The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t716100704

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First published on: 06 August 2010

To link to this Article: DOI: 10.1080/17470218.2010.495783
URL: http://dx.doi.org/10.1080/17470218.2010.495783

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
iFirst, 1–23

Psychology Press
Taylor & Francis Group

Simultaneity and temporal order perception: Different sides of the same coin? Evidence from a visual prior-entry study

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Attended stimuli are perceived as occurring earlier than unattended stimuli. This phenomenon of prior entry is usually identified by a shift in the point of subjective simultaneity (PSS) in temporal order judgements (TOJs). According to its traditional psychophysical interpretation, the PSS coincides with the perception of simultaneity. This assumption is, however, questionable. Technically, the PSS represents the temporal interval between two stimuli at which the two alternative TOJs are equally likely. Thus it also seems possible that observers perceive not simultaneity, but uncertainty of temporal order. This possibility is supported by prior-entry studies, which find that perception of simultaneity is not very likely at the PSS. The present study tested the percept at the PSS in prior entry, using peripheral cues to orient attention. We found that manipulating attention caused varying temporal perceptions around the PSS. On some occasions observers perceived the two stimuli as simultaneous, but on others they were simply uncertain about the order in which they had been presented. This finding contradicts the implicit assumption of most models of temporal order perception, that perception of simultaneity inevitably results if temporal order cannot be discriminated.

Keywords: Prior entry; Temporal order judgement; Simultaneity; Attention.

Attended stimuli are perceived as occurring earlier than unattended stimuli (Titchener, 1908). For instance, if observers pay attention to one of two simultaneously presented stimuli, they will probably perceive the attended stimulus as occurring earlier than the unattended stimulus. This notion of *prior entry* has instigated a wide body of research over the years (e.g., Dunlap, 1910; Sanford, 1888; Scharlau, 2002; Scharlau & Neumann, 2003; Schneider & Bavelier, 2003; Shore, Spence, &

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The research reported in this paper was supported by the Deutsche Forschungsgemeinschaft (DFG), Grant Ne 366/7–2 to Ingrid Scharlau. We thank Ulrich Ansorge, Frederic Hilkenmeier, and two anonymous reviewers for helpful comments on earlier versions of the paper and Heinz-Werner Priess and Jan Tünnermann for programming parts of the software. Parts of the data in this manuscript were presented at the 50. Tagung experimentell arbeitender Psychologen [50th Conference of experimentally working psychologists], 30th March to 1st April, 2008, Marburg, Germany, and at the Herbsttagung Experimentelle Kognitionspsychologie [Autumn Conference on Experimental Cognitive Psychology], 31st October to 2nd November, 2008, Dresden, Germany.

http://www.psypress.com/qjep
DOI:10.1080/17470218.2010.495783

Klein, 2001; Stelmach & Herdman, 1991; Stone, 1926).

There are two key manipulations in a typical prior-entry experiment. The first is that either one of the two target stimuli is attended to (on prior-entry trials) or both are unattended (on control trials); the second is the variation of the temporal interval between the two stimuli, the stimulus onset asynchrony (SOA). Usually the prior-entry effect is measured using temporal order judgements (TOJs), in which the observers indicate which of the two stimuli appeared first. Prior entry represents the temporal advantage of the attended stimulus relative to the unattended stimulus and is computed from these order judgements. Though the TOJ seems to be a simple and appropriate means of measuring prior entry, it implies a variety of implicit assumptions, which constrain what can be measured. In the following section we discuss these methodological aspects of prior entry and the TOJ procedure and show how they influence interpretation of the results.

Prior entry is evident as a shift in the *point of subjective simultaneity* (PSS) from control trials (attention not manipulated) to prior-entry trials (attention manipulated). In its classical psychophysical definition, the PSS is interpreted as the temporal interval at which the two stimuli are perceived as appearing simultaneously. Surprisingly, in the most widely used binary TOJ task—deciding which of the two stimuli was presented first—there is no possibility of indicating that the stimuli were perceived as simultaneous. Technically, the PSS represents the onset difference between the two stimuli at which both order judgements are equally likely. Due to the fact that observers must, in a two-alternative forced-choice task, judge the stimuli to occur in one order or the other, the PSS is by definition the point at which they are equally likely to make either judgement (the .5 threshold). Thus, at a theoretical level, the PSS is clearly the SOA at which temporal order cannot be discriminated. But does this necessarily coincide with the perception of simultaneity, as assumed in its classical psychophysical interpretation and most of the TOJ literature? We doubt that this is the case.

In control trials, in which attention is not manipulated, the PSS usually lies at SOA zero and thus coincides with physical simultaneity.[1] In this case it is both possible and likely that the observers perceive the stimuli as simultaneous. But if attention is oriented towards one of the stimuli in a prior-entry trial—this might be towards a certain modality in a bimodal TOJ (e.g., Zampini, Shore, & Spence, 2005b) or a spatial location in a unimodal visual TOJ—the PSS is shifted towards an SOA at which the unattended stimulus objectively appears before the attended one. Thus the PSS is shifted to a temporal condition that is far away from physical simultaneity, and in which the stimuli objectively appear in succession. Therefore, observers have ample information to indicate that the stimuli are not simultaneous, such as their successive onsets, and it is the psychophysicist who decides that this point coincides with perceived simultaneity, on the basis of the order judgement thresholds.

Therefore the crucial question is whether the PSS, at a perceptual level, is actually the "point of subjective simultaneity". In the present study we attempted to answer this question. Such an answer is of general interest for both prior-entry research and beyond. The PSS is a particular case of the point of subjective equality (PSE). PSEs can be—and often are—computed in quite a variety of psychometric tasks, and our line of argument can be more generally applied to the PSE. This issue is considered in more detail in the General Discussion.

The interpretation of the PSS as the point of subjective simultaneity can be tested in a TOJ task with an additional judgement alternative that allows observers to indicate explicitly that both stimuli appeared simultaneously (e.g., Ulrich, 1987). Typically, these "simultaneous" judgements have a Gaussian distribution, the mean of which gives an estimate for timing conditions

[1] But note that some studies in both unimodal and cross-modal prior entry did not find a PSS exactly at an SOA of zero in the control conditions (e.g., Shore et al., 2001; Zampini et al., 2005b).

under which perceived simultaneity is most likely. This gives an alternative measure of the point of subjective simultaneity. Interestingly, earlier visual prior-entry studies that used such a ternary TOJ cast doubt on the assumption that observers perceive simultaneity at the PSS.

For example, Stelmach and Herdman (1991) oriented attention by instruction in a visual prior-entry paradigm. They found that the "simultaneous" judgement was used very rarely in prior-entry trials and did not coincide with the PSS computed from order judgements. In contrast, there were many "simultaneous" judgements in control trials, and their distribution indicated the PSS. The same pattern was found by Scharlau and coworkers (Scharlau, 2004; Scharlau, Ansorge, & Horstmann, 2006). These authors argued that the PSS cannot be regarded as the point of perceptual simultaneity under all conditions, such as when attention is oriented.

Interestingly in *bimodal* prior-entry research, where use of ternary TOJs is widespread, the findings support, if anything, the traditional interpretation of the PSS. For example, Zampini et al. (2007) showed that the peaks of "simultaneous" judgements, which—as mentioned above—can be used as an alternative estimate of the PSS, shift in parallel with those PSSs that are derived from order judgements. In other words, whenever attention was directed to a stimulus of a certain modality, this acceleration (which can be assessed by a horizontal shift of the order judgements) also shifted the distribution of the "simultaneous" judgements. This is an interesting finding and, contrary to what was argued above, indicates perception of simultaneity at the PSS.

But although Zampini et al.'s (2007) findings indicate perception of simultaneity at the PSS, their use of "simultaneous" judgements does not reveal the full power of ternary TOJs. Like other authors, they refer to the *peak* of "simultaneous" judgements. We argue that the question of whether the PSS actually constitutes the point of subjective simultaneity cannot be answered on the basis of the peaks of "simultaneous" judgements alone. Although it would be mathematically possible to compute a peak of "simultaneous" judgements even if only few "simultaneous" judgements were made, it seems pointless to use such a peak as indicating perception of simultaneity, given the small number of judgements involved. We therefore argue that one should also compare how frequent "simultaneous" judgements are in prior-entry trials compared to control trials. As mentioned above, Stelmach and Herdman's (1991) results, using a ternary TOJ task, indicated that "simultaneous" judgements were frequent in control trials but very infrequent in prior-entry trials. The same held true for the ternary TOJ study of Scharlau et al. (2006), in which this result was also statistically secured. Scharlau et al. and Stelmach and Herdman did not, however, compute the peak of "simultaneous" judgements. In addition the "simultaneous" category used by Scharlau et al. was heterogeneous, because it also encompassed uncertainty about temporal order.

To summarize, former prior-entry studies looked either at the "simultaneous" judgements' peaks (e.g., Zampini et al.) or at their frequency (Scharlau et al., 2006; Stelmach & Herdman, 1991). Since in the present study we are interested in the percept at the PSS—is it or is it not simultaneity?—we used both measures, peaks of "simultaneous" judgements and the overall frequencies for control and prior-entry trials, to obtain a reliable estimate for perception of simultaneity. We also used a "pure" simultaneous category, which did not contain other percepts such as uncertainty. Since in contrast to former studies we assessed perception of simultaneity by two different measures, we also asked whether peaks and overall frequencies of "simultaneous" judgements should be weighted in estimating the PSS and, if so, how.

