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Multimodal Ternus: Visual, tactile, and visuo – tactile grouping in apparent motion

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Abstract. Gestalt rules that describe how visual stimuli are grouped also apply to sounds, but it is unknown if the Gestalt rules also apply to tactile or uniquely multimodal stimuli. To investigate these rules, we used lights, touches, and a combination of lights and touches, arranged in a classic Ternus configuration. Three stimuli (A, B, C) were arranged in a row across three fingers. A and B were presented for 50 ms and, after a delay, B and C were presented for 50 ms. Subjects were asked whether they perceived AB moving to BC (group motion) or A moving to C (element motion). For all three types of stimuli, at short delays, A to C dominated, while at longer delays AB to BC dominated. The critical delay, where perception changed from group to element motion, was significantly different for the visual Ternus (3 lights, 162 ms) and the tactile Ternus (3 touches, 195 ms). The critical delay for the multimodal Ternus (3 light – touch pairs, 161 ms) was not different from the visual or tactile Ternus effects. In a second experiment, subjects were exposed to 2.5 min of visual group motion (stimulus onset asynchrony = 300 ms). The exposure caused a shift in the critical delay of the visual Ternus, a trend in the same direction for the multimodal Ternus, but no shift in the tactile Ternus. These results suggest separate but similar grouping rules for visual, tactile, and multimodal stimuli.

1 Introduction

Apparent motion requires a sequence of stimuli to be grouped into the percept of a single moving object. Wertheimer, the founder of modern Gestalt psychology, initially studied grouping principles for visual apparent motion (Wertheimer 1912/1961, 1923/1938), but grouping principles have also been observed in audition (Beauvois 1998; Bregman 1990). While apparent motion has been documented in touch (Geldard and Sherrick 1972; Kirman 1974a, 1974b), grouping principles—similar to those found in audition and vision—have not, to our knowledge, been specifically compared. We investigated the nature of perceptual grouping, both within and across modalities, using apparent motion in a competitive situation where different interpretations of the stimuli are possible.

Are Gestalt rules for motion processing similar across different modalities? Might they all be processed by a single multimodal motion mechanism? The Aristotelian notion of a *sensus communis*, a "common sensible of movement ... that [is] not special to any one sense, but [is] common to all", was rejected by Allen and Kolers (1981). A more cautious suggestion of 'overlap' between motion coding in different senses, however, receives support from several sources. There is substantial overlap in the brain areas involved in detecting motion in different modalities (Hagen et al 2002; Poirier et al 2005). Moreover, groupings of stimuli within one modality can influence the perceived organisation of another modality, suggesting a functional overlap (Craig 2006; Soto-Faraco et al 2004; Spence et al 2007). Harrar et al (submitted), for example, found support for functional overlap in the visual and tactile motion detecting mechanisms. While it is clear that there is some overlap in motion processing between the senses, the extent and significance of the overlap is largely unknown.

Many rules for perceptually tracking an object as it moves between positions have been identified as grouping principles; the object at one location needs to be perceptually related (grouped) with its existence in a previous location [see Ogmen et al (2006) for a description of how these apply to the visual Ternus illusion]. Shepard (2001) has shown that position and motion have universal grouping principles that cross auditory/visual modality boundaries. Intersensory interactions of Gestalten grouping principles have been shown (see Spence et al 2007 for a review) but there is only weak evidence for a genuinely crossmodal Gestalt—a separate mechanism, which may have similar organising principles to unimodal Gestalts, but that is only evoked for crossmodal stimuli.

