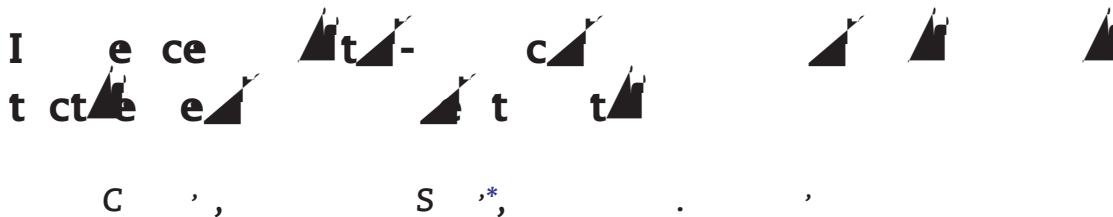


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RESEARCH****Research Report**<sup>a</sup>Department of Psychology and Key Laboratory of Machine Perception (Ministry of Education), Peking University, 100871, PR China<sup>b</sup>Department of Psychology, Ludwig-Maximilian-University Munich, Leopoldstr. 13, 80802, Munich, Germany<sup>c</sup>Department of Psychological Science, Birkbeck College (University of London), Malet Street, London WC1E 7HX, UK**ARTICLE INFO****Article history:**

Accepted 18 July 2010

Available online 24 July 2010

**Keywords:**

Intramodal

Crossmodal

Visual

Tactile

Apparent motion

**ABSTRACT**

Previous studies of dynamic crossmodal integration have revealed that the direction of apparent motion in a target modality can be influenced by a spatially incongruent motion stream in another, distractor modality. Yet, it remains to be examined whether non-motion intra- and crossmodal perceptual grouping can affect apparent motion in a given target modality. To address this question, we employed Ternus apparent-motion displays, which consist of three horizontal aligned visual (or tactile) stimuli that can alternately be seen as either ‘element motion’ or ‘group motion’. We manipulated intra- and crossmodal grouping by cueing the middle stimulus with different cue-target onset asynchronies (CTOAs). In unimodal conditions, we found Ternus apparent motion to be readily biased towards ‘element motion’ by precues with short or intermediate CTOAs in the visual modality and by precues with short CTOAs in the tactile modality. By contrast, crossmodal precues with short or intermediate CTOAs had no influence on Ternus apparent motion. However, crossmodal synchronous tactile cues led to dominant ‘group motion’ percepts. And for unimodal visual apparent motion, precues with long CTOAs shifted apparent motion towards ‘group motion’ in general. The results suggest that intra- and crossmodal interactions on visual and tactile apparent motion take place in different temporal ranges, but both are subject to attentional modulations at long CTOAs.

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**1. Introduction**

Investigating crossmodal interactions is essential for a comprehensive understanding of the perceptual system (Welch and Warren, 1986). A number of studies on crossmodal interaction have shown asymmetrical influences on the (perceived) direction of apparent motion between different modalities (Craig, 2006; Occelli et al., 2009; Sanabria et al., 2007a, 2004; Soto-Faraco et al., 2002; Strybel and Vatakis, 2004). In a typical paradigm for investigating crossmodal capture of

apparent motion (e.g., Soto-Faraco et al., 2002), a pair of stimuli in one modality is presented synchronously or asynchronously with another pair of collocated stimuli in a second modality; that is, one to give rise to an apparent-motion stream is induced in one modality and another in another modality, with either congruent or incongruent directions of motion. Observers are asked to judge the movement direction of the stimuli in the target modality, while ignoring the one in the distractor modality. Observers usually make highly accurate direction judgments with congruent motion directions, but