But if the PSS is not the point of subjective simultaneity, what is it? Several researchers interpreted the PSS as the point at which observers are maximally uncertain about perceived temporal order (e.g., Scharlau, 2007; Shore et al., 2001; Stelmach & Herdman, 1991; Sternberg & Knoll, 1973). Thus these authors assume (at least implicitly) that even though temporal order is unclear, observers perceive asynchrony and not simultaneity at the PSS. This interpretation is in line with another classical calculation of the PSS, that it can be computed as the midpoint of the *interval of uncertainty* (Woodworth & Schlosberg, 1961), in which temporal order cannot be discriminated. Note that the magnitude of this interval depends on how frequently no-order judgements are made—that is, not only judgements of simultaneity, but also judgements of uncertainty. The more no-order judgements are given, the larger is this interval of uncertainty.

To summarize, the classical interpretation of the PSS as the point of subjective simultaneity is in doubt on the basis of the empirical findings mentioned above, and to interpret it instead as a point of maximal uncertainty would be a plausible alternative. We now turn to the theoretical background of simultaneity and temporal order perception, in particular considering which predictions have been made about perception at the PSS. We outline one model of temporal order perception in more detail—the *temporal profile model* by Stelmach and Herdman (1991)—because, in accordance with the above-mentioned empirical findings and in contrast to other theories of temporal order perception, it predicts that the PSS is not a point of subjective simultaneity if attention is oriented. By the term *models of temporal order perception* we refer to models that predict when stimuli are detected (for an overview see Sternberg & Knoll, 1973). (Models of temporal duration perception—e.g., Gibbon, 1977—which predict how long stimuli are perceived, are not covered by the present study.) The majority of models of temporal order perception (e.g., Ulrich, 1987; for an overview see Sternberg & Knoll, 1973) are in accordance with the classical psychophysical interpretation of the PSS as the point of subjective simultaneity. They divide temporal events into two classes—those perceived as simultaneous and those perceived in a certain order—with the classes being mutually exclusive. By contrast, some models of temporal perception are compatible with the interpretation of the PSS as the *point of maximal uncertainty*. The temporal-profile model (Stelmach & Herdman, 1991), for instance, does not assume that the perception of simultaneity and the perception of temporal order are different sides of the same coin, but ascribes these percepts to different mechanisms. Because this might provide an interesting framework in which to consider our experiments, we present this model in more detail.

The temporal-profile model

The temporal-profile model (Stelmach & Herdman, 1991) supposes two separate detector mechanisms, one for detecting temporal order and another for detecting simultaneity. The outcomes of the detectors are weighted in a decision. The model combines comparison of arrival times as well as the whole temporal profiles of the stimuli, which are time-dependent responses of the visual system elicited by these stimuli. The *simultaneity detection mechanism* compares the size of the common area under the temporal-profile functions to that of the uncommon, or unshared, area under these functions. The larger the common areas relative to uncommon areas, the higher the probability that simultaneity is detected. For instance, if two identical stimuli appear simultaneously, their temporal profiles will completely overlap, and simultaneity will be detected.

The *temporal order detection mechanism* detects temporal order by using a time-dependent difference function of the temporal profiles of the two stimuli, and peaks in this difference function indicate that one stimulus has preceded the other. The sign of the first peak of the difference function indicates which stimulus was seen first, and its height describes the amount of asynchrony. The greater the absolute value of the first peak, the more likely is the perception of a certain order (see Figure 1 for an illustration of the order detection mechanism).

Interestingly, the temporal-profile model can explain prior entry. Attention modulates the temporal profile of the attended stimulus—specifically it leads to a steeper rise and a steeper decline and thus to a brisker temporal profile. Thus the temporal profile of an attended stimulus will reach its maximum earlier than that of an unattended stimulus. The probability that the order detector

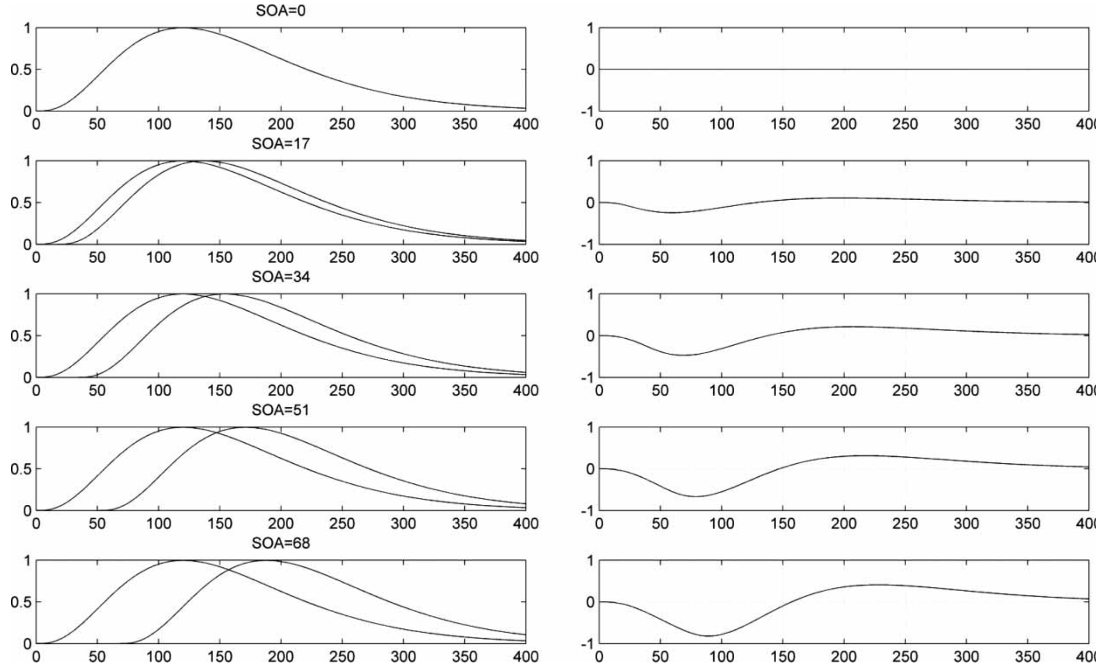

Figure 1. *The order-detection mechanism of the temporal-profile model (Stelmach & Herdman, 1991) if both stimuli are unattended. The left column shows the temporal profiles of two unattended stimuli for the SOAs (stimulus onset asynchronies) 0, 17, 34, 51, and 68. The right column shows the associated time-dependent difference function of the temporal profiles. Peaks in this difference function indicate that one stimulus has preceded the other. The sign of the first peak indicates which stimulus was seen first. We used the same formula as that of Stelmach and Herdman to modulate the temporal profiles:* $f(t, b) = [.742 * (t/b)^3/exp(t/b)]$*. Parameter* t *is time in ms,* b *is a free parameter, and .742 is a constant, which normalizes the peak of the temporal profile to one.*

responds "attended stimulus before unattended" is therefore enhanced, because the temporal difference function will show a higher peak associated with an attended stimulus. This is especially important if the stimuli are separated by small SOAs: For example, compare Figure 1, where both stimuli are unattended, with Figure 2, in which the attended stimulus leads, and Figure 3, in which the attended stimulus trails.

Due to the brisker profile of the attended stimulus, the temporal profiles of an unattended and an identical attended stimulus can never totally overlap. This also applies if the stimuli actually appear simultaneously, as the area under the temporal profile function of the attended stimulus is reduced. In consequence, the probability of detecting simultaneity is reduced. This explains why Stelmach and Herdman (1991) and Scharlau (2004) found that "simultaneous" judgements are rare in prior-entry trials. Nevertheless, the temporal-profile model also predicts a shift of the peak of the simultaneity judgements in prior-entry trials, because although the overlap can never be total, it will be greatest when the unattended stimulus precedes the attended one. Thus we can expect that the PSS does not coincide with perceived simultaneity in prior-entry trials, but it will do so in control trials, because here the temporal profiles of two identical stimuli can overlap completely.

The assumption of a brisker temporal profile for attended stimuli also leads to an interesting hypothesis concerning the discrimination of temporal order—that attending to one of two stimuli should lead to better temporal order discrimination (Stelmach & Herdman, 1991). Attention should enhance discrimination accuracy because the brisker temporal profile for the attended

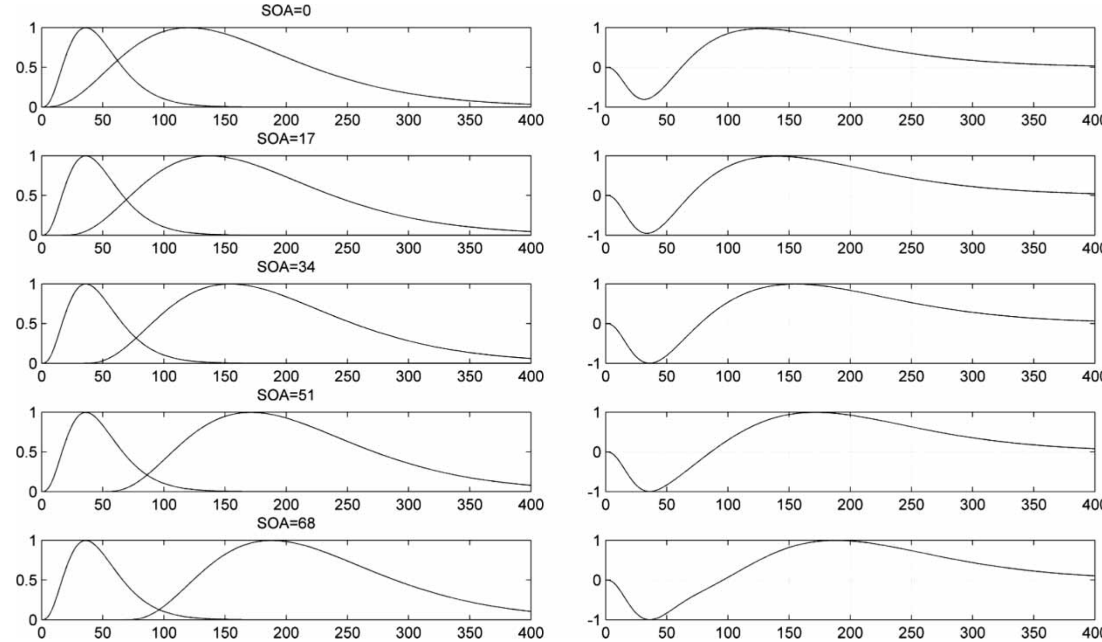

Figure 2. *The order-detection mechanism of the temporal-profile model if the attended stimulus leads the unattended stimulus for the SOAs (stimulus onset asynchronies) 0, −17, −34, −51, and −68 (negative SOAs). The left column shows the temporal profiles, the right column the difference function of the profiles.*