In order to study Gestalt grouping in touch, and compare it to visual and multimodal grouping, we used the apparent-motion stimulus known as the 'Ternus effect' (Ternus 1926/1938). The Ternus effect is an apparent-motion stimulus comprised of two sequential frames, which has two distinctly different interpretations, depending on the temporal delay between the onset of the two frames (the stimulus onset asynchrony: SOA). When the component stimuli are presented with an intermediate SOA, perception alternates between the two interpretations, but the two are never perceived simultaneously (Petersik and Rice 2006). In the first frame, two stimuli are presented at locations A and B and then removed. Following some delay, the second frame is presented with stimuli at locations B and C (see figure 1). The stimulus at location B determines the overall percept (Braddick 1974). If this central stimulus is seen as moving (from B to C), the overall percept is of group motion in which group AB moves to location BC. If, however, the middle stimulus is seen as stationary at location B, then the percept is of a single element starting at A and jumping across B to position C. How the stimulus at B is interpreted, and which percept results, varies critically with the SOA.

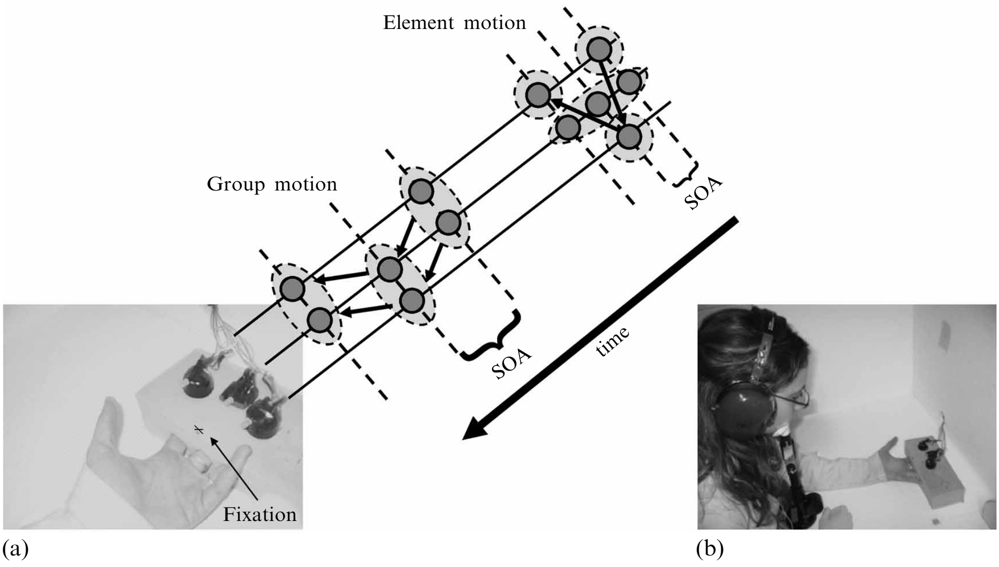

Figure 1. Stimuli used for investigating the Ternus effect. Three stimuli were placed on the index, middle, and ring fingers as shown in (a). Each stimulus consisted of a light (green LED) and a touch (a small solenoid that, when powered, pushed out a pin). Stimuli were activated in the sequence shown in (a). One pair was activated and then, after a gap (the SOA), a second pair. Two interpretations of these three stimuli were perceived: when the SOA was relatively small, element motion dominated, and when the SOA was longer, group motion dominated. The shading surrounding the stimuli shows which stimuli the subjects grouped in the two interpretations. In (b), the three stimulators are shown rigidly fixed in high-density foam into which subjects slid the first three fingers on their left hand. Subjects rested their head on a chin-rest, and wore earphones that played white noise to mask the sound of the solenoids. They fixated a small cross equidistant from all three stimulators.

Persistence is a potential problem in sensory systems (especially with respect to tracking moving stimuli) because it indicates that a stimulus is still present after it has terminated or moved on. The persistence of the middle stimulus might be one factor in determining the timing at which one interpretation turns into the other, because a longer persistence might encourage the interpretation of a stable item at B (Breitmeyer and Ritter 1986b). Breitmeyer and Ritter varied the interstimulus interval, duration, element size, contrast, and pattern of the stimuli, all of which altered the percept in a way that supported the persistence explanation for the Ternus effect (but see Kramer and Rudd 1999). In the present study, we compare the visual Ternus, the tactile Ternus, and the multimodal Ternus. Any variations we find between modalities might thus be correlated with variations in the persistence of the visual and tactile stimuli employed.

