities.

The fact that we found positive results for our configural manipulation suggests that putting dots in some kind of configuration is a more efficient way to convey information. This reminds us of the way that Braille characters are constructed. Perceptual grouping might indeed play a role in Braille reading, though whether this happens before or after learning of the characters is an open question. It has been shown that accuracy in Braille reading could be improved after training (Oshima & Ichihara, 2012). It would therefore be interesting to include Braille characters in future grouping studies, to investigate whether Braille can be learned more efficiently by some kind of pattern recognition strategy that involves Gestalt principles.

In sum, our results give evidence for perceptual grouping in the haptic modality. Grouping by proximity and grouping by configural cues can speed up the enumeration process in a haptic enumeration task. This gives further evidence for a common enumeration process in haptic and visual numerosity perception and gives evidence for modality-independent functioning of the Gestalt principles.

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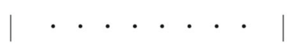
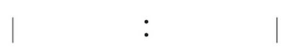
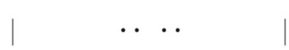
Appendix A: Visual representation of the stimuli used in Experiment 1

Number	Figure	Dots	Group size	Condition
1		1	1	Baseline (Small & Large)
2		2	2	Baseline 10 mm
3		3	3	Baseline 10 mm
4		4	4	Baseline 10 mm
5		6	6	Baseline 10 mm
6		8	8	Baseline 10 mm
7		9	9	Baseline 10 mm
8		2	2	Baseline 5 mm
9		2	2	Configural
10		4	4	Configural
11		3	3	Configural
12		4	2	Proximity
13		4	2	Configural

14	| ∷ ∷ |	8	4	Configural
15	| ∴ ∴ |	6	3	Configural
16	| • • • • • • |	6	3	Proximity
17	| • • • • • • • • |	8	4	Proximity
18	| : : : |	6	2	Configural
19	| • • • • • • • • • |	9	3	Proximity
20	| ∴ ∴ ∴ |	9	3	Configural
21	| • • • • • • |	6	2	Proximity
22	| : : : : |	8	2	Configural
23	| • • • • • • • • |	8	2	Proximity
24	| • • • |	3	3	Baseline 5 mm
25	| • • • • |	4	4	Baseline 5 mm
26	| • • • • • • |	6	6	Baseline 5 mm
27	| • • • • • • • • |	8	8	Baseline 5 mm
28	| • • • • • • • • • |	9	9	Baseline 5 mm

Appendix B

Baseline Experiment 1

Count

		stimulus							
		1	2	3	4	6	8	9	Total
response	1	78	1	0	0	0	0	0	79
	2	1	117	2	0	0	1	0	121
	3	0	2	76	6	0	0	0	84
	4	0	0	2	73	2	0	0	77
	5	1	0	0	1	11	0	0	13
	6	0	0	0	0	66	1	0	67
	7	0	0	0	0	0	1	0	1
	8	0	0	0	0	1	35	2	38
	9	0	0	0	0	0	2	38	40
Total		80	120	80	80	80	40	40	520

Horizontal Experiment 1

Count

		stimulus				
		4.00	6.00	8.00	9.00	Total
response	3	3	0	0	0	3
	4	36	4	0	0	40
	5	0	10	1	0	11
	6	1	65	9	2	77
	7	0	1	4	2	7
	8	0	0	62	8	70
	9	0	0	4	28	32
Total		40	80	80	40	240

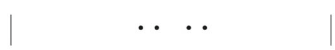
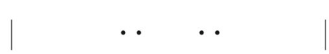
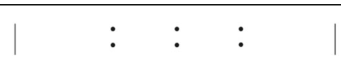
Configural Experiment 1

