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Space and time: an impact of spatial separation, apparent motion, and perceptual grouping on TOJ performance

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Abstract. This study explored the effects of spacing and objecthood (ie grouping based on closure) on temporal order judgment (TOJ) with displays that either involved successive onset of the target stimuli, resulting in apparent motion (experiments 1 and 2), or included simultaneous onset but successive shortening of the stimuli, and therefore did not result in apparent motion (experiment 3). We found a robust effect of spatial separation whose nature depended on whether or not the display allowed the emergence of illusory motion. Specifically, with apparent motion TOJ was best with the smallest spacing, but without it TOJ was worst with the smallest spacing. Moreover, overall accuracy was better with, than without, apparent motion. A small effect of objecthood—poorer TOJ performance when the elements formed an object—emerged only when spacing was not manipulated. These findings suggest that different mechanisms mediate temporal processing when we have access to motion information than when we do not.

Keywords: temporal order judgment, visual TOJ, apparent motion, spatial separation, perceptual grouping, mechanisms of temporal processing

1 Introduction

Coherent perception demands a compromise between the need to segregate properties that belong to different objects or events and the need to integrate properties that belong to the same object or originate from the same event. When stimuli occur close together in both time and space, they typically originate from the same event, and should be integrated, whereas with longer temporal intervals or greater spatial separation perceptual unity is less likely and the perceptual system should segregate the stimuli into separate events. The temporal order judgment (TOJ) task—where observers judge which of two stimuli, presented successively within a single trial, appeared first—has been used extensively to examine the temporal precision of perception (eg Correa et al 2006; Hein et al 2006; Kanai et al 2009; Nicol and Shore 2007; Shore et al 2001; Stelmach and Herdman 1991). With a few exceptions (eg Carrasco 1990; Drum 1984; Hermens et al 2009; Herzog 2007; Nicol and Shore 2007; Nicol et al 2009), the spatial properties of stimuli are often studied separately from temporal parameters of visual perception. The present study directly examines the effect of spatial separation and perceptual grouping on temporal precision.

Previous work on perceptual grouping has observed a detrimental effect on temporal precision. For instance, feature fusion (ie fusion of features of stimuli that are presented in rapid succession) was degraded when visual stimuli were grouped by proximity and similarity (Hermens et al 2009). Specifically, when one stimulus was grouped with an adjacent stimulus it was less likely to be fused with the preceding stimulus, and this effect of grouping was weaker when the spatial spacing between the to-be-grouped elements was larger. These authors suggested that the observed effect of grouping on feature fusion might be mediated by dynamical lateral inhibition. Another example is a TOJ study by Nicol and Shore (2007), which demonstrated degraded performance when the two stimuli appeared at the same location rather than at different locations (cf Spence et al 2003). Worse performance was also observed when the two stimuli were grouped into a single perceptual object rather than perceived as two distinct objects (Nicol and Shore 2007). Similarly, worse performance was found when two stimuli presented to different modalities were perceived as originating from the same event (eg Vatakis and Spence 2007; Vatakis et al 2008).

Several previous studies have looked at the effect of spatial spacing on TOJ (Allik and Kreegipuu 1998; Westheimer 1983; Westheimer and McKee 1977). Westheimer and McKee (1977) were the first to test the effect of spatial spacing in a systematic manner. Observers reported the temporal order of two vertical lines presented with interstimulus spacings ranging from 0.017° to 0.75°. The interstimulus spacings that led to the best performance were between 0.03° and 0.1°; a smaller spacing than 0.03° and larger spacing than 0.1° resulted in impaired TOJ performance (see also Westheimer 1983). The decreased TOJ with spacings smaller than 0.03° was attributed to spatial resolution limitations of the retinal mosaic (Westheimer 1983) and to the fact that with these very small spacings the stimuli overlapped considerably (Westheimer and McKee 1977). As the displays used in this study elicited an illusion of motion—apparent motion (Westheimer 1983; Westheimer and McKee 1977)—the TOJ decrement with spacings larger than 0.1° could be attributed to the fact that apparent motion is weaker with larger interstimulus spacings (Burt and Sperling 1981). In another study (Allik and Kreegipuu 1998) TOJ performance was examined using two stimuli that were presented in succession at one of two spatial separations (0.04° and 10°). The better performance at the smaller spacing was likewise attributed to stronger apparent motion with smaller spacings. Thus, it is critically important to distinguish the effect of spatial separation on TOJ performance per se, from its effect on perceived motion.

