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Components of visual prior entry[☆]

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Abstract

The prior entry hypothesis contends that attention accelerates sensory processing, shortening the time to perception. Typical observations supporting the hypothesis may be explained equally well by response biases, changes in decision criteria, or sensory facilitation. In a series of experiments conducted to discriminate among the potential mechanisms, observers judged the simultaneity or temporal order of two stimuli, to one of which attention was oriented by exogenous, endogenous, gaze-directed, or multiple exogenous cues. The results suggest that prior entry effects are primarily caused by sensory facilitation and attentional modifications of the decision mechanism, with only a small part possibly due to an attention-dependent sensory acceleration.
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Keywords: Prior entry; Attention; Perception; Temporal

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1. Introduction

The prior entry hypothesis proposes that paying attention to a stimulus accelerates the sensory processing of that stimulus, and in so doing, reduces the time

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necessary for the stimulus to be perceived. The hypothesis was summarized by Titchener as "The object of attention comes to consciousness more quickly than the objects which we are not attending to" (1908, p. 251), and was originally formulated by von Tchisch (1885), Pflaum (1900) and Geiger (1903) during their studies of Wundt's (1874) "complication" experiment at his Leipzig laboratory. They invoked attention as a post-hoc explanation for errors in the judgment of the position of a moving pointer at the instant a sound was heard. Dunlap (1910) later demonstrated that the results of these experiments critically depended on eye movements and fixation, but the prior entry hypothesis persisted.

Although the prior entry hypothesis is clear and well formed, testing it requires overcoming two hurdles: consistently manipulating the attentional states of the observers and demonstrably measuring their perception. In early experiments, such as those of Hamlin (1895), Drew (1896) and Stone (1926), observers were simply instructed to attend to a particular sensory modality, while in later experiments, such as those of Sternberg, Knoll, and Gates (1971), Vanderhaeghen and Bertelson (1974), Cairney (1975a), and Shore, Spence, and Klein (2001), observers performed a task that required the use of information in one modality, or payoffs or appearance frequencies were manipulated to favor one modality. Among these studies, these methods of orienting attention did not consistently cause prior entry effects. It is possible that these methods do not effectively control the orientation of attention, but it is also possible that these methods do not always cause prior entry between modalities.

Within the visual modality, two main types of cue stimuli have been used to provide information about the location of peripheral target stimuli and to reliably orient attention covertly, without eye movements (see Yantis, 1998, for a review). Exogenous cues are typically abrupt onset stimuli presented at or near the target locations (e.g., Eriksen & Hoffman, 1972; Posner & Cohen, 1984), while endogenous cues are typically instructions or foveal stimuli that only symbolically indicate the target locations (e.g., Posner, 1980; Posner, Snyder, & Davidson, 1980). Several studies (e.g., Hikosaka, Miyauchi, & Shimojo, 1993a; Shore et al., 2001; Stelmach & Herdman, 1991) have demonstrated that both exogenous and endogenous cues cause prior entry effects within the visual modality.

The second obstacle to be overcome, measuring perception, is fundamentally difficult. Unlike behavioral reaction time that can be measured in absolute terms, the latency to perception, which presently has no known physical correlates, may only be measured in relative terms. Researchers attempting to measure perceptual latency have typically employed a temporal order judgment (TOJ) task, in which the observers report which of two stimuli they perceive first. The TOJ may be quantified by the point of subjective simultaneity (PSS), defined as the stimulus onset asynchrony (SOA) between two stimuli at which an observer is maximally uncertain about their order.

The problem with using the TOJ to measure prior entry is that attention may act during multiple stages of the stimulus–response process and might influence the behaviorally measured PSS without affecting perception. The locus of attentional action has long been discussed in the literature, with some researchers believing that attention affects sensory processing (e.g., Bashinski & Bacharach, 1980; Downing, 1988; Handy, Kingstone, & Mangun, 1996; Luck et al., 1994; Posner et al., 1980), and others that attention only affects the decision process (e.g., Müller & Findlay, 1987; Shaw, 1984). Cairney (1975b) suggested that judgment strategy was a better explanation than prior entry for his version of the complication experiment and the results of Stone's (1926) and Sternberg et al.'s (1971) studies. Jaskowski (1993; also see Spence & Driver, 1997; Spence, Shore, & Klein, 2001) argued that attention could produce response biases favoring attended stimuli, and thus shift the PSS, particularly when the temporal delay between the onsets of two stimuli is too small to permit an accurate order determination, and observers are nevertheless forced to guess.

