Multiple Fingers – One Gestalt

Alexandra Lezkan, Steven G. Manuel, J. Edward Colgate, *Fellow, IEEE*, Roberta L. Klatzky, *Senior Member, IEEE*, Michael A. Peshkin, *Member, IEEE*, and Knut Drewing

Abstract—The Gestalt theory of perception offered principles by which distributed visual sensations are combined into a structured experience ("Gestalt"). We demonstrate conditions whereby haptic sensations at two fingertips are integrated in the perception of a single object. When virtual bumps were presented simultaneously to the right hand's thumb and index finger during lateral arm movements, participants reported perceiving a single bump. A discrimination task measured the bump's perceived location and perceptual reliability (assessed by differential thresholds) for four finger configurations, which varied in their adherence to the Gestalt principles of proximity (small versus large finger separation) and synchrony (virtual spring to link movements of the two fingers versus no spring). According to models of integration, reliability should increase with the degree to which multi-finger cues integrate into a unified percept. Differential thresholds were smaller in the virtual-spring condition (synchrony) than when fingers were unlinked. Additionally, in the condition with reduced synchrony, greater proximity led to lower differential thresholds. Thus, with greater adherence to Gestalt principles, thresholds approached values predicted for optimal integration. We conclude that the Gestalt principles of synchrony and proximity apply to haptic perception of surface properties and that these principles can interact to promote multi-finger integration.

Index Terms—Haptics, multi-finger integration, gestalt, psychophysics

1 Introduction

1.1 Gestalt Grouping

Imagine yourself closing your eyes and reaching out for a piece of paper on the table in front of you. In order to find the paper you move your arm from left to right. While doing so, multiple fingers will contact a surface. Now, the perceptual task of your brain is to make sense out of those individual points of stimulation. Some of the stimulated points will be perceived as being part of the same object, such as the table; others as being caused by different objects, table and piece of paper. But, how does the brain determine which stimulation should be grouped and which should not be?

This question was first addressed for the visual sense almost 100 years ago by the so-called "Gestalt" psychologists, who proposed a set of basic principles to describe how spatially distributed and often discrete visual elements are grouped together into perceptual units. The relationships between multiple visual features that tend to support grouping include similarity, proximity, good continuation (common tangents), symmetry, closure (features that collectively enclose a region), and common fate (motion speed and direction) [1].

An analogy can be made between elements of visual grouping, which often project onto non-contiguous regions of the retina [2], and haptically grouped physical features of objects that are detected by non-contiguous regions of skin, e.g., adjacent fingertips. We suggest that, similarly to vision, grouping in the haptic sense also follows Gestalt principles. We focused on two principles that are related to the spatial and temporal coherence of cues, namely, proximity and synchrony.

Some previous research in haptic perception supports proximity as a grouping principle. Chang et al. [3], for instance, demonstrated parallels between the tendency to group by either similarity or proximity in both haptic displays (consisting of patches of variable roughness) and equivalent visual displays. Other work has suggested weaker or no effects. For example, Overvliet et al. [4] studied the influence on haptic search of both spatial proximity (varying item separation) and somatotopic proximity (exploration with one versus both hands), but found little effect of either variable. Frings and Spence [5] used a negative priming task, where participants identified a target stimulus vibration presented to one hand while ignoring a distracter vibration presented to the other. Again, no systematic effect of spatial proximity (hand separation) on response time was found. It is important to keep in mind, however, that in the two studies just described, proximity was quantitatively varied only regarding the separation between two hands, in contrast to the separation between fingers of one hand.

Some hints of a within-hand proximity grouping can be found in the literature. Overvliet et al. [6] indicated that localization of near-threshold stimuli on separate fingers of one hand was more accurate with fingers spread. The finding that spatial proximity leads to more difficult location discrimination suggests automatic integration and the

- *A. Lezkan and K. Drewing are with the Department of General Psychology, Justus-Liebig University, Giessen 35390, Germany. E-mail: {alexandra.lezkan, knut.drewing}@psychol.uni-giessen.de.*
- *S. G. Manuel, J. E. Colgate, and M. A. Peshkin are with the Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208. E-mail: steven.manuel@u.northwestern.edu, {colgate, peshkin}@northwestern.edu.*
- *R. L. Klatzky is with the Department of Psychology & the Human Computer Interaction, Carnegie Mellon University, Pittsburgh, PA 15213. E-mail: klatzky@cmu.edu.*

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potential for grouping of such multi-finger cues. Similarly, proximity effects were reported for haptic contour detection performed with one hand [7]. However, most previous studies on grouping by proximity did not systematically vary the separation between fingers of one hand. The present research directly addresses this issue.

Recent findings in the last decades have added further visual grouping principles to the classical set. One of these, synchrony, is particularly interesting in the context of the haptic modality. The principle of synchrony postulates that elements that change at the same time are grouped together [8]. Synchrony is subsumed under common fate, but does not require that motion be induced by the stimulus. The principle of synchrony is in our view especially interesting for the haptic sense, which is characterized by the generation of sensory signals via active hand movements [9]. In a world of continuous surfaces, distributed contact across separate fingers is likely to be synchronized. Conversely, synchronized stimulation within the modality of touch may support the percept of an integrated external world.

Previously, grouping like effects for simultaneous stimulations were reported in the funneling illusion [10], [11]. In funneling, the simultaneous vibratory stimulation of two or more locations on the skin leads to an illusionary vibration sensation between the real points of stimulation. The location of the sensation depends on the ratio between the strengths of single stimuli [12]. In everyday life however, simultaneous stimulation most likely occurs on multiple fingertips during active exploration movements. Evidence of synchrony based grouping effects in active haptic perception was reported by Manuel et al. [13]. The study demonstrated that grouping of spatially separated, virtual bumps rendered by lateral forces could be induced by increasing the degree of temporal synchrony between the individual bump stimuli.

The purpose of the present research was to extend the findings of Manuel et al. with a more systematic study. The aim is to investigate the influence of the grouping principles of proximity and synchrony in active touch. Given that grouping principles promote the integration of different stimulus components into a unified percept, we approach the question by utilizing the well-defined framework of cue integration. We argue that this framework provides well-established methods to find out whether and in how far stimuli are integrated and, hence, is well suited to assess the strength of grouping effects.

1.2 Cue Integration and Grouping

Perception in a multimodal context is based on combining redundant sensory inputs to form unified percepts. For example, holding a pen in the hand leads to both tactile and kinesthetic information about its diameter. Ernst and Bülthoff [14] summarized the literature and concluded that the Maximum Likelihood Estimation (MLE) model is an appropriate description of the integration of such redundant information. Simply put, the MLE model states that an estimate of a property of the world, e.g., a physical parameter, is computed as the weighted average of individual estimates derived from each available sensory input. The weights are considered optimal if they are in direct proportion to the contributing estimate reliabilities (the inverse of the perceptual variance). Thus, in optimal integration more reliable estimates contribute more to the final percept. Weighted averaging with optimal weights leads to the maximal reliability of the final percept [14]. Weights can be assessed by the Point of Subjective Equality (PSE) in a multi-cue discrimination task, in which slight discrepancies between cues are introduced. The Just Noticeable Difference (JND) in the same task measures differential thresholds, i.e. the reliabilities.