Testing the order of stimulus *offsets* rather than onsets provides a way of reducing, or eliminating, the impact of apparent motion (Tadin et al 2010). For onsets the two stimuli were presented successively, as in previous studies, but in the offset task the stimuli were presented simultaneously and were turned off successively, practically preventing the perception of motion. A considerably smaller effect of spatial spacing was found with the offset task; but only three, relatively large, spatial spacings (3.3°, 8°, and 20°) were used, which may not be optimal for the study of spatial and temporal interactions.

The goal of the present study was to advance our understanding of the interplay between spatial and temporal aspects of perception by establishing a more comprehensive view of how spacing affects TOJ performance. In particular, we were interested in comparing the effects of spatial separation on TOJ with and without the involvement of apparent motion. To that end, we systematically tested the effects of interstimulus spacing by employing stimuli with several interstimulus spacings (0.15°–4.8° across the different experiments). These spacings are, on the one hand, large enough to avoid spatial resolution limitations, and, on the other hand, not large enough to prevent the emergence of spatial effects. Importantly, the stimuli—two vertical lines—were either presented successively and therefore elicited an illusion of motion (experiment 1) or they were presented simultaneously but transformed successively and therefore did not involve perceived motion (experiment 3). Given previous findings (Allik and Kreegipuu 1998; Tadin et al 2010; Westheimer and McKee 1977), we expected to find better TOJ with smaller interstimulus spacings when TOJ involved motion perception and possibly a smaller effect of spatial spacing when TOJ did not involve apparent motion.

Additionally, because the distance between two stimuli (ie proximity) is an important factor in perceptual grouping (eg Wertheimer 1938), and because it was already suggested that perceptual grouping is an important factor in TOJ (eg Nicol and Shore 2007; Nicol et al 2009), we also employed a manipulation of perceptual grouping based on closure (experiments 1 and 2). In addition to the two target lines, the display included two horizontal lines that either grouped with the two vertical lines to create a closed object (figure 1a) or did not group with the vertical lines (figure 1b). On the basis of previous studies (eg Nicol and Shore 2007), we expected to find poorer TOJ when the stimuli are grouped into a single object.

Finally, the simultaneous manipulation of these two factors—interstimulus spacing and objecthood based on closure—allowed us to test whether these factors interact with each other. Specifically, because closer stimuli tend to be grouped together more frequently (eg Kubovy and Van den Berg 2008), the effect of interstimulus spacing might be weaker when the stimuli are organized into an object.

2 Experiment 1

In this experiment the observers' ability to judge temporal order was measured using the classical successive presentation of stimuli, a method which typically elicits an illusion of motion (eg Allik and Kreegipuu 1998; Westheimer and McKee 1977). Two vertical lines were presented one after the other with one of two possible SOAs (12 ms, 24 ms), and the task was to indicate which line appeared first. To examine the effect of interstimulus spacing, the distance between the two lines varied systematically (0.15°, 0.3°, 0.6°, 1.2°); and to examine the effect of perceptual organization, two horizontal lines were presented simultaneously at the beginning of the trial. The interstimulus spacing between the two horizontal lines was such that they were either grouped with the vertical lines to create an object ('object-present' condition—figure 1a) or not ('object-absent' condition—figure 1b). In accordance with previous studies (Allik and Kreegipuu 1998; Nicol and Shore 2007; Nicol et al 2009; Westheimer and McKee 1977), we expected TOJ to deteriorate with increasing spacing and in the object-present condition.

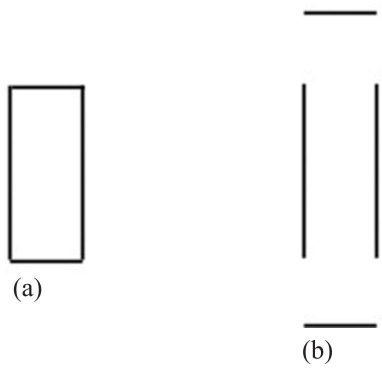

Figure 1. A schematic example of the stimuli employed in experiments 1 and 2: (a) object-present condition; (b) object-absent condition.