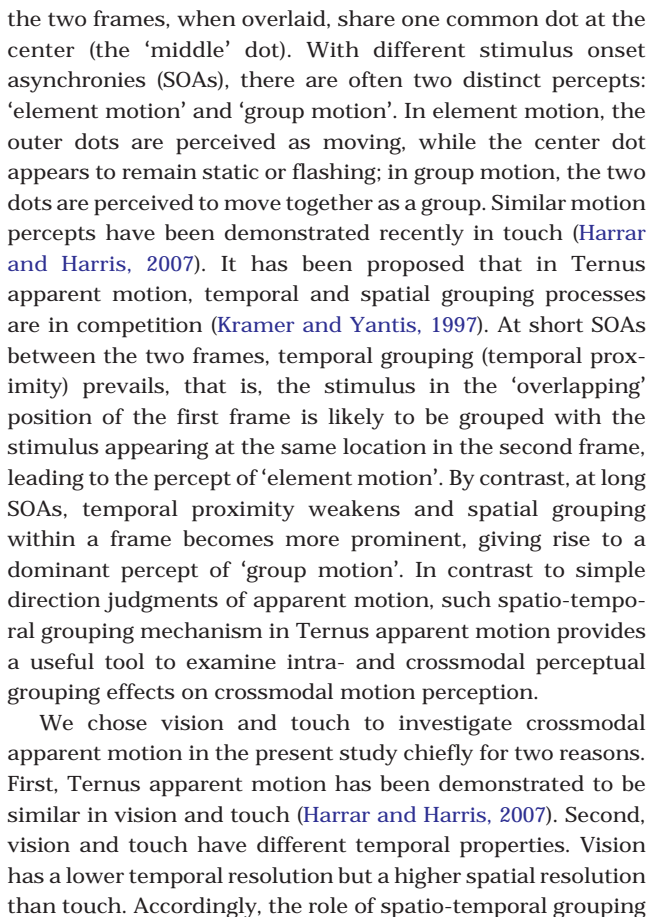
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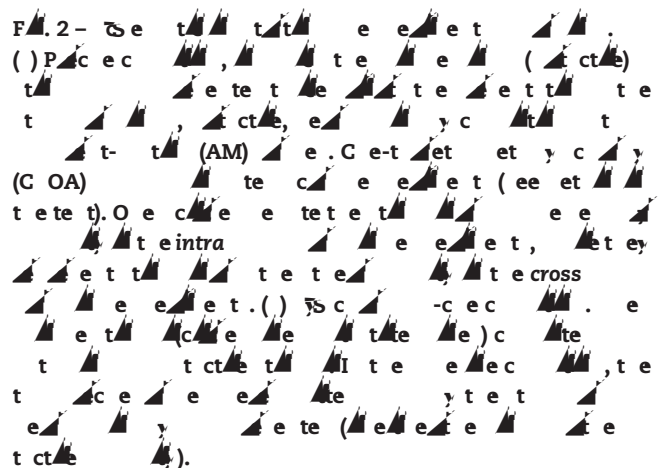
their performance is relatively poor with incongruent directions in the 'synchronous' condition. This phenomenon has been termed 'dynamic-capture effect' (Soto-Faraco et al., 2002, 2004a,b). However, if the distractor stimuli are presented asynchronously, the capture effects become weak or even disappear, owing to a reduced crossmodal interaction of two (temporally separated) motion streams (Soto-Faraco et al., 2004a,b). Performance in the incongruent condition also depends on which modality has been selected as (irrelevant) distractor modality. For example, direction judgments of auditory apparent motion have been shown to be reduced to chance level by incongruent visual apparent motion, while the direction of visual apparent motion is rather unaffected by incongruent auditory apparent motion (Sanabria et al., 2007a, 2004; Soto-Faraco et al., 2002). Besides audio-visual interactions, asymmetric dynamic-capture effects have also been observed between touch and vision, and touch and audition (Craig, 2006; Lyons et al., 2006; Occelli et al., 2009).

Recently, dynamic-capture effects have been found to be dependent on intramodal motion grouping (Sanabria et al., 2005, 2004; Lyons et al., 2006), stimulus intensity (Occelli et al., 2009), as well as attention (Oruc et al., 2008). For example, Sanabria et al. (2005, 2004)

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To induce non-motion perceptual grouping, we introduced rhythmic precues or synchronous cues from the stimulus in the middle position of the Ternus display (Fig. 2). Rhythmic cues extended the presentation rhythm of the (repeated) middle stimuli to prior to the onset of the Ternus apparent-motion display, which is analogous to the enhancement of apparent motion in the distractor modality by increasing the number of distractors prior to the onset of the target stimuli in previous studies (Sanabria et al., 2005, 2004). However, the major difference is that we only manipulated non-motion temporal grouping, instead of both spatial and temporal grouping. Synchronous cues, implemented by adding synchronous



stimuli in the irrelevant modality to the middle position, could enhance the multisensory salience of the middle stimuli, which is similar to the auditory intensity modulation in [Occelli et al.'s \(2009\)](#) study of audiotactile crossmodal dynamic capture. As shown in most crossmodal dynamic-capture studies, increasing the distractor and target asynchrony would eventually diminish the crossmodal interaction due to clearly separated motion streams ([Soto-Faraco et al., 2004a,b](#)). In order to systematically investigate the crossmodal interaction by temporal grouping and attention, we varied the onset asynchronies between the distractor stimuli and the target Ternus display (henceforth, we will refer to the distractor stimuli as '(pre-) cues' and the asynchrony as cue-target onset asynchrony, CTOA). If the crossmodal interaction operates (only) within a short temporal range, one would expect precues with long CTOAs not to influence the perception of apparent motion. However, crossmodal cueing has also been shown to enhance perceptual sensitivity ([Eimer et al., 2002](#); [Gray and Tan, 2002](#); [Kennett et al., 2001](#); [Macaluso et al., 2000](#)); thus, in the Ternus display, it may improve the detection of stimuli within one frame and enhance the spatial linkage (grouping) of these stimuli. On this logic, one would expect modulations of apparent motion induced by crossmodal precues even with long CTOAs. Furthermore, crossmodal temporal grouping may be weaker than intramodal temporal grouping ([Gilbert, 1938](#)) and it may operate via different mechanisms. Thus, in the present study, we also compared the effects of intra- with those of crossmodal temporal grouping.