There are two common alternative models to MLE found in the literature [15], [16], [17]. The first, suboptimal integration, also refers to a weighted average of multiple contributing cues, but the weights are not assumed to be optimal. This leads to the fact that the reliability of the final percept does not reach maximal values [15]. However in both integration models the reliability of the multi-cue estimate is no lower than that of the least reliable single cue estimate. A cue switching model, on the other hand, assumes no integration of contributing cues. Instead, for each occurrence of a stimulus, the parameter estimate in question is computed using only one of the contributing cues at a time. For that occurrence, each contributing cue has a certain probability of being used for the parameter estimate [16]. Cue switching predicts that JNDs are no lower than the best cue-specific JND. In other words, the final perceptual reliability will not exceed reliabilities of the single estimates. The three models just described represent a continuum of integration, from optimal use of cues according to reliability (MLE) to treating the multiple sources independently.

An underlying assumption of cue integration is that the contributing cues originated from the same source. Consistent with this assumption, it has been shown that integration is systematically degraded as the attribution to a common source is weakened [18]. On this basis, integration can be directly linked to grouping. That is, since grouping involves attribution of distinct cues to the same source, as required for cue integration, we should be able to use the extent of integration as an indicator of grouping strength. The more likely it is that two spatially separate cues actually refer to the same shared parameter, the more their integration should obey optimal integration theory. In general, then, increased grouping strength should result in increased reliabilities of the final parameter estimation, consistent with the MLE model.

Studies focusing on inter-modal cue integration support the influence of grouping principles. Results from multisensory integration research demonstrate effects that are in good agreement with the principle of proximity as well as the principle of synchrony. For instance, it has been shown that visual and haptic cues are integrated optimally when the sources spatially coincide (i.e., proximity is maximized), and that integration degrades with separation [19]. Temporal synchrony has also been reported to effect the integration of cues [20]. Auditory and tactile stimuli were integrated automatically if appearing simultaneously, and this effect disappeared gradually with temporal asynchrony.

The goal of this research was to investigate whether temporal and spatial coherence, represented by the Gestalt principles of synchrony and proximity, determine the integration of cues from multiple fingers. In order to stimulate fingers independently we made use of the "virtual bumps" phenomenon, which we describe next.

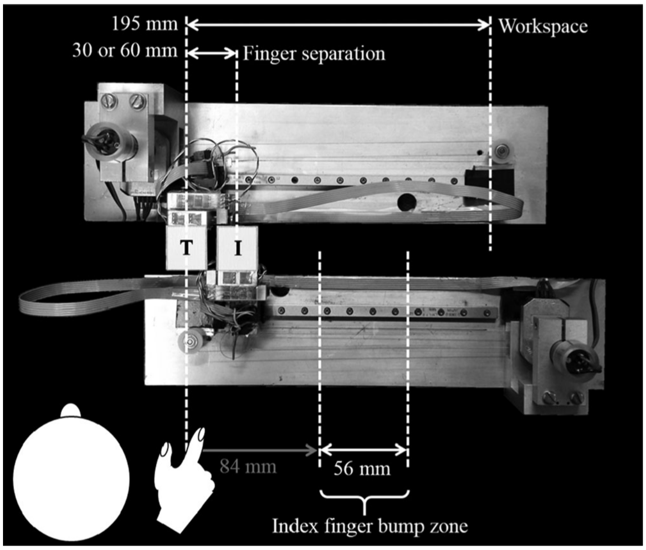

Fig. 1. Haptic slider interface. The sliders for thumb and index finger are marked with T and I, respectively. The interface is viewed from above. The participant is sitting as pictured in front of the left end.

1.3 Virtual Bump Illusions

Hayward and Robles-de-la-Torre [21] initially demonstrated illusory contours or "virtual bumps" using lateral force feedback on a physically flat surface more than ten years ago. They showed that perception of a bump can be produced by first resisting and then assisting the motion. Since then, there have been many studies investigating the way that haptic cues on a single finger are integrated to form illusory contours [22], [23], [24]. However, few have studied these contour illusions in the context of multiple fingers [13], [25]. In this paper we examine the situation in which two fingers on the same hand encounter virtual bumps at roughly the same time, and we show that, under certain circumstances, two physical bumps are perceived as a single bump in between the fingers. Specifically, we use the perceived bump location and perceptual reliability to demonstrate the necessity of fingertip spatial proximity and force synchronization between fingers in order to achieve perceptual integration. Thus, we provide evidence for the Gestalt grouping principles of proximity and synchrony for percepts in a multi-finger task.

If an illusory surface contour arising from multi-finger contact does in fact constitute an instance of haptic grouping, adherence to Gestalt-like principles would not only demonstrate the first multi-finger grouping principles but might also be directly applicable to the design of surface haptic interfaces. The present research evaluates the role of grouping in these effects by measuring how strongly force cues are integrated across the fingers under different conditions of exploration.

1.4 Multiple Finger Illusion in Previous Work

In our previous work, Manuel et al. [13] independently rendered two virtual bumps to the index finger and thumb, respectively, using the apparatus pictured in Fig. 1. Each finger could feel only its respective bump and not the other. The locations of the two bumps were varied such that their separation ranged from 0 to 42 mm. Participants were trained to maintain a nominal finger separation of 42 mm; thus at 42 mm of separation, the two bumps were encountered by the index finger and thumb nearly simultaneously. Participants were asked to report the number of bumps in the objective world and the number of times they encountered each bump. Additionally, they indicated the locations of the bump(s).

It was found that as the degree of simultaneity increased (bump separation approached 42 mm), almost all participants increasingly perceived a single bump as opposed to two. Furthermore, location estimation data gathered during the experiment suggested that the bump was perceived *in between* the two finger locations. We refer to these two effects together as perceptual collapse.

For participants who did not follow this trend (3 of 10), we infer that the cognitive nature of the task may have influenced interpretation of the sensory phenomena. The possibility of penetration by cognitive and conscious effects is supported by work of Anema et al. [26], who showed that explicit localizing is influenced by factors beyond low-level somatosensory processing. Patients with an inability to explicitly individuate between fingers (finger agnosia) were still able to discriminate between fingers on more psychophysically based measurements.

The present study, which uses a two-alternative forced choice location discrimination task rather than localization reports, was intended to show the illusion on a somatosensory level and thereby exclude a purely cognitive explanation. The implicit measurement used here allows determining where exactly the bump is located. If it appears to be between the fingers, we will be further able to differentiate whether this is due to integration or cue switching, by a comparison of predicted and observed reliabilities. We predict that an illusory bump will be reported, consistent with integration, when the display adheres to the grouping principles of synchrony and proximity.