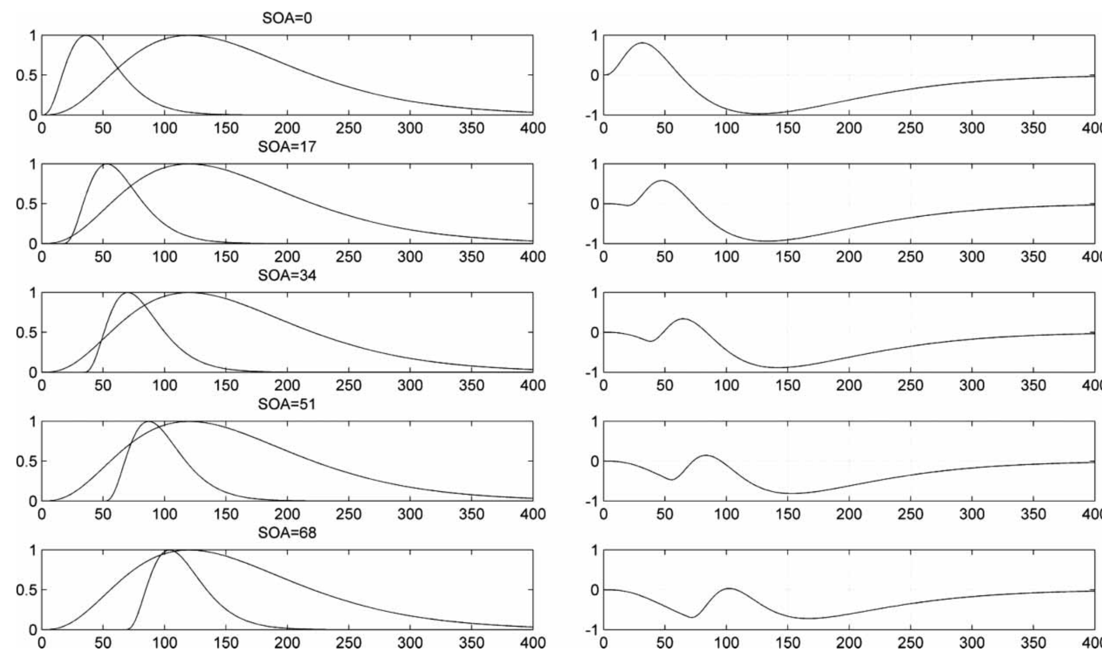

Figure 3. *The order-detection mechanism of the temporal-profile model if the unattended stimulus leads the attended stimulus for the SOAs (stimulus onset asynchronies) 0, +17, +34, +51, and +68 (positive SOAs). The left column shows the temporal profiles, the right column the difference function of the profiles.*

stimulus leads to clearer peaks in the difference function for small SOAs (see Figures 1, 2, and 3). Stelmach and Herdman indeed found better temporal order discrimination if one stimulus was attended. However, other studies have failed to find this effect (e.g., Scharlau, 2007; Scharlau & Neumann, 2003), although they used the binary TOJ, which might not be sufficiently sensitive; moreover, although they also used a unimodal visual paradigm, they manipulated attention by peripheral cues, whereas Stelmach and Herdman manipulated attention by instruction. In the present study we investigated whether there would be a change in discrimination performance with peripheral cues and a nonbinary TOJ.

To summarize, the PSS, the most widely used parameter for assessing temporal order perception, might be misleadingly interpreted as the point of perceived simultaneity. This doubt is backed up by empirical findings as well as theoretical models and considerations. In the present study we aimed to clarify this issue. In the prior-entry paradigm we scrutinized whether perceived simultaneity and perceived temporal order are two sides of the same coin—that is, whether simultaneity is perceived if the exact order of stimuli cannot be discriminated. In contrast to former studies, we used both peak and overall frequency of "simultaneous" judgement to answer this question.

EXPERIMENT 1

In order to delve into exactly what observers perceive at the PSS, we provided judgement alternatives for the perception of simultaneity as well as for uncertainty about the temporal order. Thus the observers could indicate a specific order of the two targets, or that they were simultaneous, or that they were uncertain. We expected that the PSS in the control condition would be the true point of subjective simultaneity, while in prior-entry trials the PSS would be accompanied by maximal uncertainty and not simultaneity. In the following paragraphs, we explain how these hypotheses can be tested at the operational level.

Predictions about prior entry

As in earlier studies (e.g., Scharlau et al., 2006; Scharlau & Neumann, 2003) we induced prior entry using a peripheral cue. Also in line with these studies, we used a cue that could be backward masked by the target; this ensured that observers could not mistake the cue for the target, an argument made against attentional effects of peripheral cues by Pashler (1998; see Scharlau & Neumann 2003, Experiment 2, for a more thorough discussion). This is an entirely methodological measure; the logic of this study does not presuppose masking.[2]

Earlier studies on prior entry elicited by peripheral cues (Scharlau, 2004; Scharlau et al., 2006) found that its size—the degree to which attention accelerates the attended stimulus—depends on the degree of spatio-temporal interference in the stimulus sequence. Interference arises, for example, if the stimulus at the unattended location appears closely after the cue and, being a target, captures attention away from the cue. Prior entry is then smaller. As Scharlau et al. argued, order judgements should be analysed separately for high-interference and low-interference conditions. Following these authors, the best method is to divide the judgements into the classes "attended stimulus first" and "unattended stimulus first" and to interpret the former, derived from low-interference trials, as the true measure of prior entry (for a more thorough discussion see Scharlau et al.). Apart from the issue of being able to evaluate true prior entry—that measured under conditions that reflect purely the accelerating effect of attention on information processing unbiased by other influences—measuring the effect under high-interference trials, or even averaging across low- and high-interference trials, might reduce the sensitivity of the experimental

[2] Note that recent studies on prior entry by masked cues termed the speed-up as "perceptual latency priming", relating it to the broader topic of processing of nonconscious information (priming). As this is of no special relevance for the present study, we use the more common term "prior entry" here.

paradigm. Thus, we also looked at high- and low-interference conditions separately.

Predictions about discrimination accuracy

As mentioned above, the temporal-profile model predicts that directing attention to one of the stimuli leads to higher discrimination accuracy. Since earlier findings on prior entry by peripheral cues did not support this (e.g., Scharlau, 2002; Scharlau & Neumann, 2003), we wanted to test this in more detail with a four-alternative TOJ.

Predictions about judgement times

Judgement times provide further insight into temporal perception, especially with respect to uncertainty. We can assume that observers are slowest in their judgements if they are maximally uncertain. Shore et al. (2001), who regard the PSS as a "point of maximum uncertainty", interpreted the peak of the average judgement times in an unspeeded TOJ task as an indicator of maximal uncertainty. We follow this procedure and take the peak of judgement times as an additional indicator of the PSS. Additionally, judgement times should be influenced not only by uncertainty, but also by the degree of spatio-temporal interference under which they are made. Observers should judge faster under low interference and slower under high interference. (Note, however, that assessing the PSS by judgement times might be problematic because judgement times often vary strongly between participants; for a more detailed discussion of using peak judgement times as estimates of the PSS see Scharlau, 2007.)

Predictions about "uncertain" judgements

We included "uncertain" judgements mainly to avoid any contamination of "simultaneous" judgements with other perceptions, as could have occurred in the method used by Scharlau et al. (2006). For example, "simultaneous" might be used as a leftover category, which would not serve our present purpose. In order to avoid this, observers were provided with the opportunity to indicate directly that they were uncertain about the temporal properties of the sequence. However, "uncertain" judgements may also provide important evidence. If the PSS in prior-entry trials is the point of maximal uncertainty, this should be reflected in the respective judgements. That means that "uncertain" judgements should show a peak at PSS in prior-entry trials.

To summarize, for Experiment 1 we made the following predictions:

1. Simultaneity judgements would be less frequent in prior-entry trials than in control trials.
2. Although the frequency of the simultaneity judgements would be considerably lower in prior-entry trials (see Prediction 1), their distribution would be shifted in the direction of the shift of the order judgements.
3. In prior-entry trials the peak of the "uncertain" judgements would correspond to the PSS.
4. Peaks in judgement times would indicate the point of maximum uncertainty, and these peaks would correspond to the PSS shift.
5. Judgement times would also reflect the degree of spatio-temporal interference under which they were made—specifically that observers would make the judgement "attended stimulus first" faster than the judgement "unattended stimulus first" when attention is manipulated.
6. The size of prior entry would be larger for order judgements made under low spatio-temporal interference than for those made under high interference.
7. The discrimination accuracy would be higher for prior-entry trials.