Because of the inherent differences in persistence of the visual and tactile systems, the stimulus will continue to be signaled by each system for a different period of time after the stimulus is removed. Which signal determines the multimodal Ternus effect? If the multimodal Ternus grouping can be predicted from a combination of the two unimodal organisations—not a separate suprasensory mechanism—then it should be describable by some mathematical combination. In an integration model, information from all modalities is combined into a multimodal signal which determines the percept by either overlapping with the signal from the second frame (element motion) or decaying before the next signal commences (group motion). All modalities contribute to the combined signal with various weighting being given to each. In a statistically optimal integration model (see Knill and Richards 1996 for an explanation of Bayesian Inference) the weighting is proportional to the reliability of each signal. We compared our multinomial data with that predicted by an integration model.

On the other hand, if there were a separate suprasensory motion mechanism, then the probability of perceiving the middle stimulus as stationary or moving (in a multimodal Ternus configuration) would not necessarily be predictable from the unimodal response functions.

Comparing the critical delay of the Ternus phenomenon for different stimuli allows us to compare Gestalt groupings in different senses and crossmodally. Does the touch system have similar Gestalt grouping patterns to vision that might guide motion perception? When visual and tactile stimuli are both used, in the multimodal condition, will the organisational structure of one sense influence or override the organisational structure of the other? Or might there be evidence for a genuine intersensory Gestalt that is separate and different from each of the unimodal organising structures? We, therefore, measured the Ternus effect at a range of different SOAs using visual and tactile stimuli, and a spatially coincident combination of visual and tactile stimuli to facilitate multimodal integration (Soto-Faraco et al 2002). In a second experiment we looked at the effect of repeated exposure on the three Ternus effects.

2 General methods

2.1 *Subjects*

There were ten volunteer subjects (one female, all right-handed) with a median age of 26 years. Some subjects were paid at York standard rates. All experiments were approved by the York Ethics board. The same subjects participated in experiments 1 and 2.

2.2 *Touch stimulation*

Touch stimulators were made from small solenoids. When the solenoid was powered, a central pin was pushed out. The pin extended about 1 mm from the edge of the cup, and hit the skin surface with a force of a light tap spread over a surface area of about 1 mm^2. Solenoids were controlled by appropriately amplified 5 V signals from a CED1401

(Cambridge Electronic Design, UK) interface box controlled by a PC. A carefully positioned photocell showed that there was a 5 ms delay to either fully extend or retract the pin in the solenoid. Subjects listened to white noise at a volume set by the subject so that they could not hear the solenoids. All touches were 50 ms in duration.

2.3 *Visual stimulation*
Visual stimulation was provided by green LEDs that were controlled directly by 5 V signals from a CED1401 interface box controlled by a PC. All visual stimuli were 50 ms in duration.

2.4 *Procedure*
Before the experiment, each subject was shown a demonstration of the traditional visual Ternus effect on a computer screen to demonstrate how, at short delays, element motion dominated, while at longer delays, group motion was perceived.

Three fingers on the left hand (index, middle, and ring) were slid palm-up through holes in high-density foam which also held three multimodal stimulators (see figure 1). Each stimulator contained a light and a tactile stimulation device controlled separately. Three types of Ternus displays were randomly presented to the subject: the traditional visual Ternus with the three lights, the tactile Ternus with three touches, or the multimodal Ternus with three light–touch combinations. The interval between the times when the first and second stimulus went on (AB), and when the second and third (BC) stimulus went on (SOA), was varied. For both experiments described in this paper, there were 9 different SOAs equally spaced between 80 and 320 ms, and each was presented 10 times in a random order. Since there were three types of Ternus effects, with 9 SOAs, each presented 10 times, subjects made a total of 270 responses, which took around 20 min to complete.