1.5 Aim of the Current Experiment

The present study is intended to test the hypothesis that both the level of synchrony between force cues and the degree of proximity between fingers in external space can promote grouping and, therefore, integration. We propose that as the stimuli exhibit stronger adherence to the Gestalt principles, integration will approach optimality. Thus, the observed reliability should get closer to the maximal level as predicted by MLE model of optimal sensory integration.

Similarly to [13], on each trial two separate bumps were rendered for the thumb and index finger respectively. The two bumps were spaced at finger spacing so that they were experienced by the two fingers nearly simultaneously, but in different spatial locations. In the discrimination task, the location of the index finger bump in such a two-finger stimulus was compared to a single bump presented to the index finger. The relative distance of the single-finger comparison stimulus to the index finger bump in the standard two-finger stimulus was systematically manipulated.

For the two-finger stimuli, both fingers moved together. We defined four finger configurations, which were intended to induce variations in adherence to the Gestalt principles of proximity and synchrony (as illustrated in Fig. 2 and described below). PSEs, assessing the perceived location, and JNDs, assessing differential thresholds and, thus, reliability,

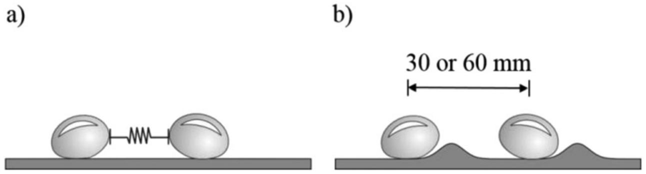

Fig. 2. Manipulations of the standard stimuli in the two-finger conditions: (a) Virtual spring. (b) Finger separation.

were measured for each condition using the method of constant stimuli. A shift in the reported index-finger bump location (PSE) toward the thumb would indicate an automatic influence of the task-irrelevant finger. Decreased JNDs were used as indicators of cue integration, as optimal integration predictions represent the lowest JNDs and cue switching the highest. We tested whether conditions with higher adherence to Gestalt principles have decreased JNDs. Additionally, empirical JNDs were compared to theoretical predictions from different models (optimal, suboptimal, no integration/cue switching).

2 Materials and Methods

2.1 Apparatus

As shown in Fig. 1, the experimental workbench consisted of a haptic slider interface and a touch screen. The participant was seated so that the slider interface was in front of his right hand at the distance of his forearm. A touch screen was placed to the left of the participant in order to display instructions and record responses.

The haptic slider interface consisted of two slider surfaces for two fingertips, constrained to slide along the same axis independently of one another. The total workspace reachable by both sliders together was 195 mm in length. Each slider surface was mounted on its own cable-driven linear bearing equipped with load cells to measure forces exerted by the finger on the slider surface on an axis normal to the surface as well as on the axis of travel.

Each slider was driven using a force control loop closed around the slider's lateral direction load cell, in order to mask the inertia and friction. The control loop operated at 1 kHz and was computed on a PC/104 stack running an xPC Target real-time operating system. Automation of the experimental protocol was done on a PC running a Matlab script, communicating with the PC/104 stack. Visual feedback and user input was accomplished using a touch screen monitor located next to the slider apparatus. Maxon RE-16 motors drove the sliders with up to 1 N of force, although the experiment required less than 0.7 N to render bumps effectively. We used Futek LSM250 parallelogram load cells with a full-scale reading of 1.1 N. 320 grit sandpaper was used as the slider surfaces to ensure zero slip even at low levels of applied normal force. A thin wire was placed underneath each sandpaper sheet to form a roughly 1 mm wide ridge, which participants could use to align their fingers with the center of each slider.

Because the experiment requires participants to keep their dominant arm elevated for extended periods, we used a forearm sling to reduce fatigue. The sling's support wires extended 8 feet upward to the ceiling, so the direction of tension during movement was largely insensitive to the position of the arm. In addition, to prevent visual cues from affecting responses, the participant's view of the device was obstructed by a metal sheet.

2.2 Stimuli

All stimuli consisted of either one or two virtual Gaussian bumps. Slider surface elevation was held constant while lateral forces were independently rendered to the fingers as a function of respective slider positions. Lateral forces (representing bumps) were rendered irrespective of the participant's applied normal force; the lateral force applied by the device was a function of slider position alone. Participants were trained to maintain a normal force of 0.5 N. Thus, a constant normal force was assumed for displaying lateral forces to render the desired bump size. This contrasts with an idealized frictionless bump in which lateral force would be proportional to the participant's applied normal force. The forces corresponded to the lateral component of the reaction force that would be imposed by a Gaussian-shaped bump with a standard deviation (σ) of 8 mm and a height (h) of 5 mm, according to Equation (1)

$$F_L = F_N h \frac{(x-\mu)}{\sigma^2} e^{\frac{-(x-\mu)^2}{2\sigma^2}}, \tag{1}$$

where F is the applied force, F_N is the assumed normal force (0.5 N), h is the bump height, x is the current finger position, μ is the bump center position and σ is the bump standard deviation. The location of the bump center presented to the index finger was systematically varied between 84 and 140 mm from the leftward limit of the workspace.

The Gestalt principles of proximity and synchrony were instantiated for two-finger stimuli as follows. To vary proximity, the thumb and index fingers experienced identical bumps, but the thumb was stimulated on a point of the track shifted by either 30 or 60 mm to the left of the index finger bump. To vary synchrony, a virtual spring was present or absent. The effect was similar to having a physical spring pinched between the fingers. The spring constant was 0.1 N/mm and exerted only repulsive forces between fingers. Spring width was set to 5 mm greater than finger separation so that a comfortable compression force of 0.5 N would allow fingers to rest at their proper separations. The mechanical linkage induced by the spring had two effects that would be expected to affect the perception of synchrony. First, it enforced a finger separation close to the bump separation, reducing temporal noise relative to the self-controlled separation of the no-spring equivalent. Second, it was intended to create a virtual object held within the pinched fingers, which would inherently link stimulation to them and support the impression of synchrony. Interactions between proximity and synchrony would be informative as to the relative weight of the Gestalt principles, but we make no a priori predictions.