Changing the instructions in a TOJ reveals the dependence of the results on cognitive factors. Using multimodal experiments, Frey (1990) found that the prior entry effect reversed to favor the unattended stimulus when observers were instructed to report which stimulus occurred second, compared to when they reported which stimulus occurred first. Within the visual modality, Shore et al. (2001) found that when the observers judged which stimulus came second instead of first, the PSS decreased but did not reverse as in Frey's study, causing them to conclude that cognitive factors contributed to but did not consume the prior entry effects they observed.

To confirm the prior entry hypothesis with behavioral measurements, it is necessary to eliminate changes in the decision process as an explanation. But as demonstrated in Appendix A.1, a reduction of the stimulus transmission time would be expected to produce the same pattern of results in a simple model of the TOJ as would a shift in a decision criterion that favors the attended stimulus. It is fundamentally impossible to distinguish the two. Another type of perceptual judgment that could be used instead of the TOJ is the simultaneity judgment (SJ), in which observers report whether two stimuli appeared simultaneously or successively. In theory, the SJ more accurately estimates purely sensory effects. If the simultaneity criterion depends only upon the difference between the onsets of two stimuli and not their order, then sensory acceleration can be inferred directly from the SJ data, independent of an observer's simultaneity threshold criterion. As demonstrated in Appendix A.1, varying the width of the simultaneity threshold interval alters the amplitude but not the mean of SJ response distribution.

To our knowledge, only two known studies have investigated how attention affects SJs. In Stelmach and Herdman's (1991) Experiment 5, observers adjusted the delay between two stimuli, one occurring at an exogenously cued location. To achieve the appearance of maximal simultaneity, the unattended stimulus needed to lead the attended stimulus by about 23 ms, smaller than the 50 ms effects reported in their TOJ experiments. Carver and Brown (1997) found that pairs of stimuli in exogenously cued locations were less likely to be judged as simultaneous across a range of SOAs than were pairs of stimuli in uncued locations. They interpret this as indicating that attention narrows the simultaneity threshold interval.

Several researchers have combined the SJ and TOJ into a single judgment using a ternary response task (e.g., Ulrich, 1987). In this task, observers may use a third "simultaneous" response option in addition to the regular TOJ responses. This does not alleviate the problem of the TOJ but instead compounds it by involving additional decision criteria that may vary among observers. Using the ternary response task, Stelmach and Herdman (1991) demonstrated that exogenous cues shift the PSS, but their observers rarely employed the "simultaneous" option when attending to peripheral locations. Jaskowski (1993) used the ternary response task and found no prior entry effect for endogenous cues.

The prior entry hypothesis makes a specific prediction that attention accelerates sensory processing. As mentioned above, attention could also influence the decision mechanism to produce indistinguishable results in a TOJ experiment. While the SJ should be less susceptible to such cognitive effects, a third possible effect exists that could be mistaken for prior entry in both TOJ and SJ experiments. Since exogenous cues occur in the spatial vicinity of the targets, local sensory interactions might occur between the cue and target stimuli, as both stimulate some of the same receptors and neurons in the ascending visual pathways. The cue stimuli might induce excitatory or refractory states that could influence the processing of subsequent stimuli, or the neural activity profiles of the cues could be misidentified or incorporated into the measurement of the onsets of the targets. For example, Fendrich and Corballis (2001) suggested, based on their version of the visual–auditory complication experiment, that the perceived timings of two temporally proximal stimuli are shifted towards temporal convergence. Such sensory facilitation might accelerate sensory processing or reduce the time necessary for stimuli to be registered by a central decision mechanism, but, being independent of attention, would not properly be termed prior entry.