Method

Participants

All participants in this series of experiments were students of Paderborn University, Germany. They either were paid or participated for course credit. They had normal or corrected-to-normal vision, verified by a simple test. A total of 24 volunteers (6 male and 18 female, mean age 23.5 years, ranging from 18 to 34) took part in the first experiment. A total of 2 participants were excluded because they showed flat psychometric functions that could not be analysed parametrically.

Apparatus
Stimuli were presented in dark grey (26.6 cd/m^2) on a light-grey background (93.4 cd/m^2) on a 17″ cathode ray tube monitor. The refresh rate of the monitor was 60 Hz, and its resolution was set to 1,024 × 768 pixels. The experimental program was written in Matlab 7.5.0 and made use of the Psychtoolbox 3 (Brainard, 1997; Pelli, 1997). Participants sat in a dimly lit room. Viewing distance was fixed at 57 cm by a chin rest. The centre of the monitor was at eye level. Participants responded by pressing the keys 8, 6, 2, and 4 on the number block of a standard keyboard using the preferred hand. Four alternative mappings varied the respective numbers for indicating the judgement alternatives. The different mappings were balanced over participants.

Stimuli
To provide maximal comparability, we used the same stimuli as those in earlier studies that found robust prior entry (e.g., Scharlau, 2004; Scharlau et al., 2006; Scharlau & Neumann, 2003). In each trial, a pair of visible targets, one diamond and one square, was presented (Figure 4).

Attention was manipulated by presenting peripheral cues. They were smaller replicas of the targets and were backward masked by them, which ensured that their detectability was reduced (Scharlau & Neumann, 2003). Such backward masking with nonoverlapping stimuli is especially efficient and often perfect at SOAs between 40 and 80 ms. As in the present study the SOA between cue and target was 68 ms, we expected good masking (Breitmeyer, 1984; Scharlau & Neumann, 2003). As an additional means of avoiding cue–target confusions, we always paired the cued target with a cue of the opposite shape. That is, a square target was cued by a diamond at the same location, and a diamond target was cued by a square cue. Shape-incongruent cueing provides a (possibly conservative) estimate of prior entry that is not inflated by cue–target confusions.

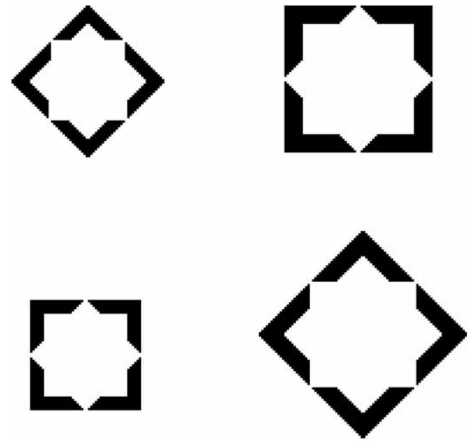

Figure 4. *Cues (left side) and target stimuli (right side). The stimuli were used in all experiments. Cueing was always shape incongruent: If the cue was a diamond, the cued target was always a square, and vice versa.*

The target pair was horizontally aligned above or below fixation with the stimuli at a horizontal distance of 6.3° from fixation. The cue, which always had the alternative shape to the cued (and masking) target, fitted exactly into the inner contours of the respective target. Edge length of targets was 2.1°; edge length of cues was 1.6°.

General procedure
Each trial started with the presentation of a fixation cross in the centre of the screen, which remained visible during the entire trial. After 800 ms to 1,200 ms the target pair was presented, one target to the right of fixation, the other to the left. Whether the pair was presented above or below fixation was randomized. Target shapes at right and left locations were also randomized over the trials.

Targets were presented with SOAs ranging from −68 to +68 ms in steps of 17 ms. Negative SOAs were arbitrarily assigned to trials in which the attended target led. Targets were turned off after 34 ms. In half of the trials, one of the targets was preceded by a cue (prior-entry trials). This was the attended target or comparison stimulus, while the uncued target was the standard stimulus. The cue was also turned off after 34 ms, and the cueing SOA between cue and target was 68 ms. Each of the two target shapes was cued equally often. In the uncued control trials, one of the target stimuli was defined as the comparison and one as the standard stimulus, matching the conditions of the prior-entry trials. In total there were 18 experimental conditions: 9 (SOAs) × 2 (control trials/prior-entry trials). Each condition was presented 32 times in random order.

Participants judged the temporal order of the targets with the judgement alternatives "diamond first", "square first", "simultaneous", and "uncertain". They were assigned randomly to one of four mappings. The instructions emphasized accuracy and did not require fast responding. Before data recording, participants underwent 32 warm-up trials; after each warm-up trial, error feedback was provided. If participants judged "uncertain", "uncertain" was given as feedback. During these warm-up trials no cues were presented. During the experiment proper a self-terminated break was made after every 40th trial. A session had a mean duration of 50–55 min.

Results and discussion

The judgements "square first" and "diamond first" were translated into the judgements "comparison stimulus first" and "standard stimulus first". For each target SOA and cueing condition the frequencies of the four judgements ("comparison stimulus first", "standard stimulus first", "simultaneous", "uncertain") were calculated. The distributions of these judgement frequencies can be seen in Figure 5.

For the order judgements, psychometric functions were approximated by logistic functions with the psignifit toolbox 2–5–6 for Matlab (Hill, 2008). It implements the maximum-likelihood method as described by Wichmann and Hill (2001). We computed prior entry as the difference between the .5 thresholds for trials with and without manipulation of attention. To assess the different degrees of spatio-temporal interference, we computed prior entry separately for each order judgement. Note that for binary TOJs, the PSS is identical to the .5 threshold of each of the two order judgements, because with only two alternative judgements, either one of the order judgements is given, so that the frequencies of both judgements must add up to 1.0. Yet in a TOJ with multiple alternatives, the PSS does not have to be the .5 threshold of any one of the order judgements, because the probabilities of the order judgements differ as a function of the frequencies of the additional judgement alternatives. To determine the PSS under these conditions, Woodworth and Schlosberg (1961) recommend computing the midpoint between the .5 thresholds of the two order judgements. This PSS represents the midpoint of the interval of uncertainty. Note that in prior-entry trials the theoretical meaning of the PSS computed as midpoint between the .5 thresholds of the order judgements is unclear. We did not expect it to be a point of subjective simultaneity in prior-entry trials and asked whether it might be a point of maximal uncertainty. However, it should be a point of subjective simultaneity in control trials and should lie around objective simultaneity (SOA zero). For convenience, we report the midpoint of the order judgement .5 thresholds as the PSS, but note that for prior-entry trials no theoretical interpretation of this midpoint as a point of subjective simultaneity is intended. As a measure of discrimination accuracy, the difference limen (DL, defined as the interquartile range) was computed from the order judgements.[3] Median judgement times were computed for each combination of judgement alternative and SOA.

Where possible, we used *contrast analyses*. Contrast analysis allows the experimenter to test directional hypotheses. It can be regarded as a special form of the analysis of variance (ANOVA), in which sums of squares are contrast

[3] We want to stress that DLs computed from binary and multiple-alternative TOJs cannot be compared directly, because the additional judgement alternatives reduce error variance for the two order judgements. In consequence, psychometric functions are probably steeper in TOJs with more than two alternatives. DLs should therefore be smaller.

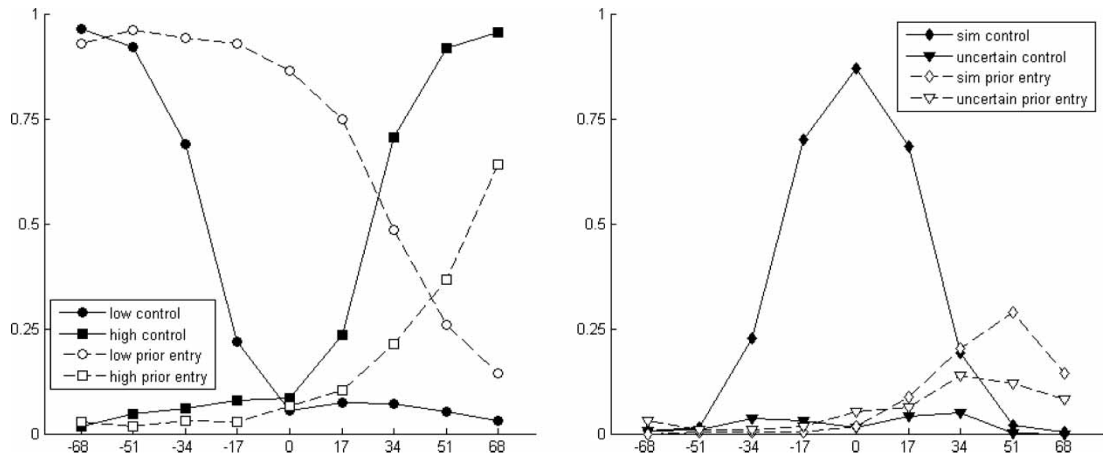

Figure 5. *Experiment 1: The left panel shows the judgement frequencies for the order judgements "comparison stimulus first" (low interference) and "standard stimulus first" (high interference) for control trials and prior-entry trials as a function of SOA (stimulus onset asynchrony). The right panel shows the judgement frequencies for the "simultaneous" and "uncertain" judgements for cued and control trials as a function of SOA.*

weighted. For effect sizes, we use *r-contrast*, a correlation that can be interpreted as a combination of the degree to which the observed data of each participant reflect the hypothesized data pattern and the degree of similarity between the data patterns of the individual participants (Furr, 2008) and Cohen's d (Cohen, 1992).The squared r-contrast can be seen as a proportion of the variance that is accounted for. For multiple comparisons the alpha level was adjusted using the Bonferroni correction.