2.3 Participants

A total of nine right-handed Northwestern University students (five female, four male) were tested. One participant had to be excluded for reasons described in the analysis. The remaining participants ranged in age from 18 to 23 years of age and reported no cutaneous or motor impairments. All

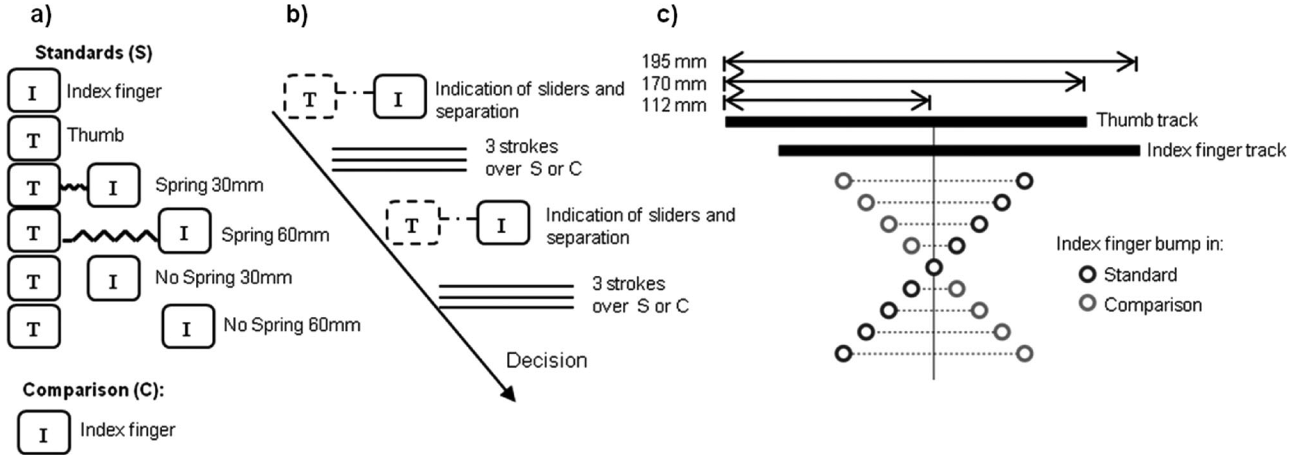

Fig. 3. (a) Overview of all one- and two-finger configurations for standard or comparison stimuli. (b) Time sequence of a trial. (c) Spatial arrangement of index finger bumps for pairs of standard and comparison stimuli.

participants were right handed and naïve to the purpose of the study. Participants gave consent using Institutional Review Board (IRB) protocol STU00025168 and the study was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Participants were compensated for their involvement.

2.4 Experimental Design

In each trial participants successively explored two stimuli and judged which bump was further to the left. One of the stimuli was the standard and the other one the comparison. We randomized whether the standard or the comparison was presented first. There were six total standards. The first four were composed of combinations of two-finger separations (30 or 60 mm) and two inter-finger virtual spring states (with or without spring). For these two-finger standards we asked the participant to compare the bump presented to the index finger in the standard with the comparison bump. The remaining two standards were index finger only and thumb only stimuli. All possible standards and comparisons are displayed in Fig. 3a.

For two-finger standards, the thumb bump was placed either 30 or 60 mm to the left of the index finger bump depending on the finger separation, such that both fingers would cross their respective bumps nearly simultaneously. For single-finger standards, a single bump was rendered to the finger used. The other finger did not touch the slider.

Each standard was paired with each of nine comparisons 24 times. The comparison consisted of a virtual bump that was always presented just to the index finger. The single finger comparisons were defined by their relative shift from the index finger bump in the two-finger standard stimulus. The comparisons were arranged in nine equal steps between 56 left to 56 mm right from the standard index finger bump. The range and the step size of 14 mm were defined based on a pre-study conducted with four participants (three females, average age of 23.8 years) with the PHANToM 1.5 A haptic force feedback device at the Justus-Liebig University, Giessen. In the pre-study, single-finger JNDs for bump localizing with the index finger had reached an average of 32 mm. In the current experiment, stimuli were defined aiming to capture $+/-$ 1.75 JNDs for bump localizability. Due to workspace limitations, the absolute position of each standard-comparison pair was varied systematically such that bumps were never closer than 24 mm to the workspace limits. For this purpose index finger bumps of each standard-comparison pair were arranged symmetrically around a line slightly shifted to the right from the midline of the overall workspace (see Fig. 3c). Furthermore, the exploration of a stimulus could either start in the left or the right end of the track, as indicated by instructions on the participant's screen.

Overall the experiment included: 6 standards (2 [separation] $\times$ 2 [spring] $+$ 2 [single-finger]) $\times$ 2 [stimulus order] $\times$ 2 [starting point] $\times$ 9 [comparisons] $\times$ 6 [repetitions] $=$ 1296 trials. All two- and single-finger standards were presented in a random order within each repetition (groups of 216 trials).

2.5 Procedure

Participants were told that during their finger movements the device would exert lateral forces on each fingertip, which would give the impression that they were feeling bumps. They placed their right arm in the sling. Possible finger combinations were: index finger only, thumb only, and both fingers with a separation of either 30 or 60 mm (see Fig. 3a). The left slider could only be used by the thumb and the right slider by the index finger. For the two-finger conditions, both sliders were occupied. For the single-finger stimuli, participants were instructed to keep the hand posture the same as that for the two-finger stimuli but without touching the un-used slider.

The time sequence of a trial is plotted in Fig. 3b. Each trial started with the visual representation of the location of the slider(s) to use as well as the target position(s) for the appropriate slider(s). To start a stimulus presentation in the two-finger conditions, the participant had to achieve the correct finger separation, starting side of the workspace and normal force levels. The stimulus was not rendered until all criteria were met. Participants were instructed to make three unidirectional movements for each stimulus (forth - back - forth). In the two-finger condition, participants moved both sliders at the same time. They moved with an instructed velocity of 14 cm/sec, enforced by a metronome, and a normal force of 0.5 N. With the exception of initial training, no visual feedback was given during stimulus exploration. Afterwards, the presentation of the second stimulus of the trial followed in the same manner. At the end of each trial, the participant used a touch screen to respond. In the single-finger conditions, participants compared the location of standard bumps presented to either just the thumb or just the index finger to comparison bumps presented to just the index finger and reported which bump (first stimulus or second) was further to the left. For the two-finger conditions, they compared the location of standard bumps presented to both the thumb and the index finger to comparison bumps presented to just the index finger; in this case they reported which bump stimulus presented to the index finger was more to the left. Feedback was offered reminding the participant to attend to velocity, force or separation after the trial if movement errors were recorded. Movement errors were defined by a deviation of more than 50 percent from target force or velocity, or more than 20 percent from target separation. These values were averaged over the three movements during a stimulus exploration. Trials with movement errors were not repeated in the main experiment (20 percent). All trials entered in the data analyses.

The entire experiment was divided into three sessions (432 trials each). Each session lasted about 2–2.5 hours. The first session additionally contained a two-step training period. During the training no lateral forces were rendered by the sliders. Consequently, no location judgments were necessary. Each segment of the training comprised 40 trials with one stimulus presented per trial. Trials including movement errors were repeated. Thus, the duration depended on movement performance, but on average the two training segments lasted between 15 and 25 minutes altogether. In the first segment, accurate finger separation and velocity were trained. The second segment trained participants to additionally maintain the constant 0.5 N normal force. In each session, breaks were imposed after each 40 minutes of experiment time. After finishing the experiment participants were additionally asked how many bumps they perceived during explorations with both fingers; they generally reported experiencing a single bump.