Specifically, in Experiments 1 and 2, we manipulated intramodal temporal grouping of the middle stimuli within a given (either the visual or the tactile) modality by presenting the middle stimulus twice prior to the Ternus display. In Experiment 1, the SOA between the two precues as well as the CTOA were kept the same as the SOA between the Ternus frames to maintain the same presentation rhythm, so as to enhance the temporal grouping. Note that the CTOA (and thus the SOA between the two precues and that between the two Ternus display frames) varied randomly across trials. We refer to this as *rhythmic-cue condition*. The sequence of stimuli and their timing was essentially the same in Experiment 2, except that the CTOA between the second precue and the first Ternus frame was fixed and either short or long CTOAs (170 vs. 530 ms). Short and long CTOAs were compared in order to examine the dynamic change of the cueing effect. Experiments 3 and 4 were designed to examine the crossmodal effects of tactile precues and tactile synchronous cues on visual apparent motion. The presentation rhythm in Experiment 3 was the same as that as in Experiment 1, and fixed short and long CTOAs were compared in Experiment 4 (similar to Experiment 2). Experiments 5 and 6 were analogous to Experiments 3 and 4, however with the cue and target modalities switched.

([Treutwein and Strasburger, 1999](#)). [Fig. 3](#) illustrates typical results and psychometric estimates for one observer, namely, for the rhythmic-cue and baseline conditions in the visual Ternus apparent-motion task with intramodal cues (Experiment 1). Subsequently, for each observer, the SOA at which he/she was equally likely to report the two different motion percepts was calculated by estimating the point of subjective equality (PSE) from the psychometric curve. We refer to this point as the *transition threshold*. In addition, the just noticeable difference (JND) between the two motion percepts was obtained from the psychometric curve by estimating the SOA difference between 50% and 75% of 'group motion' responses. The mean PSEs and JNDs (as well as their associated standard errors) for all experiments are presented in [Table 1](#) as a function of the cueing condition.

## 2.1. 1 2.

Two experiments investigated apparent motion with the Ternus frames preceded by intramodal (pre-) cues. In Experiment 1, a rhythmic precue condition was compared with a baseline condition (without precue). In Experiment 2, two precue conditions with fixed CTOA were introduced along with a baseline condition. Since visual and tactile apparent motion were tested in separate sessions, below we report the analysis of variance (ANOVA) and paired t-test results separately for each modality and experiment.

### 2.1.1. V.2(the)-331-e14.653th

## 2. Re t

The percentages of 'group motion' responses were calculated for each condition individually for each observer; then the psychometric curves were fitted using a logistic function

Condition	Metric	JND, ms (AM = 100 ms)	Precue with fixed CTOA		Precue with fixed CTOA		
			Baseline	Rhythmic precue	Synchronous cue	Baseline	170 ms
Intramodal visual AM	PSE	163.6 ± 5.1	190.6 ± 7.6		157.0 ± 7.2	214.4 ± 6.9	170.2 ± 6.9
	JND	23.1 ± 1.8	32 ± 5.2		25.7 ± 2.7	45.9 ± 4.2	31.4 ± 3.4
Intramodal tactile AM	PSE	164.5 ± 10.5	154.5 ± 9.7		169.3 ± 9.7	227.3 ± 14.2	138.7 ± 5.9
	JND	28.9 ± 4.5	22.1 ± 3.6		27.7 ± 3.4	45.9 ± 6.9	23.4 ± 2.8
Tactile cue, visual AM	PSE	176.2 ± 8.5	166.9 ± 6.3	154.7 ± 7.8	163.8 ± 7.5	166.5 ± 7.8	152.5 ± 6.4
	JND	28.1 ± 3.5	19.2 ± 2.1	19.0 ± 1.9	27.9 ± 3.4	25.6 ± 2.2	20.7 ± 1.8
Visual cue, tactile AM	PSE	152.7 ± 6.1	150.5 ± 7.0	146.1 ± 5.2	154.4 ± 6.7	154.1 ± 6.9	144.7 ± 7.1
	JND	25.4 ± 2.2	23.2 ± 2.7	23.1 ± 2.3	23.3 ± 3.2	22.7 ± 2.4	19.2 ± 2.9