2.1 *Method*

2.1.1 *Participants.* Seventeen students from the University of Haifa participated in the experiment. All had normal or corrected-to-normal vision, and all were naive as to the purpose of the experiment.

2.1.2 *Stimuli and apparatus.* The stimuli were presented using MATLAB and the Psychophysics Toolbox extensions (Brainard 1997) on a 17″ monitor of an IBM compatible PC (resolution = 1024 × 768; 85 Hz). The fixation mark was a 0.3° × 0.3° black cross presented in the center of a white background. The TOJ stimuli were two black vertical lines (2.4° × 0.03°) that appeared to the left and to the right of the fixation mark. The distance between the two vertical lines was chosen randomly from 4 possible interstimulus spacings (0.15°, 0.3°, 0.6°, or 1.2°). Thus, the center of each vertical line appeared in one of 4 possible eccentricities (0.075°, 0.15°, 0.3°, 0.6°). Two identical black horizontal lines were presented directly above and below the fixation mark. The thickness of the horizontal lines was always 0.03°, but their length matched the interstimulus spacing between the vertical lines (ie if on a specific trial the interstimulus spacing between the vertical lines was 0.3°, the length of the two horizontal lines was also 0.3°). The interstimulus spacing between the two horizontal lines was either

2.4° or 3.6° (ie the center of each horizontal line appeared at an eccentricity of either 1.2° or 1.8°). The smaller spacing matched the length of the vertical lines, and therefore the 4 lines formed a rectangle—object-present condition (figure 1a). With the larger spacing no object was formed—object-absent condition (figure 1b).

2.1.3 *Procedure.* Each trial began with the presentation of the central fixation cross for 1000 ms, followed by the presentation of two horizontal lines (figure 2a). After 1000 ms the first vertical line was presented to the left or right of fixation with equal probability. The second vertical line followed after either 12 ms or 24 ms, and the display stayed on until response. The task was to indicate which of the two vertical lines (the one to the left or the one to the right) appeared first. The response was not speeded. The order of the various conditions (objecthood: object present versus object absent; interstimulus spacing between vertical lines; SOA; and presentation order: left line first versus right line first) was randomized. Each observer participated in 32 practice trials and 768 experimental trials.

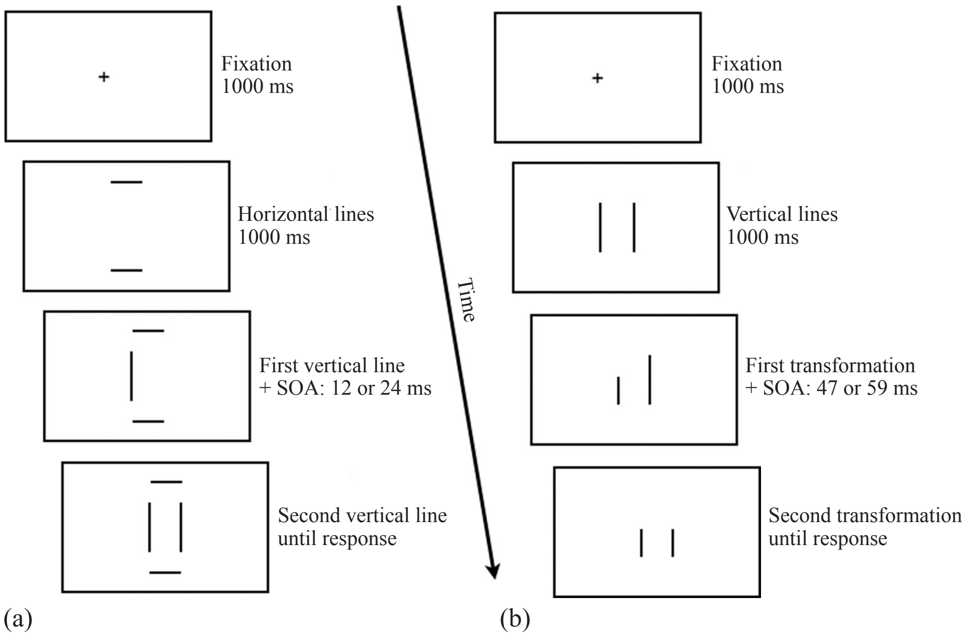

Figure 2. A schematic example of the sequence of events in: (a) experiments 1 and 2; (b) experiment 3.