2.6 Data Analysis

We calculated the proportion of trials in which the participant perceived the standard to be more to the left than the comparison. This was plotted as a function of the relative shift of the comparison bump from the standard bump. Then cumulative Gaussian functions were fit to the individual psychometric functions for each standard (see Fig. 4 for example data). For this purpose the psignifit toolbox for MATLAB that implements maximum-likelihood estimation procedures [27] was used. PSEs were estimated by the Gaussian parameter μ and JNDs by σ (84 percent discrimination thresholds). In Fig. 4 the PSE is marked as the shift (comparison relative to the standard) corresponding to a 50 percent proportion of reporting the standard to the left. The JND is shown as the difference between the shifts associated with 50 percent and 84 percent proportions. Each JND is assumed to be composed of the sum of the σ for standard and the σ for comparison stimulus. One participant was excluded from data analysis because of JNDs above values that we were able to measure precisely with the present design (>100 mm). JNDs measured in the single finger conditions were used for model predictions of the two-finger

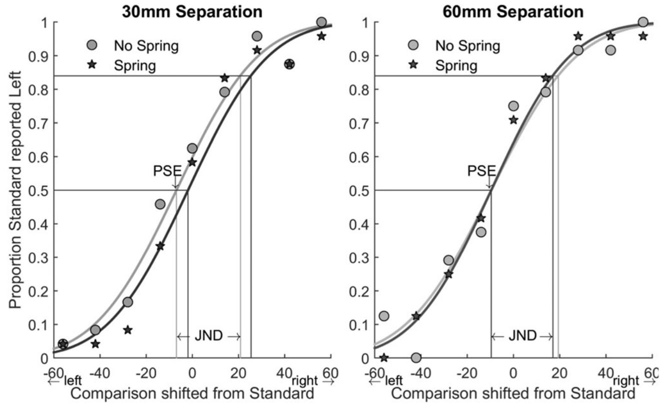

Fig. 4. Psychometric functions of participant 4 for all four two-finger conditions.

JNDs. We compared JNDs for the two-finger conditions to predictions of the three models (for details see Appendix).

In the case of optimal integration (MLE) predictions of JNDs (J_{it_mle}) can be calculated from measured JNDs (index finger: J_i & thumb: J_t) in the single-finger conditions under certain assumptions:

$$J_{it\_mle} = \sqrt{J_i^2 - \frac{J_i^4}{4J_t^2}}. \quad (2)$$

Suboptimal integration uses the empirical weight of the thumb (w_{t_emp}), for the weighted averaging of individual estimates. Empirical weights were defined as the ratio between the PSE and the finger separation. JNDs (J_{it_si}) are predicted as follows:

$$J_{it\_si} = \sqrt{w_{t\_emp}^2 * \left(J_t^2 - \frac{J_i^2}{2}\right) + \left(1 - w_{t\_emp}\right)^2 * \frac{J_i^2}{2} + \frac{J_i^2}{2}}. \quad (3)$$

In the case of cue switching, thus no integration, empirical weights estimated the probability that each of the finger locations determines perceived bump location (see [15], [17] for details). JNDs (J_{it_cs}) are further influenced by the finger separation (S):

$$J_{it\_cs} = \sqrt{w_{t\_emp}\left(\mathrm{S}^2 + (\mathrm{J_t^2} - \frac{\mathrm{J_i^2}}{2})\right) + (1 - w_{t\_emp})\left(\frac{\mathrm{J_i^2}}{2}\right) + (w_{t\_emp}\mathrm{S})^2 + \frac{\mathrm{J_i^2}}{2}}. \quad (4)$$

3 Results

3.1 Manipulation Check: Two-Finger

In the two finger conditions, virtual bumps presented to the thumb and index finger differed in their position on the track. Bumps were perfectly temporally synchronized if participants maintained initial finger separation during the hand movements. The actual synchronization of bumps was measured as variability of the time delay in crossing the bump center between both tracks. As should be the case, the mean of the delay did not differ significantly from zero for the spring ($\mathrm{M} = -0.656$ msec, $t(7) = -0.587, p = 0.576$) or for the no spring condition ($\mathrm{M} = 1.573$ msec, $t(7) = 0.893, p = 0.401$), but the standard deviation of the delay within the three strokes of a trial was significantly higher in

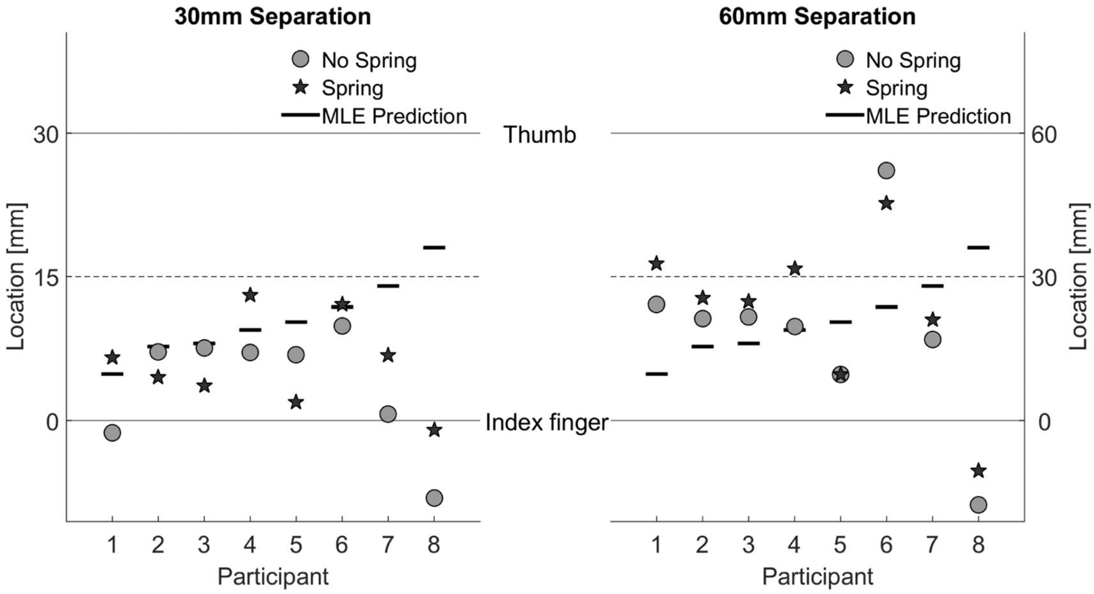

Fig. 5. Individual PSEs for all four two-finger conditions. Black lines represent MLE prediction for each participant.

the no spring condition (STD = 28.082 msec versus STD = 16.452 msec, $t(6) = -4.610, p = 0.004$), suggesting synchronization was more consistently produced in the spring condition, as desired.