Prior entry

Experiment 1 revealed substantial prior entry for both order judgements (see Figure 5): "comparison stimulus first", $t(21) = 22.06, p < .001, d = 4.81$, and "standard stimulus first", $t(21) = 10.21, p < .001, d = 2.23$. As can be seen in Figure 5, we found much larger prior entry under low spatio-temporal interference conditions—that is, for the judgement "comparison stimulus first" ($M = 60$ ms)—than under high-interference conditions ($M = 37$ ms), $t(21) = 5.02, p < .001$ (one-tailed), $d = 1.10$. That means that the size of prior entry depends heavily on the degree of competition between the attention-capturing cue and the uncued target. Experiment 1 thus replicated recent findings (Scharlau, 2004; Scharlau et al., 2006) and supports the conclusion that prior entry evoked by cueing should be assessed separately for different levels of cue−target competition. The judgement "comparison stimulus first" possibly provides a more exact estimate of prior entry, because it is derived under low spatio-temporal interference. Providing separate estimates for the two order judgement types of "comparison stimulus first" and "standard stimulus first" is therefore an important improvement by the multi-alternative TOJ as used in Experiment 1. We furthermore computed the PSS as the midpoint of the .5 thresholds of the order judgements. As expected, it lay near the objective simultaneity in control trials ($M = -0.7$ ms) and was shifted to an SOA at which the unattended stimulus preceded the attended stimulus in prior-entry trials ($M = 48$ ms), $t(21) = 23.00, p < .001$ (one-tailed), $d = 5.00$. But note that we did not expect the PSS to actually be a point of subjective simultaneity in prior-entry trials and tested whether it might be a point of maximal uncertainty (see paragraph on the uncertain judgements).

Discrimination accuracy

Unexpectedly, Experiment 1 contradicted the temporal-profile model's prediction that attention improves temporal discrimination. In contrast, observers' discrimination accuracy was worse than that in control trials. A contrast analysis of DL-scores of both order judgements (with contrast weightings of $\lambda = .5$ for control trials and $\lambda = -.5$ for prior-entry trials) revealed better discrimination for control trials ($M = 8$ ms) than for prior-entry trials ($M = 18$ ms), $t(21) = -4.35$, $p < .001$, r-contrast = .69. Note that we chose the smaller contrast weight for prior-entry trials, because better discrimination accuracy would be indicated by a lower DL score for prior-entry trials. This finding also contrasts with those from recent studies on prior entry by masked peripheral cueing, which did not reveal any change in discrimination accuracy (Scharlau, 2007; Scharlau et al., 2006). It is possible that using the present four-alternative TOJ provided enough sensitivity to reveal such differences.

Simultaneity judgements

Experiment 1 confirmed our hypothesis that visual attention, while leading to prior entry, also impairs the perception of simultaneity (see Figure 5). Observers judged "simultaneous" more frequently in uncued control trials than in cued prior-entry trials, $t(21) = 16.85$, $p < .001$, $d = 3.68$. (Due to numerous "simultaneous" judgement frequencies near or at the extremes, we used arcsine-transformed data for this analysis.) This finding is central to our hypothesis: It clearly indicates that when attention has been manipulated by peripheral cues, and prior entry is present, the PSS does not correspond to perceived simultaneity.

Whereas the former test concerns the overall frequency, we also tested hypotheses about the peak of the "simultaneous" judgements. To estimate peaks of the "simultaneous" judgements, we approximated the "simultaneous" judgements with a three-parameter non-normalized Gaussian distribution, $y = a * \exp[-(x - x_0)^2/(2 * s^2)]$. Parameter x_0 represents the maximum's location on the x-axis (the peak in our terminology), while a is the maximum of the distribution (the peak's height), and s represents the standard deviation. One observer was excluded from statistical analysis because he never judged "simultaneous" in prior-entry trials. Both approximations showed excellent fits: $R = .99$, $t(20) = 412.83$, $p < .001$, $d = 92.31$, for control trials, and $R = .99$, $t(20) = 271.15$, $p < .001$, $d = 60.63$, for prior-entry trials (R represents the Pearson correlation between the data and a Gaussian distribution). In line with our hypothesis, the maximum for "simultaneous" judgements was high for control trials ($M = 0.93$) and substantially reduced for trials with manipulated attention ($M = 0.32$), $t(20) = 14.79$, $p < .001$ (one-tailed), $d = 3.31$. As expected, the maximum for control trials lay near objective simultaneity ($M = -0.56$ ms), whereas the maximum for prior-entry trials was shifted away from the point of objective simultaneity and towards the PSS ($M = 46.51$ ms), $t(20) = 26.32$, $p < .001$(one-tailed), $d = 5.89$.

Regarding the dramatically decreased overall frequency of "simultaneous" judgements and their strongly reduced peak in prior-entry trials, it seems pointless to speak of a "point of subjective simultaneity" at the PSS once attention has been differentially directed to one of the targets. Simultaneity of the targets is clearly not the predominant percept under this condition. By contrast, for uncued targets, the PSS indeed turned out to be the point of subjective simultaneity, and the PSS corresponded, as expected, to objective or physical simultaneity.

"Uncertain" judgements

We expected a peak of "uncertain" judgements at the PSS in prior-entry trials and possibly in control trials as well, because at physical simultaneity the discrimination should be most difficult. Thus, we approximated the "uncertain" judgements with the same Gaussian distribution as the "simultaneous" judgements, $y = a * \exp[-(x - x_0)^2/(2 * s^2)]$.

There seem to be manifold strategies for using this category, and this led to several problems. A total of 4 observers never judged "uncertain"; 2 further observers never judged "uncertain" in control trials; 2 other observers' judgements could not be approximated (R near zero); and the maxima of 2 observers' approximated functions lay far beyond the tested SOA range (> 500 ms). All these 10 observers had to be excluded from the analysis of the uncertain judgements, and the following analyses should therefore be interpreted with caution.

The fit of the remaining approximated functions was acceptable: $R = .67$, $t(11) = 7.88$, $p < .001$, $d = 2.38$, for control trials, and $R = .87$, $t(11) = 25.24$, $p < .001$, $d = 7.61$, for prior-entry trials. The mean maximal frequency of "uncertain" judgements was near the point of objective simultaneity ($M = 0.5$ ms) for control trials, while for trials with manipulated attention the mean maximal frequency was shifted in the direction of the PSS shift, $M = 42$ ms, $t(11) = 5.03$, $p < .001$(one-tailed), $d = 1.52$.

Thus the use of "uncertain" judgements neither supported our hypothesis that the PSS is a point of maximal uncertainty nor provided clear evidence against it. Although the maximum of the uncertain judgements was, as expected, shifted in the direction of the PSS shift, observers used it so rarely that any conclusions would be premature.

How can this result be understood? The use of the "uncertain" judgement may be biased by the observers' attitude towards it (e.g., Fernberger, 1930). Responding "uncertain" might be considered as an undesirable response, because it indicates that the observer does not know the correct answer. Therefore observers' rare use of the "uncertain" judgement does not necessarily reflect their actual uncertainty. To reduce such concerns of the observers, we replicated Experiment 1 and relabelled the "uncertain" judgement as "asynchronous, but uncertain about temporal order". However, this measure did not change the results—"asynchronous but uncertain about temporal order" judgements were also very rare, although again shifted in accordance with the PSS. We turn to this topic again in Experiment 2.

Judgement times

We assessed judgement times for each order judgement to provide an indirect measure of uncertainty. Predictably, judgement times had to be aggregated across SOAs because some observers never used a specific judgement for some of the SOAs, resulting in missing values. We therefore divided the SOAs into the most interesting categories: large negative SOAs (−68 ms, −51 ms, −34 ms), small SOAs (−17 ms, 0 ms, +17 ms), and large positive SOAs (+34 ms, +51 ms, +68 ms). With this arrangement 13 of 24 observers had no missing values. We expected that judgement times would peak corresponding to the PSS shift—at small SOAs for control trials and at large positive SOAs in prior-entry trials. Moreover, spatio-temporal interference by the cue should influence judgement times: For the judgement "comparison stimulus first" observers should judge faster in cued prior-entry trials because interference is low, whereas they should judge more slowly in prior-entry trials for "standard stimulus first" when interference is high. Because these two influences overlap in the present experiment, we computed a contrast analysis that tested a prior-entry hypothesis reflecting only prior entry against a second combined hypothesis reflecting both prior entry and spatio-temporal interference. Table 1 shows

Table 1. *Contrast analyses: Weights of judgement times for Experiments 1 and 2*

		Hypothesis	
Judgement	*SOA*	*Prior entry*	*Combined*
"Comparison stimulus first"			
Control trials	negative	1	1
	small	2	2
	positive	1	1
Experimental trials	negative	1	0
	small	1	0
	positive	2	1
"Standard stimulus first"			
Control trials	negative	1	1
	small	2	2
	positive	1	1
Experimental trials	negative	1	1
	small	1	1
	positive	2	2

Note: The contrast analyses were computed with λ-contrast weights. To receive these contrast weights, the weights presented in the table had to be standardized to a mean of zero. SOA = stimulus onset asynchrony.

the weights for both hypotheses. Note that for both the maxima of uncertainty were expected at the location of the PSS—at small SOAs for control trials and at large positive SOAs in prior-entry trials.

The contrast analysis indicated that the combined hypothesis explained the data slightly better, $t(12) = -1.36$, $p < .10$, r-contrast = .37. After Bonferroni adjustment of the alpha level the prior-entry hypothesis was not significant, $t(12) = 1.74$, $p < .10$, r-contrast = .45, whereas the combined hypothesis revealed a marginally significant effect, $t(12) = 2.13$, $p < .05$, r-contrast = .52. Apart from the problem of missing values, judgement times might be an index of uncertainty: Their maxima were roughly compatible with the prior-entry hypothesis, if it was combined with assumptions about spatio-temporal interference.