2.2 *Results*

A within-observers three-way ANOVA (SOA × objecthood × interstimulus spacing) was performed on TOJ accuracy. Better performance was seen at the longer SOA ($F_{1,16} = 362.2$, $p < 0.0001$; cf Correa et al 2006; Hein et al 2006; Kanai et al 2009; Shore et al 2001; Stelmach and Herdman 1991). TOJ accuracy was also better for smaller interstimulus spacings ($F_{3,48} = 68.2$, $p < 0.0001$). Least significant differences (LSD) a posteriori analysis indicated that all pairwise comparisons of the different spacings were significant ($p < 0.05$). There was also a significant interaction between interstimulus spacing and SOA ($F_{3,48} = 11.06$, $p < 0.0001$). The impact of interstimulus spacing was more pronounced for the shorter SOA than the longer SOA (figure 3).

The grouping of the horizontal lines with the target lines to create a perceptual object had no impact on performance. No other effects and interactions of the three-way ANOVA reached statistical significance ($p > 0.1$).

We also calculated the JND—the minimum temporal interval required between the onset of the first and second target to perform the TOJ task at 75% accuracy. Following Nicol and colleagues (Nicol and Shore 2007; Nicol et al 2009), we converted the proportion of

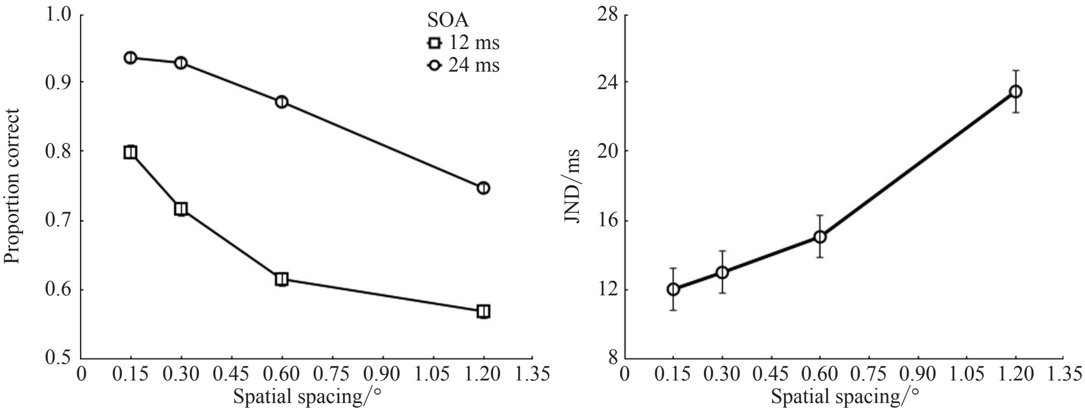

Figure 3. Observers' accuracy and JND in experiment 1 as a function of interstimulus spacing and SOA. Error bars correspond to 1 SE.

right first responses to the equivalent *z*-scores under the assumption of a cumulative normal distribution (cf Finney 1964). We used the best-fitting straight line for each individual in each spacing and objecthood condition to calculate the JND. A within-observers two-way ANOVA (objecthood × interstimulus spacing) was performed on these JNDs. We excluded from this analysis the data of two observers because their average R^2 was low (0.62, 0.71), and in at least one of the conditions their R^2 was very low ($R^2 < 0.1$). The average R^2 of the other observers ranged from 0.83 to 0.96. In accordance with the analysis of the accuracy measure, JND was smaller for smaller interstimulus spacings ($F_{3,42} = 33.7$, $p < 0.0001$) (figure 3). LSD a posteriori analysis indicated that the JND of the largest spacing (1.2°) was significantly larger than the JNDs of all the other spacings. Additionally, the difference between the JND of the smallest spacing (0.15°) and that of the 0.6° spacing was significant. No other significant effects were found.