A series of four experiments was conducted to distinguish among the mechanisms, illustrated in Fig. 1, that could produce behavioral results that might be attributed to prior entry: attention-dependent sensory acceleration (prior entry), attention-dependent modifications of the decision mechanism (cognitive effects), and attention-independent sensory acceleration (sensory facilitation). In each experiment, observers made both SJs and TOJs in separate sessions. In Experiment 1 we sought to confirm

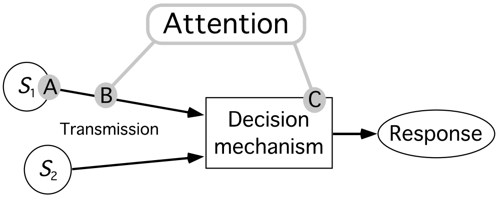

Fig. 1. Three different mechanisms could be responsible for producing behavioral responses that appear to support the prior entry hypothesis. Attention could affect judgments of the temporal order of two target stimuli, S_1 and S_2, at multiple points during the stimulus–response process. One possibility is that attention might accelerate the transmission of one stimulus relative to the other, e.g., by reducing transmission time. This is known as prior entry (B). Another possibility is that attention might have cognitive effects, altering criteria within the decision process that compares the arrival times of the stimuli and leads to a behavioral response (C). The third mechanism, sensory facilitation, is not caused by attention, but instead by local sensory interactions between the target stimuli and the cue stimuli used to orient attention (A).

that exogenous cues caused prior entry and to test the dependence of these effects upon the behavioral task. In Experiments 2 and 3, to distinguish the effects of attention from those of local sensory facilitation, we used endogenous and gaze-directed cues to eliminate sensory transients at the target locations, and we found that local sensory transients were necessary for prior entry. In Experiment 4, we employed multiple exogenous cues to retain sensory transients while reducing or eliminating their attentional capture.

2. Experiment 1

2.1. Introduction

The goal of the first experiment was to replicate experiments in the literature that have demonstrated prior entry effects using exogenous cues within the visual domain and to test the task-dependence of the results. TOJs are susceptible to response biases and other cognitive influences, rendering their results difficult to interpret. In this and subsequent experiments we also employed a SJ that may be less dependent upon cognitive factors and thus more accurate in measuring changes in perceptual latency. A comparison between the results of the two judgments will provide an estimate of the relative contributions of sensory acceleration and of cognitive factors.

2.2. Apparatus

A Matlab (The Math Works, Natick, MA) computer program with Psychophysics Toolbox routines (Brainard, 1997; Pelli, 1997) running on a Macintosh G3 computer (Apple Computer, Cupertino, CA) controlled the stimulus presentation and data collection. The stimuli were displayed on a ViewSonic P817 21-in. monitor (ViewSonic, Walnut, CA) driven at 158.1 Hz by a MP 850 video card (Village Tronic Computer, Sarstedt, Germany). All reported presentation times were quantized by the monitor refresh time of 6.3 ms. Manual responses were collected on the computer keyboard with an estimated timing accuracy of 8 ms.

2.3. Observers

Nine graduate students at the University of Rochester, aged 23–33 years, five female, participated in the experiment. One observer reported being left-handed. All reported normal or corrected to normal vision, were paid for their participation, and were naïve to the purpose of the experiment. Eight of the observers had previously participated in Experiments 2 and 3.

2.4. Stimuli

The stimuli were presented in a room dimly illuminated by indirect lighting on a uniform gray background, 12.5 cd/m^2, with CIE (Commission International d'Eclairage) color coordinates $x = 0.289$ and $y = 0.314$. Two 0.3° circular targets were presented at pseudorandom positions located within an annulus centered at the fixation point, at a radius uniformly ranging from 6.5° to 7.5°. The location of one target was cued by a thin 0.5° white ($84.2\,\mathrm{cd/m^2}$, $x = 0.286$, $y = 0.309$) concentric ring. Placing the stimuli at approximately equal eccentricities avoided the dependence of the TOJ on eccentricity reported by Rutschmann (1966). The separation of the stimuli was constrained to be at least 7° to reduce the invocation of motion mechanisms that considerably improve the resolution of temporal order (Allik & Kreegipuu, 1998; Exner, 1875; Westheimer, 1983; Westheimer & McKee, 1977).