Each stimulus configuration (one of three Ternus types with one of 9 SOAs) was repeated three times before subjects could respond. Subjects rested their chin on a chin-rest and fixated a small black cross on the foam, 2 cm from each stimulus (see figure 1) throughout the experiment. After the third repetition of a stimulus, subjects responded in their own time to the type of motion they perceived, using foot pedals. Subjects lifted up their left foot to indicate element motion, and the right foot to indicate group motion.

2.5 *Data analysis*
The probability of perceiving group motion was plotted as a function of the SOA and a cumulative Gaussian $\left[f(x) = a/\{1+\exp[-(x-x_0)/S]\}\right]$ was fitted to the data, where a is the height of the cumulative Gaussian, x_0 is the peak of the Gaussian, or the inflection point of the cumulative Gaussian, and S is the standard deviation of the curve. The point at which subjects were equally likely to report either type of motion had a probability of 50% (x_0 in the above equation). This delay is also called the point of subjective equality (PSE) since it is the delay at which the Ternus effect is equally likely to be perceived as element or group motion. We call this particular delay the 'critical delay' since it is the delay at which the perception changes. The just noticeable difference (JND) is the delay required in order for subjects to reliably (84% of the time) perceive either element or group motion; the JND is one standard deviation (S).

3 Experiment 1
In this first experiment, we varied the SOA between frames in order to find the critical delay at which the perception changes from element motion to group motion for visual, tactile, and multimodal Ternus effects. The unimodal values were compared to assess the similarity between modalities when it comes to grouping patterns.

3.1 *Results*

Figure 2 shows the transition between the two interpretations of motion (element or group) as a function of the SOA between frames. In figures 2a, 2b, and 2c the transitions for the visual Ternus, the tactile Ternus, and the multimodal Ternus are shown for each individual subject and for the mean. Plotted through the mean data points are the best-fit cumulative Gaussians. In figure 2d the mean data for visual, tactile, and multimodal Ternus are compared. While the visual, tactile, and multimodal Ternus effects have similar response patterns, the PSE points revealed an important difference. A repeated-measures ANOVA found a significant main effect on the PSE of the stimulus type used ($F_{2,18} = 4.42$, $p = 0.05$) and no difference of the JNDs ($F_{2,18} = 2.892$, $p = 0.113$).