2.3 *Discussion*

We replicated previous results showing better TOJ performance with longer SOAs and shorter spatial separations (cf. Allik and Kreegipuu 1998; Westheimer 1983; Westheimer and McKee 1977). Additionally, the impact of spacing was more pronounced with the shorter SOA. These findings support the role of apparent motion in driving performance because the illusion is stronger with smaller spatial separations and shorter time intervals. Since our smallest spacing was above the limits of spatial acuity (ie greater than 0.03°), the monotonic decrease in performance with increasing interstimulus spacing was expected (cf Burt and Sperling 1981). This effect was further explored in experiment 3.

We did not replicate the negative impact of objecthood on temporal resolution (eg Nicol and Shore 2007; Nicol et al 2009). This finding was further explored in experiment 2.

3 Experiment 2

Previous studies suggested that TOJ is worse when the target stimuli are grouped into an object (Nicol and Shore 2007; Nicol et al 2009). For instance, in one experiment Nicol and Shore (2007) presented two targets of different color, to either the same spatial location or different spatial locations. The task was to indicate which target color appeared first; performance was better when the targets were presented to different locations. In another experiment they presented two half rectangles that, depending on their orientation, either appeared as two separate objects or were grouped into a single whole rectangle; performance was better when the two half rectangles appeared as two separate objects. In this context the lack of an objecthood effect in experiment 1 was surprising. Perhaps any effect of objecthood was overshadowed by the highly robust effect of interstimulus spacing (21% difference between TOJ accuracy in the smallest and largest spacing). To explore this possibility, we employed here only a single interstimulus spacing (0.45°) to directly examine the effect of objecthood. An effect of objecthood would be manifested by a poorer TOJ performance when the various lines formed and object (object-present condition).

3.1 *Method*

3.1.1 *Participants.* Nineteen naive observers from the University of Haifa, with normal or corrected-to-normal vision, participated in this experiment; none of them participated in experiment 1. Two were excluded from the analyses because their accuracy level was below 60%.

3.1.2 *Stimuli, apparatus, and procedure.* The stimuli and procedure were similar to experiment 1, apart from the fact that only one interstimulus spacing between the vertical lines was employed—0.45°; accordingly, the length of the horizontal lines was also fixed at 0.45°. Each observer participated in 400 experimental trials.

3.2 *Results*

A within-observers two-way ANOVA (SOA × objecthood) was performed on the TOJ accuracy data of experiment 2. As in experiment 1, accuracy was higher with the longer SOA ($F_{1,16} = 297.92$, $p < 0.0001$; figure 4). Unlike experiment 1, TOJ was less accurate when the lines formed an object than when they did not ($F_{1,16} = 11.64$, $p < 0.005$). All other effects and interactions did not reach statistical significance ($p > 0.1$).

We also calculated the JND for each observer in each of the objecthood conditions. The average R^2 ranged between 0.81 and 0.99. A one-way within-observers ANOVA (objecthood) was performed on these JNDs. Similar to the pattern of results of the accuracy analysis, a small but significant effect of objecthood emerged ($F_{1,16} = 6.9$, $p < 0.02$). The JND was larger when the lines formed an object than when they did not (figure 4).