The colors of the two targets were red ($x = 0.623$, $y = 0.340$) and green ($x = 0.292$, $y = 0.601$), randomized among the trials. To ensure the targets were of equal brightness, at the beginning of the experiment, targets stimuli were presented at the same size and a typical spatial configuration used in the experiment, and their colors were alternated at 15 Hz at a luminance level of approximately $16\,\mathrm{cd/m^2}$. Each observer adjusted the ratio of the color intensities to minimize the heterochromatic flicker (see e.g., Tansley & Boynton, 1978).

2.5. Procedure

Observers were seated with their eyes level with and approximately 55 cm away from the fixation point and were instructed to maintain fixation. The observers' heads were not restrained, and their eye movements were not monitored. The experiment consisted of two forced-choice tasks, the SJ and TOJ, performed independently during separate sessions on different days to avoid interactions between the judgments (e.g., see Allan, 1975). The observers were divided into two groups, one making the SJ on the first day, and the other making the TOJ.

For the SJ, the observers were instructed to press one key if the two targets appeared simultaneously ("at the same time"), and to press another key if the targets appeared successively ("at different times, or one before the other"). For the TOJ, the observers were instructed to press a key indicating the color of the target that appeared first. Observers were instructed to make their best guess when uncertain, and that although their responses were not timed, that a prolonged decision would not be helpful, and to respond as quickly as possible while maintaining accuracy.

The two targets were presented either simultaneously or in either order separated by an SOA of 25, 50, 75, or 100 ms. The cue was presented either simultaneously with its target, or preceding it by a cue lead time of 40, 75, 125, 200, 500, or 1000 ms. This range was chosen to sample the effects of exogenous attention, which are present as early as 25 ms after the cue, reach a maximum around 100–150 ms, and decrease to a sustained level by 400 ms or less (Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Murphy & Eriksen, 1987; Nakayama & Mackeben, 1989; Posner & Cohen, 1984). The cues and targets remained visible until the observers responded. A typical stimulus time course is illustrated in Fig. 2.

The method of constant stimuli was used to sample the psychometric function. The 54 combinations of cue lead times and target SOAs were each repeated 20 times