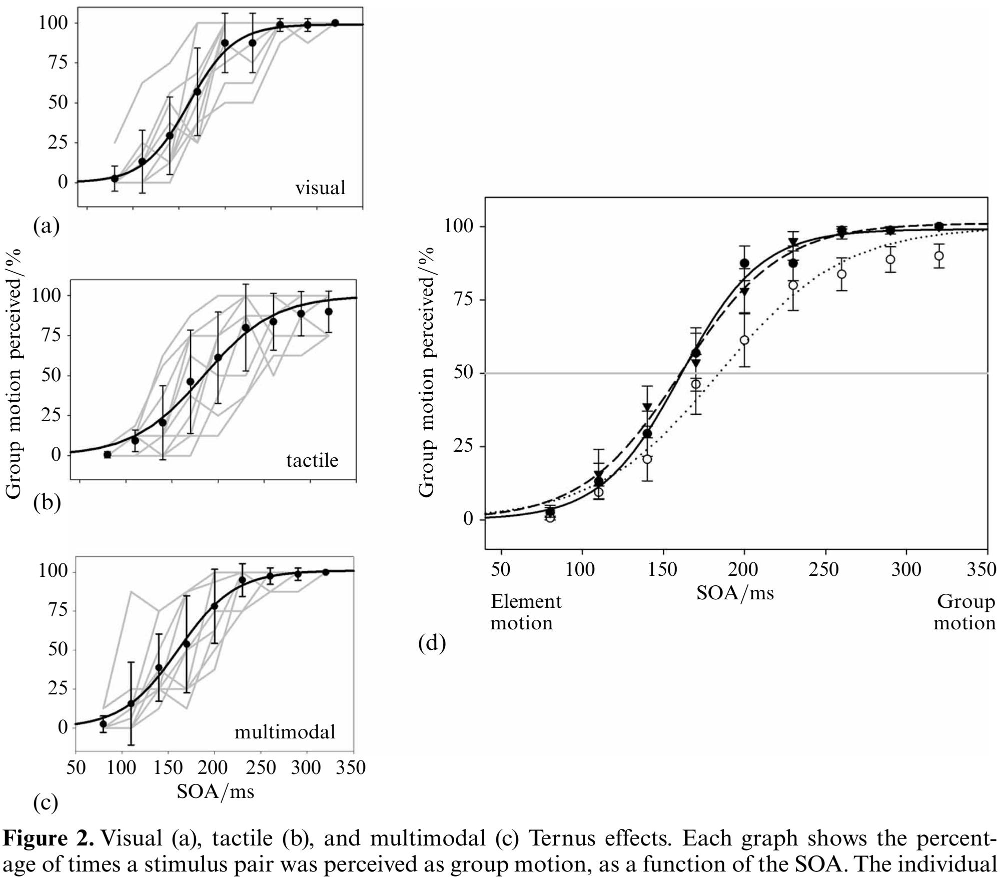

Figure 2. Visual (a), tactile (b), and multimodal (c) Ternus effects. Each graph shows the percentage of times a stimulus pair was perceived as group motion, as a function of the SOA. The individual subject's responses are plotted as grey lines and the average is shown as filled symbols with standard error bars. The best-fit cumulative Gaussians are plotted through the average data points (thick black lines). The lines in (d) are the average lines from the three graphs on the left (visual: solid black line, filled circles; tactile: dotted line, open circles; multimodal: dashed line, filled triangles). The SOA associated with a 50% group motion perception is the critical delay.

Pairwise comparisons revealed a significant difference between the critical delay of the tactile Ternus and the previously studied visual Ternus ($t_9 = -2.36$, $p = 0.042$). See table 1 for all PSEs and JNDs. The visual Ternus (figure 2a) had a mean PSE at a shorter SOA than the PSE of the tactile Ternus (figure 2b). The PSE of the multimodal Ternus (figure 2c) was not significantly different from the visual Ternus PSE ($t_9 = 0.17$, $p = 0.87$) or tactile Ternus PSE ($t_9 = 2.06$, $p = 0.07$).

Table 1. PSE and JND for pre- and post-exposure to visual group motion. The mean and standard error are presented ($n = 10$).

	Experiment 1 (pre-exposure)			Experiment 2 (post-exposure to visual group motion)		
	light	touch	multimodal	light	touch	multimodal
PSE	162.4 ± 9.1	195.1 ± 16.8	161.3 ± 10.7	195.7 ± 11.6	193.8 ± 13.7	181.5 ± 9.8
JND	20.8 ± 3.7	35.8 ± 9.5	20.1 ± 3.8	23.9 ± 4.2	46.8 ± 9.9	23.9 ± 3.9

3.2 *Discussion*

The three stimulus types we used all showed clear Ternus effects with short SOAs being associated with the percept of a single element jumping, and longer SOAs being associated with the percept of group motion. The critical delays occurred at different SOAs for the visual and tactile Ternus effects. If persistence contributes to the Ternus effect, then these variations in the critical delay between modalities might signal differences in persistence; the tactile Ternus can thus be used as an indirect measure of tactile persistence. The data obtained here suggest that touch might have a longer persistence than vision (critical delays of 195 ms versus 160 ms, respectively). However, persistence may not be the only factor in determining the shift from element motion to group motion in the Ternus effect (Petersik and Rice 2006). Breitmeyer and Ritter (1986a) suggest that the perception of a Ternus display is determined by static pattern integration, persistence, and the properties of motion-detecting mechanisms.