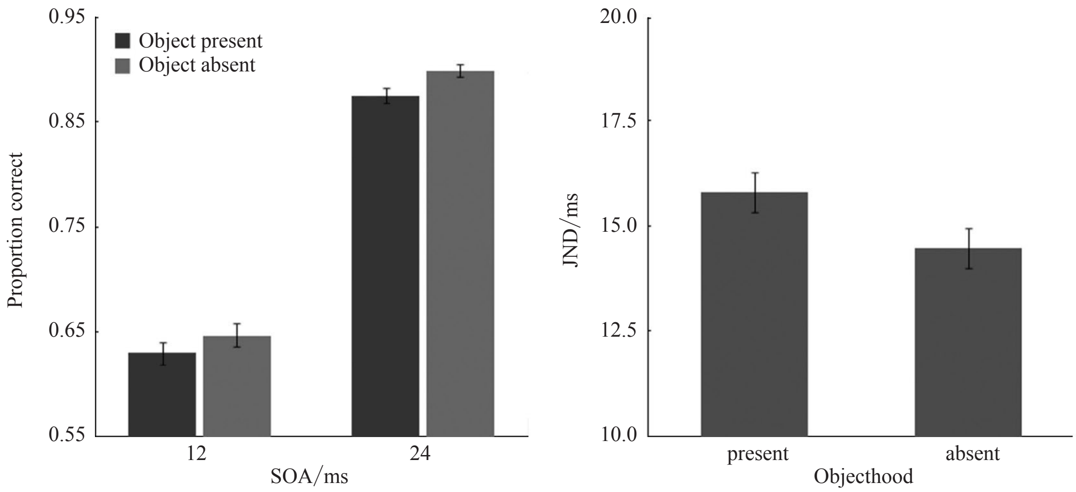

Figure 4. Observers' accuracy and JND in experiment 2 as a function of SOA and objecthood. Error bars correspond to 1 SE.

3.3 *Discussion*

The removal of the interstimulus spacing manipulation resulted in the emergence of a small but significant effect of objecthood. Similar to previous studies (eg Nicol and Shore 2007; Nicol et al 2009), we have found that judging the temporal order of stimuli is harder when these stimuli belong to the same object. It may be that, when the target stimuli integrate with the horizontal lines, the perception of motion is reduced. In experiment 3 we examined the impact of the percept of motion on TOJ performance directly.

4 Experiment 3

Experiment 1 demonstrated that TOJ performance is more accurate when the spacing between the target stimuli is smaller. However, in that experiment and in previous studies with similar findings (eg Allik and Kreegipuu 1998; Westheimer and McKee 1977) the successive onset of the target stimuli created an illusion of motion. In the present experiment our aim was to see if a similar effect would be found when this illusory motion was prevented. To that end, we eliminated the successive onset of stimulus presentation. Instead, both target stimuli were presented simultaneously and then transformed (ie made shorter) successively (figure 2b). Interstimulus spacing was also manipulated, with similar values to those in experiment 1, but with a wider range (0.15°–4.8°). On the basis of pilot experiments, we increased the SOA values (to 47 ms and 59 ms) to ensure that performance was not at chance level.

To verify objectively that the stimuli employed in this experiment do not evoke perception of motion, we performed a pilot experiment in which we presented to ten participants the stimuli of experiment 1 (ie with successive onset) and those of this experiment (ie with simultaneous onset but successive transformation). All methodological details were identical to those used in the corresponding experiments. The two stimuli types were presented in separate blocks, and their order was counterbalanced across participants. The participants were asked to report verbally whether they had a sensation of motion (to the left or to the right). Each participant observed 30 trials of each type—60 trials overall. Two participants had no sensation of motion at all, regardless of stimuli type. The other eight participants did not have a sensation of motion when there was successive transformation but no successive onset (ie with the stimuli of this experiment); however, with successive onset they reported a sensation of motion (ie when presented with the stimuli of experiment 1).

Compared with experiment 1, we expected to find in the current experiment a reduced impact of interstimulus spacing, since in a previous study (Tadin et al 2010) spacing had a smaller influence when observers judged relative offsets rather than onsets.

4.1 *Method*

4.1.1 *Participants.* Forteen naive observers from the University of Haifa, with normal or corrected-to-normal vision, participated in this experiment; none of them participated in the previous experiments. Two observers were excluded from the analyses because their accuracy level was below 60%.

4.1.2 *Stimuli, apparatus, and procedure.* The stimuli and apparatus were similar to experiment 1 except for the fact that there were no horizontal lines. The vertical lines were presented with a height of 2.4° and subsequently changed to a height of 1.6°. A wider range of interstimulus spacings between the vertical lines was employed (0.15°, 0.3°, 0.6°, 1.2°, 2.4°, or 4.8°).

4.1.3 *Procedure.* Each trial began with 1000 ms of the central fixation cross, followed by the presentation of both vertical lines (figure 2b) for 1000 ms, after which the first vertical line was shortened from 2.4° to 1.6°. The second vertical line was shortened either 47 ms or 59 ms after the shortening of the first line, and the display stayed on until response. Observers reported which of the two vertical lines (the one to the left or the one to the right) was shortened first. The response was not speeded. The order of the various conditions (interstimulus spacing; SOA; and shortening order: left line first versus right line first) was randomized. Each observer participated in 32 practice trials and 768 experimental trials.