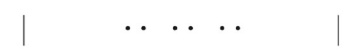
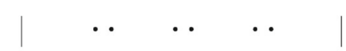
Count

		stimulus						
		2.00	3.00	4.00	6.00	8.00	9.00	Total
response	2	40	0	0	0	0	0	40
	3	0	40	0	0	0	0	40
	4	0	0	80	1	0	0	81
	5	0	0	0	4	0	0	4
	6	0	0	0	72	5	2	79
	7	0	0	0	1	1	2	4
	8	0	0	0	2	72	8	82
	9	0	0	0	0	2	28	30
Total		40	40	80	80	80	40	360

Appendix C: Visual representation of the stimuli used in Experiment 2

Number	Figure	Dots	Group size	Condition
1		1	1	Baseline
2		2	2	Baseline
3		3	3	Baseline
4		4	4	Baseline
5		6	6	Baseline
6		8	8	Baseline
7		9	9	Baseline
8		6	3	Proximity 10 mm
9		8	4	Proximity 10 mm
10		9	3	Proximity 10 mm
11		4	4	Configural (Small & Large)
12		9	3	Configural 10 mm
13		6	3	Configural 10 mm

14		3	3	Configural (Small & Large)
15		6	3	Proximity 20 mm
16		8	4	Proximity 20 mm
17		9	3	Proximity 20 mm
18		9	3	Configural 20 mm
19		6	3	Configural 20 mm
20		4	2	Proximity 10 mm
21		2	1	Configural (Small & Large)
22		8	2	Configural 10 mm
23		6	2	Configural 10 mm
24		4	2	Configural 10 mm
25		8	4	Configural 10 mm
26		4	2	Proximity 20 mm
27		8	2	Configural 20 mm
28		6	3	Configural 20 mm

29		4	2	Configural 20 mm
30		8	4	Configural 20 mm
31		6	2	Proximity 10 mm
32		8	2	Proximity 10 mm
33		6	2	Proximity 20 mm
34		8	2	Proximity 20 mm

Appendix D

Baseline Experiment 2

Count

		stimulus							
		1	2	3	4	6	8	9	Total
response	1	40	0	0	0	0	0	0	40
	2	0	37	5	1	0	0	0	43
	3	0	3	34	5	0	0	0	42
	4	0	0	1	34	2	0	0	37
	5	0	0	0	0	7	0	0	7
	6	0	0	0	0	29	2	4	35
	7	0	0	0	0	2	4	0	6
	8	0	0	0	0	0	27	14	41
	9	0	0	0	0	0	7	20	27
	10	0	0	0	0	0	0	2	2
Total		40	40	40	40	40	40	40	280

Horizontal Small Experiment 2

Count

		stimulus				
		4	6	8	9	Total
response	3	2	0	0	0	2
	4	38	7	0	0	45
	5	0	1	0	0	1
	6	0	70	4	3	77
	7	0	1	6	1	8
	8	0	1	67	3	71
	9	0	0	3	33	36
Total		40	80	80	40	240

Horizontal Large Experiment 2

Count

		stimulus				
		4	6	8	9	Total
response	4	39	1	0	0	40
	6	1	77	6	2	86
	7	0	0	2	1	3
	8	0	2	69	2	73
	9	0	0	2	35	37
	10	0	0	1	0	1
Total		40	80	80	40	240

Configureal Small Experiment 2

Count

		stimulus						
		2	3	4	6	8	9	Total
response	2	40	0	1	0	0	0	41
	3	0	38	2	0	0	0	40
	4	0	2	76	2	1	0	81
	6	0	0	0	76	9	3	88
	7	0	0	0	0	2	2	4
	8	0	0	0	2	67	0	69
	9	0	0	1	0	1	34	36
Total		40	40	80	80	80	40	360

Configural Large Experiment 2

Count

		stimulus						
		2	3	4	6	8	9	Total
response	2	40	0	1	0	0	0	41
	3	0	38	1	0	0	0	39
	4	0	2	77	0	0	0	79
	6	0	0	0	78	4	1	83
	7	0	0	0	0	0	1	1
	8	0	0	0	2	76	5	83
	9	0	0	1	0	0	33	34
Total		40	40	80	80	80	40	360

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