The critical delay of the multimodal Ternus was very similar to that of the visual Ternus. Does this mean that the multimodal Ternus effect is dominated by the visual Ternus? In order to try and tease apart the visual and multimodal effects, we shifted the critical delay of the visual Ternus and looked to see if the critical delay of the multimodal Ternus was similarly affected. A common shift would indicate a common mechanism.

4 Experiment 2

Petersik and Pantle (1979) showed that after repeated exposure to group motion visual Ternus, subjects became less likely to report group motion and more likely to perceive element motion; the visual-motion-detecting mechanism seems to change the Gestalt grouping criterion in just a few minutes. The question here is: does a change induced in the grouping of *visual* patterns also affect the grouping of *tactile* and *multimodal* patterns? If it does, then this would suggest a single motion-detecting mechanism for vision, touch, and multimodal motion stimuli. In order to test for common shifts, we tested the visual, tactile, and multimodal Ternus effects after exposure to visual group motion.

4.1 *Methods*

Subjects were initially presented with 2.5 min of visual group motion (SOA = 300 ms). Subjects then completed the same task as in experiment 1 (foot-pedal responses to indicate group or element motion perception in visual, tactile, and multimodal Ternus effects) with top-up exposure of 5 s after every 5 responses. The beginning and end of the top-up period was indicated by a beep. During the exposure, subjects were encouraged to concentrate on the perception of group motion, which helped maintain this perception since, after repeated exposure to a Ternus effect with any SOA, the perception becomes bistable (Kolers 1972). With the initial exposure periods and top-ups inserted into experiment 1, the 270 responses now took about 30 min. Half of the subjects performed experiment 2 before experiment 1; in this case, there was a 15 min minimum break before running experiment 1.

4.2 *Results*

Results are summarised in figure 3, which compares on the left, the before and after repeated exposure (experiment 1 and experiment 2, respectively) response curves as a function of SOA for the visual (figure 3a), tactile (figure 3b), and multimodal (figure 3c) Ternus effects. On the right, the mean critical delays (PSE) pre- and post-exposure are directly compared (figure 3d). A repeated-measures ANOVA of the PSEs showed no main effect of stimulus ($F_{2,18} = 0.079$, $p = 0.15$), and no main effect of exposure ($F_{1,9} = 3.29$, $p = 0.10$), but a significant interaction effect between stimulus and exposure ($F_{2,18} = 3.98$, $p = 0.037$). This interaction can be explained by looking at the effect of exposure on each Ternus separately.