the effect of CTOA to be significant,  $F(2,24)=34.9$ ,  $p<0.001$ ,  $\eta^2=0.744$ . Bonferroni-corrected pairwise comparisons against the baseline showed the PSE to be significantly higher in the short-CTOA condition,  $p<0.001$ , and marginally higher in the long-CTOA condition,  $p=0.062$ . These results indicate that precueing (i.e., flashing) the middle LED prior to the Ternus display biased the visual apparent motion percept towards 'element motion' (Fig. 4a).

Further analyses showed that the JNDs were not different between the rhythmic precue and baseline conditions,  $t(12)=1.9$ ,  $p=0.08$ . However, presenting the precue with fixed CTOAs yielded a significant effect,  $F(2,24)=26.8$ ,  $p<0.001$ ,  $\eta^2=0.69$ : the JND in the short-CTOA condition compared to both the long CTOA and the baseline condition ( $p<0.01$ ), while there was no difference between the latter ( $p=0.154$ ). This means that a precue with fixed short CTOA (170 ms) decreased

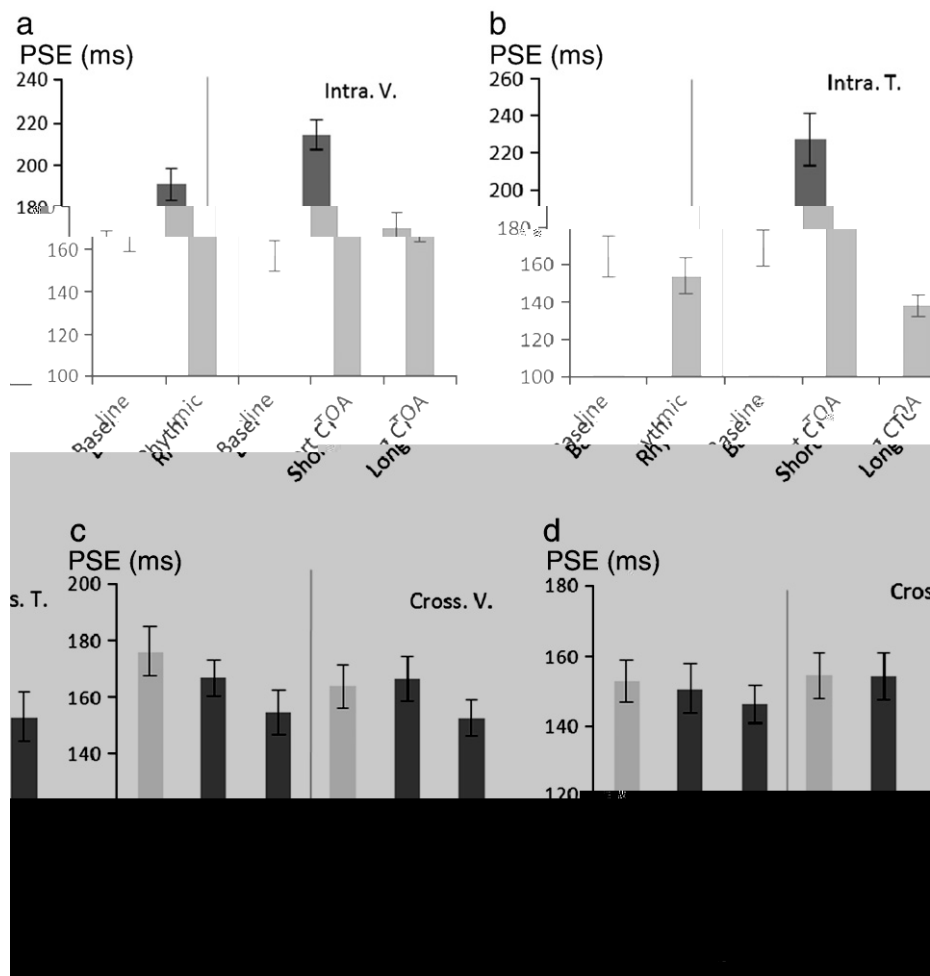


Fig. 4. PSE (ms) for different conditions and modalities. (a) Intramodal visual (Intra. V.), (b) Intramodal tactile (Intra. T.), (c) Cross-modal visual (Cross. V.), and (d) Cross-modal tactile (Cross. T.). Error bars represent standard error.



the sensitivity for distinguishing between the two visual motion percepts.