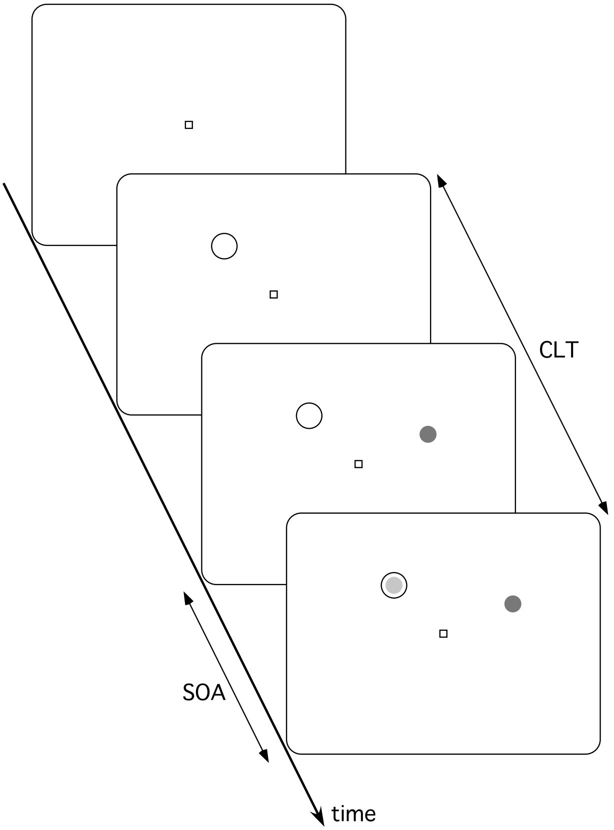

Fig. 2. A typical stimulus frame time sequence for Experiment 1. This sequence begins with a fixation point in an otherwise empty visual field. A ring-shaped cue is presented, followed by two circular targets, one outside the cue (uncued target) and one within (cued target). The targets may be presented simultaneously or successively. The stimulus onset asynchrony (SOA) between the cued and uncued targets was varied across conditions as was the lead time between the cue and the cued target (CLT). In separate sessions, the observers performed two different tasks. In one session, the observers performed a temporal order judgment (TOJ), deciding which target appeared first; in the other session, observers performed a simultaneity judgment (SJ), deciding whether the two targets were simultaneous or not. The illustrated SOA is negative because the uncued target was presented before the cued target, but positive SOAs, for which the cued target is presented first, were also used in the experiment. The figure is not to scale—for clarity, the sizes of the targets and cue have been exaggerated relative to their distances.

with all conditions randomly interleaved. Each experimental session lasted approximately 1 h, during which the observers were automatically allowed to rest and break fixation after every 50 stimuli presentations and to resume the experiment when ready. Text on the computer monitor reminded the observers to maintain fixation before resuming. The observers were given no feedback about their progress other than being informed when they were 25, 50, 75, and 90% complete.

2.6. Eye movements

Although eye movements were not monitored, it is unlikely that eye movements could affect the conclusions. For exogenous cues, the most significant attentional effects are expected to occur at cue lead times too short to permit observers to execute saccades selectively to the unpredictable cued locations before the target stimuli were presented. Crawford and Muller (1992), for example, found that saccadic latencies to such attentional cues averaged over 200 ms. Also, Stelmach and Herdman (1991) monitored eye movements in one of their attentional TOJ experiments but did not observe a difference when trials with eye movements were excluded.

2.7. Analysis

Although the observers were informed that their responses were not timed, their reaction time (beginning from the onset of the second target stimulus) was monitored, and abnormally delayed responses were excluded. To determine outlier points, the skew (as defined by the quotient of the third central moment and the cube of the standard deviation) of the distribution of reaction times was calculated for each observer, each cue lead time, and each SOA. If the skew was greater than 1.2, a value chosen to eliminate only responses occurring in the extreme tail of the reaction time distribution, the trial with the maximum reaction time was discarded, and the procedure was iterated until the skew of the remaining distribution was less than 1.2. Reaction time was not a planned variable of interest and was not analyzed further.

The PSSs were determined through a global maximum likelihood optimization procedure that fit the TOJ data to a cumulative normal distribution function, $\Phi(0, \Delta t + \alpha, \sigma)$, and the SJ data to a difference of cumulative normal distribution functions, $\Phi(\tau, \Delta t + \alpha, \sigma) - \Phi(-\tau, \Delta t + \alpha, \sigma)$, where τ is the simultaneity threshold interval, Δt is the SOA between the target stimuli, α is the sensory processing delay between the stimuli, and σ is the width of the underlying distribution of the difference of the stimuli arrival times. The derivation of these functions is described in Appendix A.1. The variances of the estimates of these model parameters were derived for each observer as described in Appendix A.3, and the PSSs reported were computed as the weighted averages of the α parameters across all observers for each condition.

The prior entry hypothesis was tested by evaluating the experimental data within the context of three types of generative models based on Sternberg and Knoll's (1973) general models. In these models, described in Appendix A.1, the decision about the temporal order or simultaneity of two stimuli is based only upon the difference of their arrival times at a central decision mechanism. The deterministic decision rule is a simple model for the TOJ in which observers make a deterministic choice about the order of the stimuli based on their arrival times. This is the model used to examine the PSS above, and the model that has typically been used in the literature. The α parameter in this model may be influenced by both sensory and cognitive factors and its measure alone cannot be used to reliably estimate prior entry. In the other two models, the triggered-moment and the perceptual-moment models, observers are only able to determine the order of the stimuli if the interval between their arrival times exceeds a simultaneity threshold interval. Otherwise, the observer can only guess the order. The difference between the two moment models is subtle. In the perceptual-moment model, observers have discrete moments of perceptual time with a duration τ that occur clocklike, independently of the occurrence of any stimuli. If two stimuli happen to arrive within the same perceptual moment, then they are perceived simultaneously. In the triggered-moment model, the simultaneity interval is initiated by a stimulus, and subsequent stimuli are perceived as simultaneous if the arrive within a duration τ.