4.2 *Results*

A within-observers two-way ANOVA (SOA × interstimulus spacing) was performed on the TOJ accuracy data. As in the previous experiments, accuracy was higher with the longer SOA ($F_{1,11} = 21.23$, $p < 0.001$). There was a significant effect of interstimulus spacing

($F_{5,55} = 3.77$, $p < 0.01$). As can be seen in figure 5, this effect was nonmonotonic. TOJ accuracy was poorest when the interstimulus spacing was the smallest (0.15°). Accuracy of the larger spacings was higher and remained almost unchanged: only very mild performance deterioration was observed with increasing interstimulus spacing. This pattern of results was verified by an LSD a posteriori analysis: performance in the smallest spacing was significantly worse than in all the other spacings ($p < 0.01$), apart for the largest spacing (4.8°): the difference between the smallest and largest spacing was only marginally significant ($p = 0.076$). There was also a marginally significant difference between the largest spacing and the spacing of 0.3° ($p = 0.085$). All other effects and interactions did not reach statistical significance ($p > 0.1$).

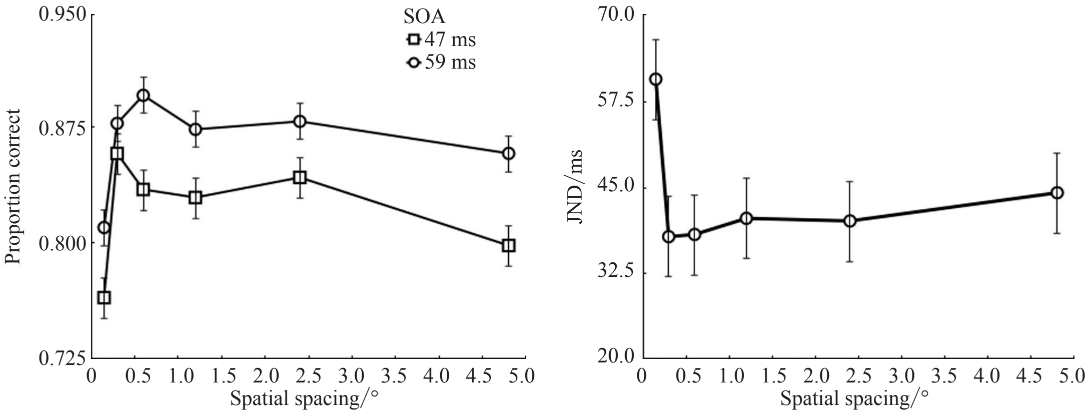

Figure 5. Observers' accuracy and JND in experiment 3 as a function of interstimulus spacing and SOA. Error bars correspond to 1 SE.

In addition, JNDs were calculated for each observer in each of the spacing conditions, and a one-way within-observers ANOVA was performed on these JNDs. The average R^2 ranged from 0.91 to 0.99. As with the accuracy measure, JND varied significantly as a function of interstimulus spacing ($F_{5,55} = 4.24$, $p < 0.005$). JND was largest with the smallest spacing (figure 5) and the effect of interstimulus spacing was not monotonic. LSD a posteriori analysis indicated that the JND of the smallest spacing (0.15°) was significantly larger than the JNDs of all the other spacings ($p < 0.002$). There were no other significant effects.

4.3 *Discussion*

Eliminating the potential for apparent motion drastically reduced the effect of spatial spacing beyond the smallest spacing tested. These results are consistent with the findings of a previous study that eliminated the potential for apparent motion by using stimulus offsets (Tadin et al 2010). Our range of interstimulus spacings included values much smaller than the 3° minimum used previously. The smallest value tested here (0.15°) revealed an interesting outcome: in experiment 1 performance was significantly better at this spacing than in all larger spacings, whereas here performance at this spacing was significantly worse than in all larger spacings. Because apparent motion could be perceived in experiment 1 but not here, this different pattern of results implies that apparent motion plays a critical role in the effect of spacing on TOJ. The role of apparent motion in TOJ performance is further discussed in the general discussion.