### 2.1.2. Tactile apparent motion

In contrast to visual apparent motion, for tactile apparent motion, there was no significant difference in the PSEs between the rhythmic precue and baseline conditions [paired *t*-test:  $t(12) = -0.68$ ,  $p = 0.51$ ]. However, in Experiment 2, the short and long CTOAs had a differential influence on tactile apparent motion [repeated-measures ANOVA:  $F(2,24) = 38.6$ ,  $p < 0.001$ ,  $\eta^2 = 0.76$ ]: the PSE was higher compared to the baseline with short CTOAs, and lower with long CTOAs (Bonferroni-corrected comparisons, all  $p$ 's  $< 0.01$ ). That is, with short CTOAs, the precue shifted tactile apparent motion towards 'element motion', and with long CTOAs towards 'group motion'; by contrast, the rhythmic precues (with SOAs ranging between 80 and 260 ms) fell in-between the short and long CTOAs, failing to show a CTOA influence (Fig. 4b).

Analyses on JNDs showed that the CTOA (configuration) between the precue and Ternus display influenced the JNDs greatly. Rhythmic cues reduced the JND relative to the baseline condition (indicative of an increase in sensitivity),  $t(12) = 2.78$ ,  $p < 0.05$ , while precues with short CTOAs induced a larger JND (decrease in sensitivity) compared to the baseline and precues with long CTOAs,  $F(2,24) = 13.5$ ,  $p < 0.001$ ,  $\eta^2 = 0.53$ , pairwise comparisons  $p$ 's  $< 0.01$ .

### 2.2. 3 4. ( - )

Experiment 3 was designed to examine the effects of rhythmic tactile precues and synchronous tactile cues on visual apparent motion. A repeated-measures ANOVA of the PSEs revealed a significant influence of the type of cue [ $F(2,24) = 5.78$ ,  $p < 0.001$ ,  $\eta^2 = 0.325$ ]. Bonferroni-corrected pairwise comparisons showed that the PSE was significantly lower in the synchronous cue relative to the baseline condition,  $p < 0.05$ , while there was no difference between rhythmic cues and the baseline,  $p = 0.132$ , or between rhythmic and synchronous (pre-) cues,  $p = 0.310$ . These results indicate that synchronously presented 'middle' taps bias the visual apparent-motion percept towards 'group motion'. With fixed CTOAs (Experiment 4), CTOA was also revealed to have a significant influence on the transition threshold for visual apparent motion [ $F(2,24) = 9.75$ ,  $p < 0.01$ ,  $\eta^2 = 0.448$ ]. The PSE was significantly lower in the long-CTOA (530 ms) condition relative to

both the baseline,  $p < 0.05$ , and the short-CTOA (170 ms) condition,  $p < 0.05$ ; there was no difference between the two latter conditions,  $p = 1.0$ . That is, with the long CTOA, the tactile precue biased the visual apparent-motion percept towards 'group motion' (Fig. 4c).

The analyses of the JNDs showed that both rhythmic and synchronous tactile (pre-) cues enhanced the sensitivity for visual apparent motion [Experiment 3, repeated-measures ANOVA:  $F(2,24) = 9.4$ ,  $p < 0.01$ ,  $\eta^2 = 0.439$ ]. With both types of cue, the JNDs were reduced compared to the baseline condition [Bonferroni-corrected comparisons: rhythmic precue vs. baseline,  $p < 0.01$ ; synchronous cue vs. baseline,  $p < 0.05$ ]. A similar crossmodal enhancement of sensitivity was also observed in the tactile precue condition with the (fixed) long CTOA [Experiment 4:  $F(2,24) = 8.7$ ,  $p < 0.01$ ,  $\eta^2 = 0.42$ ; CTOA<sub>530</sub> vs. baseline,  $p < 0.05$ ; CTOA<sub>530</sub> vs. CTOA<sub>170</sub>,  $p < 0.05$ ], though not with the (fixed) short CTOA [CTOA<sub>170</sub> vs. baseline,  $p = 0.787$ ].

### 2.3. 5 7. ( - )

The same analyses as in previous section were performed to examine the effects visual (pre-) cues on tactile apparent motion. The visual rhythmic and synchronous (pre-) cues (Experiment 5) did not significantly influence the transition threshold (PSEs) for tactile apparent motion,  $F(2,24) = 1.500$ ,  $p = 0.243$ ,  $\eta^2 = 0.111$ , nor did it influence the sensitivity (JND) of discriminating between the two alternative motion percepts,  $F(2,24) = 1.12$ ,  $p = 0.34$ ,  $\eta^2 = 0.085$ . However, with fixed CTOAs (Experiment 6), the precues had impact on the transition thresholds of tactile apparent motion,  $F(2,24) = 9.67$ ,  $p < 0.01$ ,  $\eta^2 = 0.446$ . Further comparisons showed that this effect was mainly due to the long-CTOA (530 ms) condition, which biased towards 'group motion' percept [CTOA<sub>530</sub> vs. baseline,  $p < 0.01$ , CTOA<sub>530</sub> vs. CTOA<sub>170</sub>,  $p < 0.01$ ]. However, similar to the rhythmic and synchronous (pre-) cue conditions in Experiment 5, the judgment sensitivity (JNDs) was not reliably modulated,  $F(2,24) = 3.11$ ,  $p = 0.063$ ,  $\eta^2 = 0.206$ .