The prior entry hypothesis predicts that the arrival of the unattended stimulus should be delayed relative to the attended stimulus. Therefore, a non-zero sensory acceleration parameter, α, should be necessary to explain the data. This prediction was tested within the framework of each of the three types of models by comparing the relative plausibilies of a model of each type with a freely varying α to a model with α fixed to zero. It is important to realize that while observing a non-zero α is a necessary condition for accepting the prior entry hypothesis, it is not a sufficient condition, as attention-independent sensory facilitation could also cause a similar acceleration effect. The models were evaluated using the Bayesian method of inference (MacKay, 1992), described in Appendix A.2. This method of hypothesis testing ranks the probability that each hypothesis could have generated the experimental data and naturally accounts for the different number of parameters between models. In addition to testing whether a non-zero α parameter is necessary for each type of model for each experimental condition, we also compare the relative plausibilities of the three types of models.

In addition to the α, τ, and σ parameters described above, the TOJ models included a response bias parameter β, defined as the probability that an observer, when uncertain about the actual order of the stimuli, responds that the cued target occurred first. All of the parameters are discussed in more detail in Appendix A.1. The Bayesian method of hypothesis testing requires a subjective choice of plausible ranges for the parameters. In this study, the evidence for the models was numerically integrated using an adaptive multidimensional algorithm (Genz & Malik, 1980) over the following parameter ranges: $\alpha \in [-150, 150 \text{ ms}]$, $\sigma \in [0, 150 \text{ ms}]$, $\tau \in [0, 150 \text{ ms}]$, and $\beta \in [0, 1]$. Since a strong peak centered in parameter space around the optimal model parameters typically dominated the likelihood function, the results of the hypothesis tests were found not to depend strongly on the choice of these priors.

2.8. Results

For each observer, an average of 5.9% of the trials in each of the SJ and TOJ blocks were excluded from further analysis due to abnormally delayed reaction times, following the procedure described above. The weighted average of the PSSs across observers for each judgment and each cue lead time are shown in Fig. 3A. For both the TOJ and the SJ, the PSSs were non-zero at a cue lead time of 0 ms, increased to a peak at cue lead times of 40 and 75 ms for the SJ and TOJ, respectively, decreased substantially by a cue lead time of 200 ms, and then decreased slightly to a non-zero plateau by a cue lead time of 500 ms. All of the PSSs were significantly