3.2 Perceived Bump Location (PSE): Two-Finger

PSEs were of interest only for the two-finger conditions, as they are used to estimate weights. As measured by the PSE, most of the bumps were perceived at a location between thumb and index finger (see Fig. 5). For the 30 mm separation in all cases, and for the 60 mm separation in the majority of the cases, bumps were perceived to be closer to the index finger than to the thumb. Within each condition the perceived bump location was used to calculate the weight of the thumb. A weight of zero means that the thumb did not contribute to the judgment. In Fig. 6 average weights of the thumb are plotted with 97.5 percent confidence intervals. One sided t-tests against zero for the weight of the thumb were calculated separately for all four two-finger conditions. In three of four conditions the thumb was weighted significantly above zero ($p < 0.05$), as can also be seen from the confidence intervals not crossing the zero line in Fig. 6. Only in the 30 mm separation, no spring condition, did the average weight fail to reach significance, but the trend is similar ($p = 0.06$). Thus, the perceived bump location depended, as expected, on both index finger and thumb position. Further, empirical weights were compared to theoretical weights predicted by MLE (see Fig. 5). In paired t-tests empirical weights did not differ significantly from MLE predictions in all of the conditions ($p > 0.05$). The individual empirical weights were also submitted to an ANOVA with the within-participant variables Spring and Separation. The thumb location was on average weighted higher in the spring conditions than in the no spring conditions. This effect did not reach statistical significance, $F(1,7) = 2.771, p = 0.070$, but can be considered as a trend. Additionally, weighting of the thumb was significantly higher for the 60 mm separation than for the 30 mm separation ($F(1,7) = 8.347, p = 0.023$). There was no interaction between the Spring and Separation factors ($F(1,7) = 0.012, p = 0.916$).

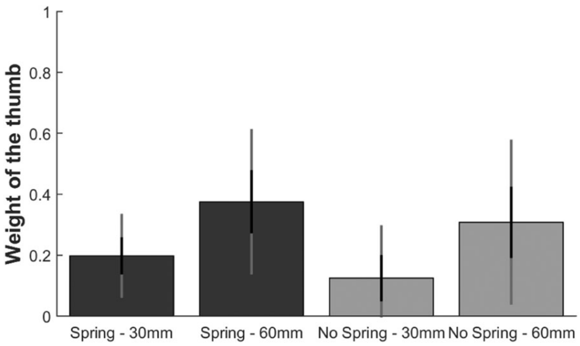

Fig. 6. Mean values, standard errors (black), and 97.5 percent confidence intervals (gray) of the weight of the thumb for all four two-finger conditions.

3.3 Discrimination Performance (JND)

In the single-finger conditions, participants compared the location of bumps presented to the thumb or index finger to bumps presented to the index finger (thumb/index or index/index, respectively). JNDs were $M = 31.084\,mm$ ($SEM = 2.822\,mm$) for index/index and $M = 39.192\,mm$ ($SEM = 4.550\,mm$) for thumb/index. This difference was significant in a t-test for paired samples ($t(7) = 2.691$, $p = 0.031$). Thus, the index finger gave a more reliable estimate for the bump location than did the thumb.

In the two-finger conditions the JNDs were affected by variables assumed to represent the Gestalt principles of proximity and synchrony (see Fig. 7). Individual JNDs were entered into an ANOVA with the within-participant variables Spring (spring versus no spring) and Separation (30 versus 60 mm).

JNDs were significantly lower in the spring conditions than in the no spring conditions ($F(1,7) = 5.950, p = 0.023$), as predicted by the principle of synchrony. There was no main effect of Separation ($F(1,7) = 0.782, p = 0.203$).

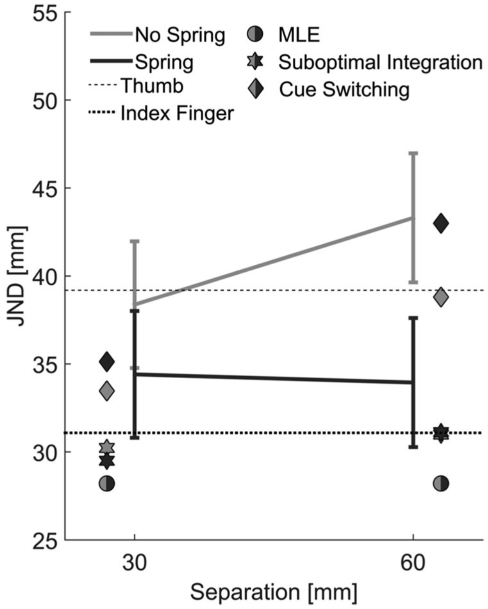

Fig. 7. Observed JNDs (means and standard errors) plotted next to the predictions from MLE, suboptimal integration, and cue switching model.

However, the interaction of Separation and Spring was significant ($F(1,7) = 4.362, p = 0.038$). As expected, separation had a greater effect in the no spring than in the spring conditions. Additionally, we computed one sided post-hoc paired sampled t-tests with a Bonferroni correction of the significance level. As expected, a significant decrease in JNDs was found between the No Spring 60 and the Spring 60 condition ($t(7) = 2.830, p = 0.013$). The JNDs in the Spring 30 condition were not significantly lower than in the No Spring 30 condition ($t(7) = 1.464, p = 0.093$). The numerically lowest and not significant difference was between the Spring 30 and Spring 60 conditions ($t(7) = 0.188, p = 0.428$). The JND was not significantly lower in the No Spring 30 than in the No Spring 60 condition ($t(7) = 1.557, p = 0.081$). Thus, the predicted effect of synchrony was confirmed by the JNDs, as was the prediction for proximity within the constraint of an interaction.

In a further analysis, observed JNDs for two-finger conditions were compared with predictions from the MLE model of optimal integration, the suboptimal integration model, and the cue switching model. In Fig. 7 the predictions of all three models are plotted next to the observed values.

MLE predictions for the two-finger conditions are based on single-finger JNDs. As a result, they were identical for all four conditions, whereas suboptimal integration and cue switching predicted different JNDs for each two-finger condition (see Fig. 7). Paired t-tests were calculated comparing observed JNDs and predictions for each model. The MLE model underestimated the JNDs in each condition ($p \leq 0.037$). Suboptimal integration predicted lower values than observed for no spring conditions ($p \leq 0.035$), but for the spring conditions predicted and observed values did not significantly differ ($p \geq 0.141$). The predictions of the cue switching model were within statistically acceptable range for all but the spring condition with 60 mm separation ($t(7) = -2.490, p = 0.042$). We will defer evaluation of the models in the context of these results to the discussion.