To sum up, Experiment 1 showed that the PSS is not necessarily the point of subjective simultaneity. It was not the PSS if attention was manipulated by peripheral cues. Although the peak of simultaneous judgements was shifted in accordance to the PSS shift, their frequency was dramatically reduced. This indicates that simultaneity was rarely perceived. But if attention was not manipulated, the PSS was indeed the point of subjective simultaneity. Thus the question of whether the PSS is a point of maximal uncertainty cannot be answered with certainty on the basis of Experiment 1. The results provided by the frequencies of the "uncertain" judgements and the latencies of the order judgements were not consistent with each other.

Before proceeding to Experiment 2 we want to mention one study on visual prior entry that apparently contradicts our results (Jaśkowski, 1993). This study found no reduction of "simultaneous" judgements if attention was directed. Jaśkowski instructed observers to direct attention to one of the target positions, either in the upper or in the lower part of the screen, while fixating the centre. A substantial number of "simultaneous" judgements was made, and there were no differences between prior-entry and control conditions. Nonetheless this finding does not necessarily contradict our hypothesis, as Jaśkowski did not find prior entry either, suggesting that he did not manipulate attention successfully.

EXPERIMENT 2

Contrary to our suggestion that observers perceive—at least in prior-entry trials—uncertainty rather than simultaneity at the PSS, observers used the "uncertain" judgement only rarely. However, as we argued above, it is perhaps premature to conclude that observers do not perceive maximal uncertainty at the PSS. First, observers might have thought "uncertain" an undesirable judgement, because not knowing the correct answer implies bad performance. Second, if one uses judgement times as an indirect measure of uncertainty, the results approximately supported our hypothesis.

To render the assessment of uncertainty less susceptible to social desirability, Experiment 2 used postdecision wagering, a method adopted from Persaud, McLeod, and Cowey (2007): After each TOJ, observers bet points on their judgements. These points were gained if the judgement was correct and lost if it was incorrect. To enhance observers' commitment to the wagering task, the two best observers received an extra financial reward. Persaud et al. (2007) showed that postdecision wagering is an appropriate technique to assess observers' confidence about a certain decision. If observers feel uncertain about temporal order they should bet low point scores, whereas they should bet high point scores if they are certain about their temporal order judgement.

For Experiment 2 we made the same predictions as those for Experiment 1. We expected:

1. A reduction in the frequency of simultaneity judgements for prior-entry trials.
2. Although the frequency of simultaneity judgements would be reduced in prior-entry trials, their peak would be shifted in the direction of the PSS shift.
3. In trials with a cue, the maximal frequency of the "uncertain" judgements would correspond to the PSS shift.

4. Peaks in judgement times would indicate the SOA at which observers were maximally uncertain (point of maximum uncertainty), and these peaks would correspond to the PSS shift.
5. Judgement times would also reflect the degree of spatio-temporal interference under which they were made—specifically, observers would make the judgement "comparison first" more quickly than the judgement "standard first" when attention was manipulated.
6. The size of prior entry would be larger for order judgements made under low spatio-temporal interference than for those made under high spatio-temporal interference.
7. We abandoned the seventh hypothesis about discrimination accuracy, as it was disproved by Experiment 1.

We expected additionally for Experiment 2 that:

1. In control trials, observers would wager the lowest scores if the two stimuli appeared simultaneously.
2. In prior-entry trials observers would bet lowest scores at SOAs at which the unattended stimulus led the attended stimulus, in correspondence to the PSS shift.
3. Observers' wagers would reflect the degree of spatio-temporal interference under which they were made, so that for the judgement "comparison stimulus first" observers would bet higher point scores in trials with attentional manipulation, while for the judgement "standard stimulus first" observers would bet lower point scores for trials with attentional manipulation.

Method

Participants
A total of 18 participants (6 male, 12 female, mean age = 24.11 years) took part in the experiment.

Stimuli and apparatus
Stimuli and apparatus were the same as those in Experiment 1.

Procedure
The general procedure was the same as that in Experiment 1 except that observers gave a ternary TOJ (two order judgements plus "simultaneous") and indicated their uncertainty indirectly by betting 1 to 6 points on their judgement. If their TOJ was correct, the points were subscribed to their virtual account. Points bet on incorrect responses were subtracted from this account. The 2 best participants received an extra financial reward—the best received 40 euros and the second best 16 euros. For the ternary TOJ observers used the three mouse buttons instead of the number block. Participants were assigned to one of two different mappings: The central mouse button always represented the "simultaneous" response, and the right and the left mouse button represented the order judgements "square first" and "diamond first", or vice versa (balanced across participants). Observers bet points on a 6-point rating scale. The scale consisted of six red buttons on the computer screen, below the fixation point. Numbers from one to six were assigned to the buttons in either ascending or descending order, depending on the mapping. Experiment 2 consisted of 18 experimental conditions: 9 (SOAs) × 2 (control trials/prior-entry trials). Each condition was repeated 32 times. Mean duration of an experimental session was 60 min.

Results and discussion

Data were treated as in Experiment 1. As in Experiment 1, prior entry was larger for the judgement "comparison stimulus first" ($M = 58$ ms) than for the judgement "standard stimulus first" ($M = 29$ ms), $t(17) = 8.97$, $p < .001$ (one-tailed), $d = 2.18$. Figure 6 shows the frequencies for both order judgements. The PSS, computed as midpoint of the .5 thresholds of the order judgements, again lay near objective simultaneity ($M = -1$ ms) for control trials and was shifted to a SOA at which the unattended stimulus preceded the attended stimulus for prior-entry trials, $M = 43$ ms, $t(17) = 17.92$, $p < .001$ (one-tailed), $d = 4.35$. Note that the results of Experiment 1 supported our prediction that the

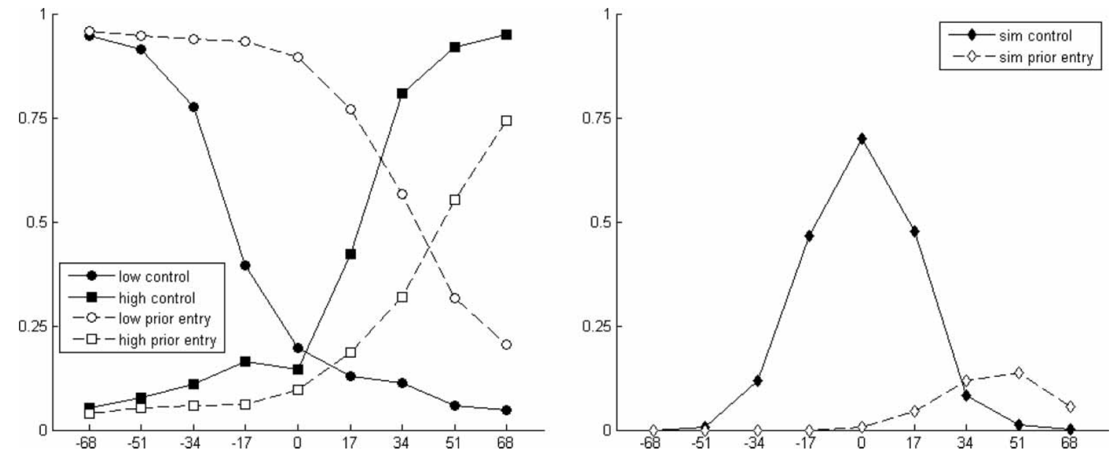

Figure 6. *Experiment 2: The left panel shows the judgement frequencies for the order judgements "comparison stimulus first" (low interference) and "standard stimulus first" (high interference) for control trials and prior-entry trials as a function of SOA (stimulus onset asynchrony). The right panel shows the judgement frequencies for the "simultaneous" judgements for cued and control trials as a function of SOA.*

PSS in prior-entry trials must not be interpreted as the point of subjective simultaneity, but using a direct method to judge "uncertain" provided no evidence that it might be a point of maximal uncertainty. In the present experiment we tested whether the PSS could be revealed as point of maximal uncertainty with a more indirect method.

Again, in contrast to the hypothesis derived from the temporal profile model, observers' discrimination accuracy was lower in trials with attention manipulated, not higher (11 compared to 17 ms for both judgements). A contrast analysis of absolute DL scores of both order judgements, with $\lambda = .5$ for control trials and $\lambda = -.5$ for trials with attention manipulated, revealed a significant negative *t*-value, $t(17) = -3.18$, $p < .01$, *r*-contrast = .61.

Simultaneous judgements

Figure 6 shows the "simultaneous" judgements. A test of the overall frequency for all SOAs showed that observers judged "simultaneous" far more frequently on control trials than on prior-entry trials, $t(17) = 9.20$, $p < .001$, $d = 2.23$ (data for this analysis were arcsine-transformed). As in Experiment 1 we approximated the "simultaneous" judgements to compare their peaks. Because he never judged "simultaneous" in control trials, one observer's judgements could not be approximated. As expected, the peak of simultaneous judgements was higher on control trials than on prior-entry trials ($M = 0.74$ vs. 0.19), $t(16) = 9.48$, $p < .001$ (one-tailed), $d = 2.37$. The location of the maximum was shifted from zero to 44 ms, $t(16) = 18.93$, $p < .001$ (one-tailed), $d = 4.73$.