### 3. D/c

The major findings of the present study are summarized in Table 2.

With non-motion intramodal precueing of the middle position, differential effects were observed between visual

Cue types		CTOA (ms)		Visual AM		Tactile AM	
Intramodal cueing	Short	170		Element M.	(-)	Element M.	(-)
	Rhythmic	80–260		Element M.		n.s.	(+)
	Long	530		n.s.		Group M.	
Crossmodal cueing	Synchronous			Group M.	(+)	n.s.	
	Short	170		n.s.		n.s.	
	Rhythmic	80–260		n.s.	(+)	n.s.	
	Long	530		Group M.	(+)	Group M.	

and tactile Ternus apparent motion. Cueing the middle flash at a fixed short CTOA or in rhythmic fashion shifted the *visual* Ternus apparent motion towards 'element motion'. In contrast, an opponent-type pattern was found for tactile precues between short and long CTOAs: precueing the middle tap at short CTOAs shifted *tactile* apparent motion towards 'element motion', while precueing at long CTOAs shifted apparent motion towards 'group motion'; rhythmic precueing (with intermediate CTOAs) did not affect the tactile apparent-motion percept. The visual modality is known to have lower temporal resolution than the tactile modality. For example, the highest flicker fusion rate is approximately 60 Hz in peripheral vision (Hartmann et al., 1979), which is substantially lower than the vibrotactile upper limit of 1000 Hz (Verrillo et al., 1969). When visual stimuli are presented in rapid succession at the same location, temporal proximity promotes visual stimuli (at the same location) to group across frames. Accordingly, in the intramodal visual precue conditions, precues with short and intermediate CTOAs may have helped the middle stimuli in the Ternus frames to be temporally grouped, as a result of which the two flanker elements (i.e., dots 'a' and 'c' in Fig. 1) became more likely to be linked, forming the percept of 'element motion'. Indeed, similar results have been reported by He and Ooi (1999). They also observed a dominant 'element motion' percept using rhythmic cueing in a four-element Ternus display, which they attributed to a perceptual bias in the apparent-motion percept owing to visual persistence. By contrast, the tactile modality has a higher temporal resolution, limiting grouping by the temporal proximity. Accordingly, an influence of temporal grouping was observed only with short CTOAs. Interestingly, rhythmic precueing did not promote temporal grouping of the middle stimuli, which means that temporal grouping is governed mainly by temporal proximity. In the precue condition with the long CTOA (530 ms), apparent-motion perception may have been modulated by a 'classical' attention effect. We will consider this later in detail along with the results in the *crossmodal* long-CTOA precue conditions.

For the *crossmodal* synchronous cue, counter-intuitively, (non-motion) synchronous *tactile* cueing of the middle position did not bias the *visual* Ternus apparent-motion percept towards 'element motion'; rather, it shifted it towards 'group motion'. By contrast, synchronous *visual* cueing had no influence on tactile Ternus apparent motion. There are several possible explanations for this dissociation. First, the sense of touch has high temporal resolution. It may thus 'freeze' the visual stimuli that occur synchronized with the tactile stimuli and thus promote segregation of two temporally proximate visual stimuli. A previous study (Vroomen and de Gelder, 2004) showed that an abrupt sound can 'freeze' the synchronous visual display and enhance the detectability of visual stimuli; perceptually, the display appears brighter or to be shown for a longer period of time. There is also evidence that temporally proximate tactile stimuli improve visual temporal discrimination (Keetels and Vroomen, 2008); and tactile intervals are perceived as longer than physically equivalent visual intervals (van Erp and Werkhoven, 2004). Accordingly, the longer (perceived) interval between the two tactile stimuli may have 'captured' the shorter visual interval, which in turn may have biased the visual Ternus apparent-motion percept towards 'group motion'. (Recall that