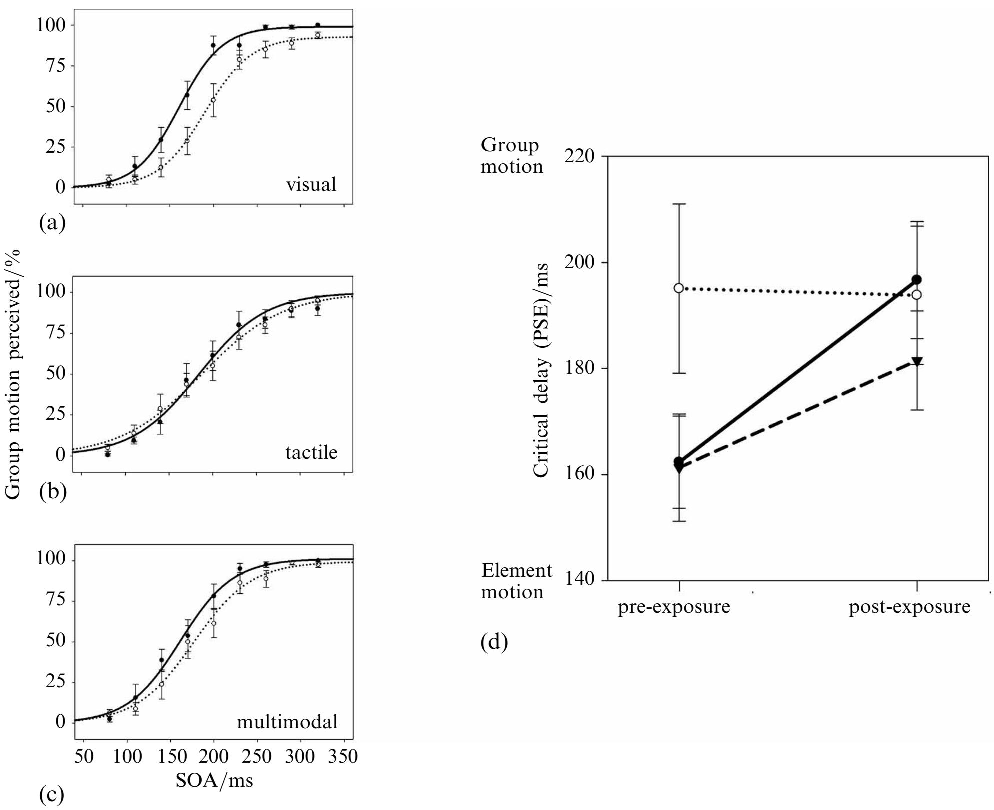

Figure 3. The effect of repeated exposure to visual group motion (SOA = 300 ms) on the Ternus effect. Graphs (a), (b), and (c) show the pre-exposure performance (filled circles, solid black lines) and post-exposure performance (open circles, dotted lines) (format as for figure 2); (d) compares critical delay for each effect, before and after exposure. The average PSEs [from (a), (b), and (c)] of ten subjects are plotted with error bars (visual: filled circles, solid black line; tactile: open circles, dotted line; multimodal: filled triangles, dashed line).

The visual PSE increased significantly (paired samples *t*-test, $t_9 = -4.060$, $p = 0.003$) but the PSE of the tactile Ternus did not change ($p = 0.93$) (see table 1 for raw numbers). There seems to be a trend for the multimodal Ternus shifting: the PSE increased in the same direction as the visual shift, but this was not a significant increase ($p = 0.112$). Following exposure, the PSE of the visual Ternus was comparable to the PSE of the tactile Ternus, and not significantly different from the PSE of the multimodal Ternus. A repeated-measures ANOVA of the JNDs revealed a significant main effect of stimulus ($F_{2,18} = 6.10$, $p = 0.03$) and a significant main effect of exposure ($F_{2,18} = 5.05$, $p = 0.05$)—see table 1 for values.

4.3 *Discussion*

Repeated exposure to visual group motion caused subjects to be more likely to see element motion in the visual Ternus, without changing the perception of the tactile or the multimodal Ternus. There was a trend for the multimodal Ternus to shift (in the same direction as the visual Ternus—consistent with Lyons et al 2006)—but this was insignificant. This lack of a common shift suggests that the touch, multimodal, and visual Gestalten grouping mechanisms may be distinct (see further discussion below).

5 General discussion

This paper represents the first systematic investigation of tactile grouping principles. The tactile grouping mechanism appears to be distinct from the well-known visual mechanism. However, they follow similar Gestalt grouping rules. When both tactile and visual stimuli were present, a multimodal Ternus effect was found. When the criterion for the visual grouping rules was adapted, the shift was not reflected in the grouping rules determining the perception in the tactile or multimodal Ternus effects.