Wagering task

We used the same SOA categories as those in the analysis of judgement times in Experiment 1; in this experiment 14 of the 18 observers had no missing values. A contrast analysis testing the prior entry and the combined hypotheses revealed that the combined hypothesis was more effective in explaining the data, $t(13) = -2.01$, $p < .05$, *r*-contrast = .49, for weights see Table 2. A contrast analysis revealed a significant effect for the combined hypothesis, $t(13) = 2.89$, $p < .01$, *r*-contrast = .63. Figure 7 shows the mean wagers as a function of SOA categories. It is evident that under low spatio-temporal interference (judgement "comparison stimulus first") observers made higher bets on cued prior-entry trials, whereas under high interference (judgement "standard stimulus first") they made higher bets on control trials.

Table 2. *Contrast analyses: Weights of the postdecisional wagering task, Experiment 2*

		Hypothesis	
Judgement	*SOA*	*Prior entry*	*Combined*
"Comparison stimulus first"			
Control trials	negative	2	2
	small	1	1
	positive	2	2
Experimental trials	negative	2	3
	small	2	3
	positive	1	2
"Standard stimulus first"			
Control trials	negative	2	2
	small	1	1
	positive	2	2
Experimental trials	negative	2	2
	small	2	2
	positive	1	1

Note: SOA = stimulus onset asynchrony.

Judgement times

Due to expected missing values for certain SOA/judgement combinations, we used the same SOA categories for the analysis of judgement times as those in Experiment 1 and as in the analysis of wagers. As in the analysis of wagers, data from 14 of 18 observers could be analysed. A contrast analysis revealed that the combined hypothesis was more effective in explaining the data, $t(13) = -2.81$, $p < .01$, r-contrast = .62. A contrast analysis of the combined hypothesis revealed a significant effect, $t(13) = 3.91$, $p < .001$, r-contrast = .54; for weights see Table 1.

Experiment 2 replicated the findings of Experiment 1 for prior entry and simultaneity. The assessment of observers' uncertainty by the postdecisional-wagering task supports the assumption of Scharlau et al. (2006) that the larger prior-entry effect for "comparison stimulus first" is due to the fact that this judgement is made under conditions of low spatio-temporal interference. Observers' wagers on their TOJs can be explained better by a combination of prior

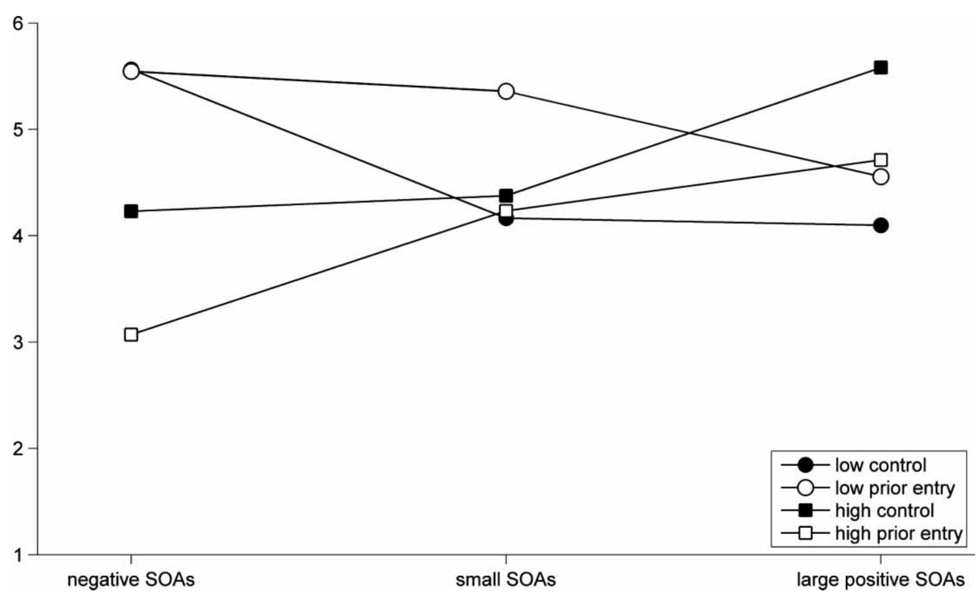

Figure 7. *Experiment 2: Postdecisional wagers (1 to 6) for the order judgement "comparison stimulus first" (low interference) and "standard stimulus first" (high interference) for control trials and prior-entry trials as a function of three SOA (stimulus onset asynchrony) categories (large negative SOAs: −68, −51, −34; small SOAs: −17, 0, +17; large positive SOAs: +34, +51, +68).*

entry and spatio-temporal interference than by prior entry alone. That means observers indicated more certainty about their TOJs by making higher wagers under low-interference conditions than under high-interference conditions.

Most importantly, the postdecisional-wagering task showed that under low spatio-temporal interference conditions the cue enhanced observers' certainty about their TOJs, whereas under high spatio-temporal interference the cue reduced it. In general, the wagering task indicates that observers were more certain than uncertain about their TOJs. Judgement times were in line with the results of the wagering task; they were influenced by the location of the PSS and by the degree of spatio-temporal interference induced by the cue—observers judged faster under low interference than under high interference.

GENERAL DISCUSSION

In the following section we first discuss the main findings of the present study. We then briefly summarize some accompanying findings and finally turn to more general questions of temporal perception and prior entry.

The findings of the present study suggest two conclusions. First, if attention is not manipulated, the PSS indeed represents the point of subjective simultaneity. Simultaneity is the predominant perception at the PSS, and the PSS coincides with objective simultaneity. Second, if attention is oriented to one of the stimuli by a peripheral cue, the PSS does not represent the point of subjective simultaneity. Although the peak of the "simultaneous" judgements was shifted in correspondence to the PSS, their frequency was strongly reduced. We argue that when estimating the PSS, the overall frequency of "simultaneous" judgements should be weighted more strongly than the location of their peak. As mentioned above, a peak can be computed on the basis of most distributions. Given that "simultaneous" judgements were very scarce—which was the case in the prior-entry trials of both experiments—the peak does not convey much information. It thus seems pointless to speak of a point of subjective simultaneity—at least if attention is directed.

The second aim of the present study was to clarify what the PSS might be, if it is not a point of subjective simultaneity. We tested the hypothesis that the PSS is the point of maximum uncertainty (derived, e.g., from Stelmach & Herdman, 1991; Sternberg & Knoll, 1973). We investigated this question in different ways. In Experiment 1, observers gave a TOJ with four judgement alternatives, which included an "uncertain" judgement. In Experiment 2 they made wagers on their ternary TOJ. Additionally, we assessed judgement times in both experiments as a further indicator of uncertainty.

Experiment 1 provided mixed results. The rare use of the "uncertain" category indicated that observers were certain rather than uncertain about their TOJ. There was no difference in "uncertain" judgements between control trials and trials with attention manipulated. Judgement times, however, showed a different pattern, which supported our hypothesis. They were slightly influenced by the location of the PSS, indicating maxima of uncertainty roughly around the PSS. A similar—but more pronounced—pattern was found in Experiment 2 when uncertainty was assessed by postdecision wagering.

In Experiment 2, observers made higher wagers under the combined conditions of low interference and prior entry. In contrast, they made lower wagers when high interference and prior entry coincided. In other words, uncertainty was caused by the combined influence of high interference and prior entry. This finding supports the assumption of Scharlau et al. (2006) that differences in prior-entry estimates for the order judgements "comparison stimulus first" and "standard stimulus first" result from the fact that the order judgements in cued trials are made under different degrees of cue–target competition. The cueing leads to higher judgement certainty, but only if there is low cue–target competition. If there is high cue–target competition—which reduces the power of the cue to attract attention—cueing reduces judgement certainty.

To summarize, some uncertainty is involved in perception at the PSS when prior entry is present.

The combined findings show, however, that no perception is predominant and that the subjective experience is heterogeneous. Although the PSS can be computed easily, its theoretical interpretation is difficult. It is the point of subjective simultaneity in control trials, but it coincides with neither uncertainty nor simultaneity in prior-entry trials.

Size of prior entry

In the following, we discuss our findings against the background of prior-entry literature. The present study replicated the observation that prior entry is substantially larger when spatio-temporal interference by the uncued target is low. Prior entry was approximately 60 ms (Experiment 1) and 58 ms (Experiment 2) for low interference, as opposed to 37 ms (Experiment 1) and 29 ms (Experiment 2) for high interference. Thus the difference between high- and low-interference conditions, 23 and 29 ms for Experiments 1 and 2, respectively, was much larger than those reported in earlier studies (which, with a cueing SOA of approximately the same size as that used here, reported maximum differences of 12 ms, Scharlau, 2004; Scharlau et al., 2006). The wagering task in Experiment 2, as well as the analysis of judgement times, indicates that this difference is due to different degrees of spatio-temporal interference: observers judged faster and made higher wagers when interference was low. Under these conditions the cue can exert its influence on attention unimpaired by appearance of the targets.

But what is the "real" prior entry? We suggest that low-interference conditions provide the better estimate of prior entry. The estimate derived from high-interference trials will be too low, because here the unattended target captures attention away from the cue. The same holds true for the estimate from binary TOJs in which low- and high-interference trials are aggregated. In the low-interference conditions, the cue has the best chance to capture attention as fully as possible. This interpretation is further backed up by the knowledge that prior entry is a purely perceptual measure—that is, free from motor preparation and, at least in our paradigm, from response bias (Scharlau, 2004). We want to add one further finding to this. In the present experiments, the cueing SOA was 68 ms, meaning that the cue could accelerate perception to at most 68 ms. As it takes about 100 to 200 ms to direct attention to a new location (e.g., Nakayama & Mackeben, 1989; Suzuki & Cavanagh, 1997), we can also expect that the full cueing SOA translates into an attentional benefit—that is, prior entry. Prior entry in low-interference conditions was 58 ms in Experiment 2 and even 60 ms in Experiment 1—almost as large as it could be.