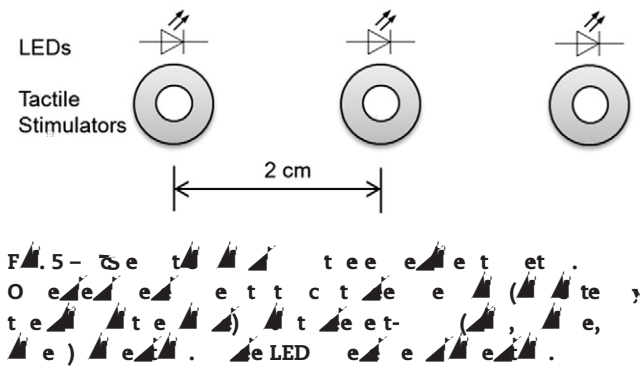
reports of 'group motion' percepts are increased at longer SOAs, Ternus, 1926). Second, the sense of touch monitors biologically vital features of the environment by means of direct contact, and may therefore capture attention more readily than other, more 'remote' senses such as vision (Gallace and Spence, 2008; Spence, 2002; Spence et al., 2001). In an event-related functional magnetic resonance imaging (fMRI) study, Macaluso et al. (2000) applied concurrent tactile stimulation to the right hand (in half of the trials) while presenting a visual stimulus in either the left or the right hemifield. They found that tactile input to the somatosensory cortex can enhance activity in visual cortex



Ternus apparent motion towards 'group motion'. This is contrast to previous studies of motion direction capture, where dynamic-capture effects were diminished when the apparent motion in the distractor modality was presented 500 ms prior to the apparent motion in the target modality (Soto-Faraco et al., 2002, 2004a,b). The absence of a capture effect for the distractor-target asynchrony condition in cross-modal dynamic-capture studies may relate to the specific task used, namely, judgment of motion direction. When distractor motion is presented separately from target motion, observers can resolve the motion direction easily and efficiently.

By contrast, in the present study, we examined the sensation of movement, which can be influenced by both attention and spatial-temporal configuration. Crossmodal-attention studies have shown that precueing in one modality can improve the perceptibility of stimuli presented in another modality at the same or nearby locations (Macaluso et al., 2000; McDonald et al., 2000; Spence and Driver, 1996). In a unimodal apparent-motion study, attention was also found to have an influence on visual persistence, duration, and consequently the perception of apparent motion (Yes-hurun and Levy, 2003). Under conditions of intra- and crossmodal precueing with a long CTOA (of 530 ms), attention would have mostly been attracted to the location where an apparent-motion stimulus was presented subsequently. Thus, the separation between the first and the second Ternus frame may have been enhanced perceptually (i.e., spatial grouping of the two dots within one frame was dominant) and, as a result, the motion percept would have been biased towards 'group motion' in three out of four cases (see Table 2, long-CTOA conditions). With long CTOAs, the fact that the precueing effect was non-significant in unimodal visual Ternus apparent motion may be due to an increasing attentional effect (favoring 'group motion') and a decreasing temporal grouping effect (favoring 'element motion') cancelling each other. Note that such a cancellation might also be at work in unimodal tactile apparent motion, but due to the high temporal resolution of tactile modality, such cancellation may shift earlier to the intermediate CTOAs.

It is worth noting that crossmodal tactile cueing enhanced visual apparent-motion discrimination (indicated by JNDs) in general, while crossmodal visual cueing did not influence the discrimination sensitivity (see Tables 1 and 2). This may be due to the relative reliability of the two



was 30 ms for the LED and 5 ms for the tactile (tap) stimuli.<sup>2</sup> The testing cabin was dimly lit, with an average ambient luminance of 0.09 cd/m<sup>2</sup>.

#### 4.3.

##### 4.3.1. Experiment 1 — Intra-modal rhythmic precue with covaried CTOA

Experiment 1 consisted of two sub-experiments, one dedicated to the visual and the other to the tactile Ternus apparent-motion task (with task order counter-balanced across participants). Prior to the experiment, participants were shown demos of ‘element motion’ (with an 80-ms SOA between the two Ternus frames) and ‘group motion’ (260-ms SOA) in visual and tactile Ternus displays, respectively, and they performed a block of trials to become familiar with these two alternative percepts.