4 Discussion

This study aimed to address the question of whether grouping principles known from Gestalt psychology promote haptic integration of information acquired with multiple fingers. During lateral arm movements, virtual bumps were presented simultaneously to the thumb and index finger of the right hand. Although the experimenter asked participants for the location of the index finger bump, they reported a bump located between index finger and thumb. When the movements of thumb and index finger were linked through a virtual spring, thus supporting the Gestalt principle of synchrony, localization of the bump was more reliable, indicating better integration of finger cues. Additionally, proximity between the cues, which was manipulated by the separation between the two fingers, interacted with temporal synchrony. Specifically, the influence of proximity was limited to trials in which synchrony was not enforced through a virtual spring. Once synchrony was enforced cues were integrated regardless of their proximity. This indicates a predominance of one Gestalt principle over another, which also has been reported previously [5]. Taken together, the results of this study show that the integration of haptic information from multiple fingers follows Gestalt principles.

Are the sensory cues from multiple fingers combined? Initially we presented three models to account for Gestalt effects: optimal integration (MLE), suboptimal integration, and cue switching (no integration). The JNDs are the means of evaluating the models. Thus far we have described the fit of means for individual conditions to the model. The pattern of means across conditions, however, is far more revealing about the relative goodness of fit. Note first that the MLE cannot fare well as a model for all the conditions of the experiment, because it predicts no effect of the variables used to instantiate the Gestalt principles. Moreover, none of the conditions produce a JND mean as low as the model demands from the single-finger data. Relaxing the integration requirement to the level of the suboptimal model predicts effects of separation and synchrony that are weaker than those observed. However, this model predicts the spring conditions fairly well. The cue-switching model, on the other hand, is the only one to successfully predict mean values in the case in which the principles are not adhered to, i.e., with no spring and 60 mm separation. It fails entirely however, to predict the elimination of proximity effects when the spring is present. One must conclude that different models account for different conditions: some level of integration when Gestalt principles, particularly synchrony, are present, and failure to integrate (cue switching) when they are absent.

Note also that the MLE underestimates the JND even in the best-case use of the Gestalt principles here. In the literature, failures of the MLE in the form of under-prediction of mean JNDs have been attributed to correlated errors in the integrated estimates [28]. However, correlated errors cannot explain our pattern of deviation from MLE predictions. If you consider correlated errors to be more probable in the spring conditions due to their higher finger interdependence, deviations from the MLE should be higher in this condition as compared to in the no spring conditions. The results indicate the opposite pattern.

How do Gestalt principles link to integration? Our data show that with higher adherence to the principle of synchrony and the principle of proximity, discrimination JNDs for the reported bump location decrease. Because MLE predictions represent the lowest JNDs and cue switching the highest, we can conclude a shift toward integration as grouping is supported. As we expected, the adherence to Gestalt principles determines whether integration will take place or not. In the literature, the observation that the brain integrates sensory cues under some circumstances and does not integrate them under other circumstances has been described in a Bayesian framework [29], which stipulates that whether integration takes place or not is determined by the probability of the causal inference of a common source. Based on past experience, people acquire priors specifying the probability that certain signals are generated by the same source. Körding et al. showed that those priors determine the mix between the integration and the no integration model for multisensory perception. As for virtual bumps on multiple fingers, Manuel et al. [30] used a paradigm similar to [13] to fit the probability of a unified percept. Here finger separation was varied while keeping the bump separation fixed, which results in a variation of the synchrony of force cues from both fingers. The probability of reporting one bump was measured. As with the multisensory research, the results were in good agreement with a Bayesian approach, with the additional assumption of coincidence avoidance. Thus, the brain seemed to use a prior of common source of multi-finger sensations while minimizing the probability of accidentally aligned signals between fingers.

Our current data shows that the adherence to Gestalt principles can promote integration. Based on the previous study and the results of the current study, we suggest that Gestalt principles function as priors in a Bayesian framework. Temporal and spatial coherence, as formalized in the principles of synchrony and proximity are able to promote integration, and therefore an assumption of a common source. However, with the reported interaction in mind, we further can speculate that the prior of temporal synchrony affected integration more strongly for this experiment. Further research should explicitly measure the probability of reporting one bump for variations in both Gestalt principles. This can then be used as priors for predicting the mix of optimal integration and cue switching for the prediction of the reported bump location.

What can we conclude about the operational level of Gestalt principles in haptic perception? In addition to demonstrating the influence of both principles in question, proximity and synchrony, we can also draw conclusions about the perceptual level of these Gestalt principles. In vision, Gestalt principles were first reported being associated with intermediate computational levels (e.g., figure/ground) and later found to occur at multiple levels of visual processing from sensory to object and space based [2]. In touch, the issue of computational level has sometimes been addressed by comparing single- and two-handed contact, with the idea that the latter must occur after primary somatosensory processing. Another issue is whether computation is done relative to the body or to the external world. For example, Yamamoto and colleagues [31], [32], [33] suggested a transition between early body-based processing, where the relative positions of the hands affected performance, to exocentric spatial coordinates, where posture was unimportant.

In the current study, the proximity conditions differed in postural (within-hand) distance, and hence in exocentric coordinates, while the local somatosensory representation at the fingers was invariant. The effect of finger separation indicates that the Gestalt principle of proximity, as instantiated here, does not reflect local skin interaction, but must have been caused by variations in finger posture. The fact that the PSE localized the percept in the spatial location between the fingers, regardless of their separation, means that the virtual bump created by synchrony moved further from each finger with respect to world coordinates, as proximity decreased. The JNDs indicate that this jump in world coordinates was accompanied by greater uncertainty.

This result fits still other observations about haptic grouping. Eimer et al. [34], for instance, demonstrated that the cutaneous rabbit illusion could be produced when the proximity of the stimuli was measured in terms of spatial instead of somatotopic distance. In that study, three taps were presented successively to three possible forearm locations. When both arms were stimulated and were spatially close to each other, participants reported that stimuli jumped between their arms. The authors demonstrated, similarly to the current results, that grouping in the cutaneous rabbit illusion operated on an external spatial rather than a somatosensory coordinate system.

5 Conclusion

This study asked the fundamental question of whether Gestalt principles operate when haptic sensations are combined across multiple fingers. The two principles of interest were proximity and synchrony. These were tested by having participants experience virtual bumps occurring at the index finger and thumb. The predominant outcome was perception of a bump located between the fingers, indicating integration across the fingers, a form of grouping. By using the reliability of localization to measure integration quality, and hence grouping effectiveness, we established that the principle of synchrony does apply to haptic cues across the hand. The emergent bump was localized more reliably, indicating stronger integration, when the movements of thumb and index finger were linked through a virtual spring, enforcing synchrony. Proximity, which was manipulated by the separation between the two fingers, influenced integration only when synchrony was not enforced, suggesting that its operation in the haptic inter-finger context is secondary to that of synchrony. Finally, comparative modeling of these effects suggest that true integration is enabled by synchrony and proximity. Without the support of these principles, cues from individual fingers may be treated independently; when the principles operate, discrimination performance approaches predictions of optimal integration models.