Discrimination performance

In both experiments, observers' temporal discrimination performance was worse if attention was manipulated. This is surprising for two reasons. First, recent studies on prior entry with masked peripheral cues found no differences in discrimination performance (Scharlau, 2004; Scharlau & Neumann, 2003). Second, Stelmach and Herdman (1991) found better discrimination accuracy, as predicted by their model.

However, both caveats can be resolved by the temporal-profile model. As can be seen in Figures 2 and 3, attending to one stimulus leads to clearer peaks in the difference function—that is, to better discrimination performance—but it does so only for negative SOAs and small positive SOAs. For the positive SOAs 34 ms, 51 ms, and 68 ms it produces a difference function without clear peaks. Such a difference function results in ambiguous order perception and thus flatter and asymmetric psychometric functions.[4] That is, for the larger positive SOAs used in the present study we cannot expect an amelioration of

[4] Note that we can only derive rough assumptions about DL from the temporal-profile model. The reason is that the temporal-profile model makes assumptions about discrimination accuracy for each SOA separately whereas DL is a parameter which applies to the whole psychometric function.

discrimination performance. However, the SOA range used in this study was small in comparison with that employed by Scharlau (2004; 0 to 128 ms) and Stelmach and Herdman (1991; 0 to 100 ms), with their largest SOAs being approximately twice as large as those in this study. For the largest positive SOAs used by these studies, attention leads again to clear peaks in the difference function and should therefore result in relatively unimpaired discrimination accuracy in comparison to that seen on control trials.

PSS and PSE

As mentioned in the introduction, the PSS is functionally equivalent to the point of subjective equality (PSE), which is computed in many psychometric tasks. In more general terms, it is functionally equivalent to the .5 threshold of any sigmoidal psychometric function in a two-alternative forced-choice paradigm. It is therefore an interesting question as to how far the results of the present paper can be generalized to other psychometric tasks.

The line-motion judgement or illusory line motion (e.g., Hikosaka, Miyauchi, & Shimojo, 1993; Scharlau & Horstmann, 2006) and spatial judgement in studies on the flash-lag effect (e.g., Baldo, Kihara, Namba, & Klein, 2002) are two examples of psychometric tasks to which our results might be applied, and which might benefit from an additional third judgement alternative. Illusory line motion refers to the perception of motion in a stationary stimulus—for example, a line—if one stimulus end is cued. The motion is typically perceived to unfold from the cued end. Following the attentional explanation, the cue captures attention and speeds up processing of parts of the stationary stimulus, proportionally to their proximity to the cue, the focus of attention. Thus, different parts of the stationary stimulus arrive with different latencies at motion detectors in the brain, causing the detection of motion. In a more complicated paradigm, Hikosaka et al. (1993) let observers judge the direction of motion in an array of vertical bars, which was presented sequentially, beginning with the bar opposite to the location of the cue. From different interbar SOAs they computed the PSE—the temporal interval between the presentations of the vertical bars at which both possible direction judgements are equally likely. They interpreted it as a reversal point for perceived motion direction and implicitly assumed a percept of no motion at the PSE. A third judgement alternative could give clarity about the percept at the PSE in such motion judgements. Is it indeed “no motion/stationary display” or perhaps maximal uncertainty about motion direction or an ambiguous percept?

The flash-lag effect refers to the observation that a flashed object, which is in perfect spatial alignment with a moving object, is typically perceived as lagging behind it. For example Baldo et al. (2002, Experiment 1) let observers judge the spatial position of two flashed dots, which lay on an imaginary line relative to two inner dots. The latter rotated on an imaginary circle. Observers had to judge whether the rotating dots lagged or led the imaginary line connecting the outer dots. Baldo et al. interpreted the PSE (both position judgements equally likely) as that angle between outer and inner dots that is necessary for the perception of alignment. But without a third “aligned” judgement alternative this interpretation is speculative. Bearing our results in mind, it is possible that observers were maximally uncertain about the spatial position at this point.

TOJ versus simultaneous judgement

The TOJ is by far the most common method in studies on prior entry. Recently, some authors used a simultaneous judgement (SJ) task. Here, observers give a two-alternative forced-choice judgement of whether two stimuli appeared simultaneously or in succession, independent of their order. Schneider and Bavelier (2003), for example, argued that the SJ is less prone to a response bias because it does not depend on correct perception of temporal order. This might be especially relevant for prior-entry experiments, because here a bias might seem likely: Whenever in doubt, observers might judge the attended stimulus to be first. Schneider and Bavelier argued that prior entry assessed by SJ more veridically represents that part of prior entry that can be attributed to attention—and they indeed found smaller prior entry in SJ than in binary TOJ. Here attention was oriented by visual peripheral cues; if attention was directed by central symbolic cues, prior entry was even absent in the SJ (except for a cue lead time of 600 ms), but not in the binary TOJ.

These findings fall into place within the ongoing debate on response bias in prior entry by indicating that a part of visual prior entry can be ascribed to a response bias and that the size of this response bias depends on the method used to orient attention. In a similar vein, Shore et al. (2001) found a larger bias with endogenous than with exogenous cueing. More importantly for the present context, Scharlau (2004) found a bias to be completely absent with masked peripheral cues, even with rigorous testing. In these studies, as well as that by Schneider and Bavelier (2003), we regard the decomposition of possible prior-entry effects into different influences—response bias, resolving uncertainty—as a major step towards the advancement of TOJ methods.

Concerning the SJ, we want to make a further point. If, as we found in the present experiments, attention attenuates the subjective perception of simultaneity, such a reduction should also be found in the SJ task, and this might shed more light on the underlying mechanisms. Unfortunately, the area under the SJ distribution has not been reported so far. Visual inspection of the data of Zampini et al. (2005b)—the only study that provides distributions detailed enough for visual inspection—indicates no reduction of the simultaneity judgements, contrary to our results. If this finding proves to be reliable, how can it be reconciled with the present findings?

One possibility is that a binary judgement like the SJ is more prone to response equalization strategies than a ternary TOJ (e.g., Erlebacher & Sekuler, 1971). This could be tested by having the same observers use the SJ and a TOJ like that used in the present experiments. Another is that all previous studies that found a reduction in simultaneity judgements were unimodal studies in the visual domain, which produced prior entry by spatial attention. Processes involved in visual prior entry might differ from those in bimodal attention. To make one—so far speculative—point: Zampini, Guest, Shore, and Spence (2005a) showed that "simultaneous" judgements in SJ were more frequent if an auditory and a visual stimulus were presented at the same spatial location than if they were presented at different locations. They explained this by multisensory binding: It is more likely that two stimuli of different modalities are bound into the same percept, and are thus perceived as simultaneous, if they are presented at the same location. Such an influence cannot interfere in visual prior entry induced by masked peripheral cues. Thus the lack of reduction in simultaneous judgements in bimodal prior-entry paradigms does not necessarily contradict the results of the present study. However, it stresses a point made by the present paper: When studying prior entry, it is very important to choose the appropriate methods carefully and that they fit the aim of the investigation being undertaken. For a more thorough discussion of TOJ versus SJ methods, although not in a prior-entry paradigm, see Van Eijk, Kohlrausch, Juola, and Van de Par (2008).

Finally, up until this point we have spoken about "prior entry" as if there were only one kind. But regarding the findings outlined above, it is far from clear that exactly the same mechanisms underlie prior entry in bimodal and unimodal situations, or with central and peripheral cues. There is some evidence against a common explanation. For example, response biases are smaller (Shore et al., 2001) or even absent (Scharlau, 2004) with peripheral cues. Also, the time course of visuospatial attention differs to some extent when exogenous or endogenous cues are employed (e.g., Hikosaka, Miyauchi, & Shimojo, 1996; Müller & Rabbitt, 1989; Prinzmetal, McCool, & Park, 2005a; Prinzmetal, Park, & Garrett, 2005b). Finally, "simultaneous" judgements may underlie partially different mechanisms in uni- and bimodal prior entry: As outlined above, multisensory binding cannot play a role in unimodal SJs but can in bimodal SJs. As these different frameworks have not been studied conjointly, we would interpret our results very cautiously and, for the time being, not apply them beyond studies in which visuospatial attention is manipulated by peripheral cues.

Prior-entry experiments assess the relative arrival times of two stimuli, one attended to, the other not. In line with the bulk of studies on TOJs, we interpret this as an acceleration of the attended stimulus. However, it is also possible that the unattended stimulus is decelerated. As far as we know, this issue is not settled. However, we want to point out that masked peripheral cues, as we used them in the present study, speed up choice reaction times by an attentional mechanism (e.g., Ansorge, 2003, Experiment 3). This makes the operation of the same mechanism in TOJs likely.

In summary, if one of two stimuli is attended to, the subjective experience at the PSS is heterogeneous and therefore difficult to interpret. Our finding is at odds with models of temporal perception, which suggest that perception of temporal order and simultaneity are different sides of the same coin: If attention is manipulated, and prior entry occurs, the percept of simultaneity is not the predominant consequence if temporal order cannot be discriminated. We furthermore confirmed the finding that a ternary or four-alternative TOJ is a more sensitive and appropriate method for estimating attentional facilitation elicited by masked peripheral cues. We ascribe this to the fact that a TOJ task with at least three judgement alternatives allows estimation of prior entry separately under high and low degrees of spatio-temporal interference. Our results also have implications for the interpretation of the PSE in other two-alternative forced-choice paradigms; caution should be exercised if the perception at the PSE is not investigated in a multiple-choice paradigm.

Original manuscript received 12 April 2009
Accepted revision received 12 April 2010
First published online day month year

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