5 General discussion

This study was motivated by several previous findings suggesting that our ability to judge the temporal order of two events is affected by the spatial properties of the visual scene (eg Allik and Kreegipuu 1998; Nicol and Shore 2007; Nicol et al 2009; Westheimer and McKee 1977). To better understand the interplay between temporal and spatial properties in determining TOJ, we explored the effects of interstimulus spacing and objecthood (ie grouping based on closure) on TOJ with displays that resulted in perceived apparent motion (experiments 1 and 2) and those that did not elicit such illusory motion (experiment 3). We found a robust effect of spacing whose nature depended on whether or not the display allowed the emergence of illusory motion, and a small effect of objecthood that did not interact with spacing. Additionally, the overall accuracy level of TOJ was considerably higher when sequential onsets led to perceived motion (experiment 1) than when there was no sequential onset and therefore no motion perception (experiment 3). In fact, we had to more than double the SOA from 24 ms in experiment 1 to 59 ms in experiment 3 to observe similar levels of accuracy (0.867 and 0.866, respectively). Thus, TOJ was considerably harder when the observers could not use apparent motion to help them perform the task. A similar conclusion was drawn from a study that assessed temporal processing by comparing detection and phase discrimination of motion versus stationary contrast oscillations (Lappin et al 2002). Performance was better with motion, rather than with stationary oscillations; these two kinds of temporal signals were postulated to stimulate different visual mechanisms with the visual system being more sensitive to motion because it is a more important form of visual information (Lappin et al 2002). In the same line, Allik and Kreegipuu (1998) suggested that TOJ of stimuli separated by a small spacing (0.04°) was considerably better than TOJ with a large spacing (10°) because with the latter the observers could not utilize motion information to perform the task. Similarly to Lappin et al (2002), they suggested that the mechanisms that analyze movement-related information have a higher temporal resolution and that this grants them access to information that is not available to other perceptual subsystems such as the one responsible for conscious experience of temporal order.

The possibility that different mechanisms are involved in TOJ, depending on whether or not the observers can utilize motion information to perform the task, is also supported by our finding that spatial spacing affected TOJ differently when the display included sequential onsets than when no such sequential onsets were employed. Specifically, with sequential onsets, TOJ was best with the smallest spatial spacing and deteriorated monotonically as this spacing increased. This pattern of results is consistent with results of previous studies that employed sequential onsets (eg Allik and Kreegipuu 1998; Westheimer 1983; Westheimer and McKee 1977). It is probably due to the fact that sequential onsets create an illusory motion, and motion perception is best when the spatial distance is small (eg Burt and Sperling 1981). In contrast, when a simultaneous onset was employed, followed by a sequential shortening of the targets, the pattern of results was different. For the larger spacings the effect of spacing was greatly reduced, consistent with the results of Tadin et al (2010) who found a smaller effect of spatial spacing for offsets than onsets. Interestingly, for the smallest spacing we found a reversed pattern of results: whereas in experiment 1 performance was best for the smallest spacing, in experiment 3 performance was worst with this spacing. Thus, for the same small spacing (0.15°) TOJ was best when apparent motion was involved but worst when no motion was involved. The substantial performance drop with the smallest spacing (figure 5) supports the claim for lower spatial precision in the mechanisms responsible for evaluating temporal order when there is no access to motion information. This is in addition to their evident lower temporal precision discussed above. Further research is required to test whether temporal processing independent of motion perception is accomplished by mechanisms with lower temporal and spatial resolution. However, everyday situations that, on the one hand, require highly precise visual temporal processing and, on the other hand, do not involve motion are relatively scarce. It is reasonable to assume, therefore, that we did not evolve independent mechanisms that are capable of high precision spatiotemporal processing when motion information is not available.

In summary, this study explored the interplay between temporal and spatial factors in determining TOJ by evaluating the effects of interstimulus spatial spacing and objecthood on TOJ with displays that either involved apparent motion or did not. Although we found only a small effect of objecthood, a robust effect of spatial spacing emerged, and it varied depending on whether or not the display created an illusion of motion. With motion, TOJ was better overall and best with the smallest spatial spacing; without motion, TOJ was poorer in general and worst with the smallest interstimulus spacing. These findings suggest that different mechanisms may mediate TOJ when motion information is not available, and that these mechanisms may have lower temporal and spatial precision.

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