5.1 *Shifting the critical delay*

In experiment 2, we were able to shift the critical delay of the visual Ternus by exposure to visual group motion. Petersik and Pantle (1979) found that repeated exposure to either element or group motion had an adaptation effect on the perception of the visual Ternus effect; after repeated exposure to one, the subject was less likely to report that particular type of motion. They used stimuli that varied in almost all respects from ours (duration 4 times longer than ours; lamp and tachistoscope presentation versus LED here; black dots on a white background versus our green LEDs; distance between the visual elements of 1 deg versus 0.5 deg here; stimuli 81 cm from observers versus 20 cm, etc) yet in both cases we found a desensitisation of group motion after repeated exposure to this type of motion. Petersik and Pantle (1979) suggested that the adaptation was evidence that the group motion process was weakened after repeated exposure to group motion, and, therefore, the element motion process became relatively stronger. This suggests, as they report, that there are at least two processes in constant competition with each other, and the perception indicates whichever is strongest at a particular time. However, opposite 'priming type' effects, in which subjects are more likely to report the type of motion to which they were exposed might also occur if the exposure to the motion type is very brief (Vroomen et al 2006). A priming effect of the visual Ternus, unlike the low-level modality-specific 'desensitisation effects' reported here, may cause common shifts in the visual, tactile, and multimodal Ternus effects, which would reveal a distinct high-level 'global priming effect'.

5.2 *An intersensory Gestalt?*

Comparisons of Gestalt grouping across modalities have mostly looked at the auditory and visual systems (for an exception see Sanabria et al 2005a, 2005b; Violentyev et al 2005). Spence et al 2007) suggest the possibility of a crossmodal Gestalt between the auditory and tactile senses. There are several models for how unimodal sensory phenomena are combined to produce multimodal percepts, for example when judging the shape of a seen and felt object (Ernst and Bülthoff 2004). Since the critical delays for the tactile, visual, and multimodal Ternus effects were different, we attempted to model the multimodal Ternus as an integration between the visual and tactile Ternus effects. We plotted the actual multimodal critical delay as a function of the model's predicted multimodal critical delay for each subject and fitted regressions to these plots.

We allowed the relative weight of the visual and tactile Ternus to be a free variable[(1)] $CD_{v,t} = CD_v$ (weight) $+ CD_t$ $(1 - \text{weight})$, where CD is the critical delay and subscripts v and t stand for visual and tactile. The weight with the highest correlation coefficient

[(1)] Following a suggestion of Salvador Soto-Faraco (personal communication, June 2006).

(the best at predicting the actual multimodal CD) was 1.0 (ie when tactile CD had no influence). This is not the statistically optimal integration weight[2]. Regressions of the multimodal Ternus PSE (data from pre- and post-exposure used) had a slope of 0.84, and a correlation coefficient (r^2) of 0.71.

The multimodal Ternus was not well predicted by a combination of the visual and the tactile Ternus effects when using any weight. The integration with the highest correlation coefficient of 0.7 (vision 100%) shows that 30% of the variability in the multimodal Ternus still cannot be accounted for. This suggests that the visuo – tactile stimuli presented simultaneously and spatially coincident (to encourage integration—Soto-Faraco et al 2002) may indeed activate a separate system: a Gestalt grouping mechanism that only operates with multimodal stimuli. This is further supported by the fact that the perception of the multimodal Ternus did not significantly shift following exposure to visual group motion which changed the perception of the visual Ternus.

6 Conclusions

The demonstration of a tactile Ternus effect shows that tactile stimuli, like visual stimuli, can be perceptually grouped in different ways. The presence of the two grouping interpretations in the tactile Ternus represents the first demonstration of explicit Gestalt grouping in the sense of touch.

Since the critical delay of the tactile Ternus is different from that of the visual Ternus, the Gestalt grouping principles in touch are revealed as similar, but not identical, to those found in vision. Repeated exposure to visual group motion caused a shift in the interpretation of visual groupings, but not of tactile groupings, further demonstrating their distinctness.

Finally, the multimodal Ternus showed no significant shift of its critical delay after repeated exposure to visual group motion, and 30% of the variance in the grouping of the multimodal Ternus could not be explained by visual responses or a visuo-tactile integration. These differences suggest a separate intersensory grouping mechanism for multimodal stimuli.

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[2] Optimal integration (Ernst and Banks 2002) was found to have an r^2 of 0.65. Also, a race model (Van Opstal and Munoz 2001) type integration was tested in which at any given SOA the multimodal curve follows the modality most likely to have reached the 'off' signal—resulting in the perception of group motion—with an r^2 of 0.67.

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