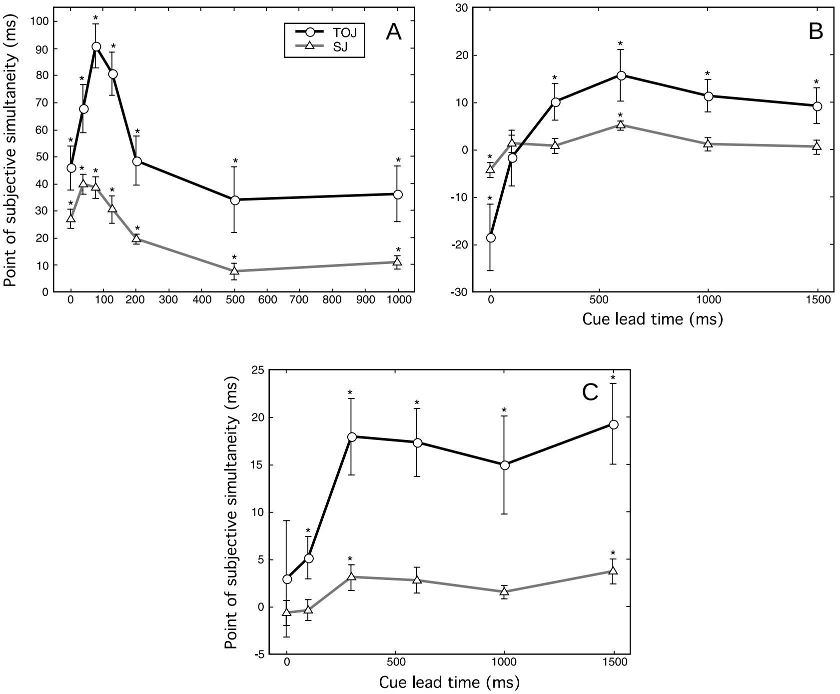

Fig. 3. Shifts in the points of subjective simultaneity (PSS) for the simultaneity (SJ) and order (TOJ) judgments caused by the attentional cues. Error bars indicate the standard error of the weighted means, and asterisks mark the points that differ significantly from zero (two-tailed *t* test on the weighted means, $p < .05$). (A) Exogenous cues (Experiment 1). (B) Central arrow cues (Experiment 2). (C) Gaze-directed cues (Experiment 3). Note that the scale differs among the graphs.

different from zero for each cue lead time for both the SJ and TOJ (*p*s < .05; all statistics were computed using a two-tailed *t* test on the weighted means). Further, the PSS for the TOJ at each cue lead time were consistently larger than and differed significantly from those of the SJ (*p*s < .05).

The results of the Bayesian inference tests are shown in Fig. 4A for the SJ and Fig. 5A for the TOJ. For both the SJ and TOJ, the models that included a non-zero α were more plausible than the models with α fixed to zero. For the SJ, the triggered-moment model was more plausible than the perceptual-moment model only for short (0 and 40 ms) and long (500 and 1000 ms) cue lead times. For the TOJ, neither the triggered-moment nor perceptual-moment models were generally much more plausible than the deterministic decision rule.

2.9. Discussion

The presence of the exogenous cue significantly affects both the SJ and TOJ, with dynamics typical of an exogenous attentional process, and at all cue lead times, a

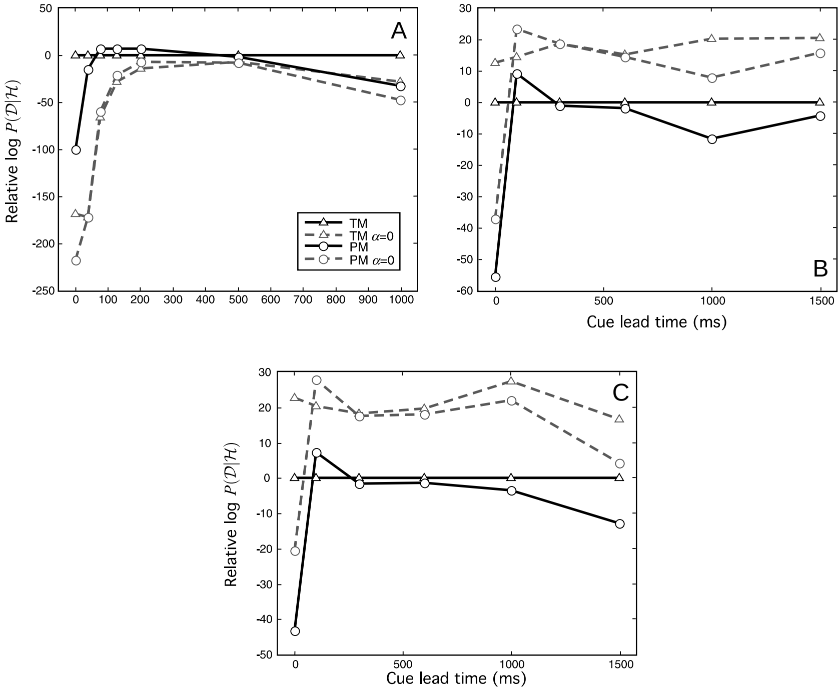

Fig. 4. Bayesian inference model comparison test for the simultaneity judgment in Experiments 1 (A) through Experiment 3 (C). The plausibilities of the triggered-moment (TM) and perceptual-moment (PM) models are compared, with the sensory acceleration parameter, α, free to vary or fixed to zero ($\alpha = 0$). The natural logarithm of the joint probability of the data from all observers given each model, $P(\mathcal{D}|\mathcal{H})$, is plotted relative to the triggered-moment model for each cue lead time.