In each (visual or tactile) Ternus apparent-motion task, there were two conditions: one with and one without precue. In the visual Ternus apparent-motion condition, a trial started with a beep, followed by a random blank interval of 300 to 500 ms. In the precue condition, the stimulus sequence was as follows (see Fig. 2a): the middle LED was briefly illuminated twice, each time for 30 ms. The SOA between the two precue stimuli was randomly selected from seven different lengths equally spaced between 80 and 260 ms. Then after a CTOA of the same length as the SOA, the first and second visual frames of the Ternus display were turned on for 30 ms, one after the other with the same SOA. Finally, after a duration of 600 ms, participants were prompted by a ‘beep’ to make a two alternative forced-choice (2AFC) judgment indicating whether they had perceived ‘element motion’ or ‘group motion’. Note that, in this condition, the SOA and CTOA were the same. In the baseline

condition without precue, only the standard visual Ternus frames were presented, with the same stimulus durations and SOA settings as in the precue condition. In the session with tactile Ternus configurations, the stimuli were tactile taps instead of the LED flashes. All other details (such as the SOA and CTOA settings etc.) were the same as in the visual Ternus apparent-motion task. For the tactile stimulation, participants had to place the tip of their left-hand ring, middle, and, respectively, index finger on the three corresponding solenoid actuators. In both (task) sessions, choice responses were collected via right-hand mouse button presses: participants pressed the left button for element motion and the right button for group motion. The inter-trial interval (ITI) varied randomly between 1200 and 1700 ms. In summary, Experiment 1 consisted of two sub-experiments, each implementing a full-factorial within-subjects design, with 2 (with/without) cue conditions  $\times$  7 SOAs. Each condition was repeated 24 times, with counter-balanced directions of motion.

##### 4.3.2. Experiment 2 — Intra-modal precue with fixed short and long CTOAs

Experiment 2 used the same settings as in Experiment 1, except that two new CTOA conditions were introduced. In contrast to the covaried CTOAs in Experiment 1 (where the CTOA was the same as the SOAs between the two precue stimuli and the two Ternus frames), the CTOAs were fixed at either 170 ms (short CTOA) or 530 ms (long CTOA), with precue–precue SOAs and the Ternus frame–Ternus frame SOAs varying in the same way as in Experiment 1.

##### 4.3.3. Experiment 3 — Effects of tactile advance and synchronous cues on visual Ternus apparent motion

To examine the influence of tactile cue stimuli on visual Ternus apparent motion, three different conditions were introduced: (a) a baseline condition, in which the standard visual Ternus display was presented without tactile taps; (b) a tactile precue condition, in which the middle solenoid tapped the middle finger twice prior to the presentation of the standard visual Ternus display (covaried CTOA, see Fig. 2A); and (c) a tactile synchronous condition, in which the onsets of the two taps applied to the middle finger were synchronized with the onsets of the two visual Ternus frames (Fig. 2B). The SOA configuration and the sequence of events on a trial were the same as in Experiment 1. And again, participants were asked to make a 2AFC judgment on the visual motion percept (‘element motion’ vs. ‘group motion’). In summary, Experiment 2 implemented a full-factorial within-subjects design, with 3 conditions  $\times$  7 SOAs; each condition was repeated 24 times, with counter-balanced directions of motion.

##### 4.3.4. Experiment 4 — Effects of tactile precues with fixed short and long CTOAs on visual Ternus apparent motion

Experiment 4 introduced the same stimulus settings as in Experiment 3, except that two precue conditions with fixed CTOA (170 and, respectively, 530 ms) were used instead of covaried CTOAs. A baseline condition was also included in Experiment 4.

<sup>2</sup> The solenoid uses pulse signal to push the central pin out, hitting the skin surface. We conducted a pilot experiment to compare the motion percepts of Ternus display produced by pulse signal of 5 ms and 30 ms. Twelve observers participate in the experiment for judging percepts of classical Ternus apparent motion. The results indicated no difference on PSEs [ $t(11)=0.61$ ,  $p=0.56$ ] and JNDs [ $t(11)=0.048$ ,  $p=0.96$ ]. In order to avoid overheating issue of solenoids, we used 5 ms ON-state in the formal experiments.

#### 4.3.5. Experiment 5 — Effects of visual advance and synchronous cues on tactile Ternus apparent motion

The stimulus settings in Experiment 5 were the same as in Experiment 2, except that the assignment of the cue and target modalities was reversed. That is, the tactile modality was the target modality in which the Ternus display was presented, while the visual modality was the cue modality, with visual precue and, respectively, synchronous-cue stimuli generated from the middle LED. Similar to Experiment 2, there were three conditions: (a) baseline condition: tactile Ternus apparent-motion display without visual events; (b) 'synchronous' condition: two middle LED flashes illuminated synchronously with the onset of the first and the second tactile frames; (c) visual precue condition: middle LED flashed twice prior to the tactile Ternus apparent-motion frames. The CTOA was covaried with the SOA of Ternus display. The procedure was the same as in Experiment 2, except that the task was changed to a 2AFC judgment on the tactile apparent-motion percept ('element motion' vs. 'group motion').

#### 4.3.6. Experiment 6 — Effects of visual precues with fixed short and long CTOAs on tactile Ternus apparent motion

Experiment 6 was analogous to Experiment 4, with the assignments of target and cue modality reversed.

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