Part of our interest in this phenomenon stems from recent advances in surface haptic devices capable of providing force feedback to individual fingertips [35], [36], [37]. A long-term goal for some of these technologies is implementation in touch screens capable of applying forces (direction and magnitude) independently to each of multiple fingertips.

As we study multi-finger surface haptic illusions, we continue to discover emergent illusions that cannot be experienced using a single finger. We have already shown that two points of contact on opposing surfaces can actually mitigate a single-finger illusory percept [25]. We have also demonstrated that the forces on individual fingers can be coordinated such that novel percepts may emerge [35]. The most basic form of emergence may well be grouping, in which case, rather than experiencing objectively distinct percepts at each fingertip, the participant experiences only one objective percept.

Adherence of this multi-finger effect to Gestalt principles gives us an indication of how we might predict and possibly control the way a user perceives spatially combined contours. One might imagine, for instance, using proximity and synchrony as surface haptic design guidelines in much the same way they are used in visual media. For instance, virtual features that are intended to be grouped might be located closer together and rendered such that both are encountered as simultaneously as possible. Furthermore, while there are likely other factors that determine the perceived location of collapsed features, finding that localization follows predictions of integration models tells us that the relative reliability between the two fingers' feature position estimates must certainly be considered in design.

APPENDIX

Given measurements from the experimental design (perceptual variance: σ_i^2 and σ_t^2; under the assumption of independent percepts of comparison and standard):

$$84\% - \text{threshold for index finger}(J_i): \quad J_i^2 = \sigma_i^2 + \sigma_i^2 \rightarrow \sigma_i^2 = \frac{1}{2}J_i^2. \quad (1)$$

$$84\% - \text{threshold for thumb}(J_t): \quad J_t^2 = \sigma_t^2 + \sigma_i^2 \rightarrow \sigma_t^2 = J_t^2 - \frac{1}{2}J_i^2. \quad (2)$$

$$84\% - \text{threshold for two fingers}(J_{it}): \quad J_{it}^2 = \sigma_{it}^2 + \sigma_i^2 \rightarrow \sigma_{it}^2 = J_{it}^2 - \frac{1}{2}J_i^2. \quad (3)$$

Location of the thumb: $\mu_t = -S$ [Separation]
Location of the index finger: $\mu_i = 0$
Empirical weight: $w_{t\_emp} = \frac{PSE}{(\mu_t - \mu_i)}$

MLE predictions [see 14]:
Location of the fused bump:

$$\mu_{it\_si} = w_{t\_mle} * \mu_t + (1 - w_{t\_mle})\mu_i$$

$$w_{t\_mle} = \frac{\sigma_t^2}{\sigma_t^2 + \sigma_i^2}$$

Variance of the location estimate of the fused bump under the assumption of independent noises:

$$\sigma_{it\_mle}^2 = \frac{\sigma_t^2 * \sigma_i^2}{\sigma_t^2 + \sigma_i^2}.$$

Substitution with (1), (2) and (3):

$$J_{it\_mle} = \sqrt{J_i^2 - \frac{J_i^4}{4J_t^2}}.$$

$$w_{t\_mle} = \frac{1}{2}\frac{J_i^2}{J_t^2}.$$

Suboptimal integration assumptions [see 17]:
Location of the fused bump :

$$\mu_{it\_si} = w_{t\_emp} * \mu_t + \left(1 - w_{t\_emp}\right)\mu_i.$$

Variance of the location estimate of the fused bump under the assumption of independent noises:

$$\sigma_{it\_si}^2 = w_{t\_emp}^2 * \sigma_t^2 + \left(1 - w_{t\_emp}\right)^2 \sigma_i^2.$$

Substitution with (1), (2) and (3):

$$J_{it\_si} = \sqrt{w_{t\_emp}^2 * \left(J_t^2 - \frac{J_i^2}{2}\right) + \left(1 - w_{t\_emp}\right)^2 * \frac{J_i^2}{2} + \frac{J_i^2}{2}}.$$

Cue Switching assumptions [see 15, 16]:
Probability of reporting the thumb location: $p_t = w_{t\_emp}$.
Probability of reporting the index finger location: $p_i = w_i = (1 - w_{t\_emp})$.
Variance of the location estimate:

$$\sigma_{it\_cs}^2 = p_t\left(\mu_t^2 + \sigma_t^2\right) + p_i\left(\mu_i^2 + \sigma_i^2\right) - \left(p_t\mu_t + p_i\mu_i\right)^2.$$

Substitution with (1), (2) and (3):

$$J_{it\_cs} = \sqrt{w_{t\_emp}\left(S^2 + (J_t^2 - \frac{J_i^2}{2})\right) + (1 - w_{t\_emp})\left(\frac{J_i^2}{2}\right) + (w_{t\_emp}S)^2 + \frac{J_i^2}{2}}.$$

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Alexandra Lezkan studied psychology and received the master's of science degree in 2013. She is currently working toward the PhD degree in the Department of Experimental and Perceptual Psychology, Justus Liebig University, Giessen, Germany. Her research interests include sensory integration and active movement control in the process of haptic exploration.

Steven G. Manuel received the PhD degree from Northwestern University in 2014 and is currently a research engineer at Samsung Research America.

J. Edward Colgate received the PhD degree from MIT, Cambridge, MA, USA, in 1988. He is the Breed University professor of design at Northwestern University in Evanston, IL, USA. He was the founding editor-in-chief of the *IEEE Transactions on Haptics*. His research interests include human–machine interaction, especially haptic interface. He is a fellow of the IEEE.

Roberta L. Klatzky received the PhD degree in cognitive psychology from Stanford University, Stanford, CA, USA. She is currently the Charles J. Queenan, Jr. professor of psychology and human–computer interaction at Carnegie Mellon University, Pittsburgh, PA, USA. Her research interests include human perception and cognition, with special emphasis on spatial cognition and haptic perception. She has done extensive research on human haptic and visual object recognition, navigation under visual and nonvisual guidance, and perceptually guided action, with application to navigation aids for the blind, haptic interfaces, exploratory robotics, image-guided surgery, and virtual environments. She is a senior member of the IEEE.

Michael A. Peshkin received the PhD degree from Carnegie Mellon University, Pittsburgh, PA, USA, in 1987. He is the Bette and Neison Harris Professor in Teaching Excellence at Northwestern University. He is a founder of four companies, most recently Tanvas. His research interests include haptics, robotics, and sensors. He is a member of the IEEE.

Knut Drewing received the PhD degree in psychology from LMU, Munich, Germany, in 2001, and the postdoctoral lecture qualification (habilitation) in psychology in 2010 from JLU Giessen. He worked in the MPIs for Psychological Research (Munich) and for Biological Cybernetics (Tuebingen). He is currently a senior scientist and private lecturer of experimental and perceptual psychology in the Department of Psychology, JLU Giessen. His research interests include haptic perception and multisensory integration.