non-zero sensory acceleration parameter, α, is necessary to explain the data. The magnitudes of the results are consistent with previous studies. Stelmach and Herdman (1991) used an exogenous cue with an offset 250 ms before the target and observed a shift in the PSS of about 50 ms for the TOJ and 23 ms for the SJ. Hikosaka, Miyauchi, and Shimojo (1993b) observed shifts of the PSS for the TOJ of about 24, 56, 19, and 8 ms for onset cue lead times of 50, 150, 400, and 1600 ms, respectively. Shore et al. (2001) used a cue lead time of 60 ms and observed a PSS shift for the TOJ of about 74 ms.

Sensory acceleration effects are present in both the SJ and the TOJ, and the discrepancy between the magnitudes of the PSSs determined from the two judgments may be explained by attention-dependent response biases or decision criteria shifts present in the TOJ but not the SJ. The existence of sensory acceleration does not necessarily validate the prior entry hypothesis, because it could be caused by sensory facilitation from the transient exogenous cues rather than by attention. That the PSS in both tasks was positive at a cue lead time of zero provides support for non-attentional sensory facilitation, since attention would not have time to be re-oriented. The relative contributions of sensory facilitation

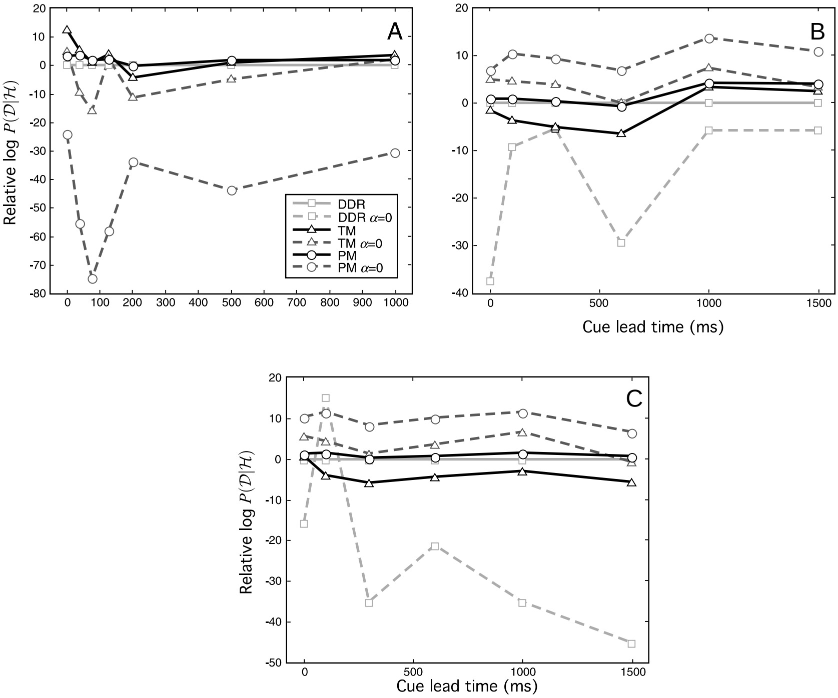

Fig. 5. Bayesian inference model comparison test for the temporal order judgment in Experiments 1 (A) through Experiment 3 (C). The plausibility of the deterministic decision rule (DRR), triggered-moment (TM) and perceptual-moment (PM) models are compared, with the sensory acceleration parameter, α, free to vary or fixed to zero ($\alpha = 0$). The natural logarithm of the joint probability of the data from all observers given each model, $P(\mathcal{D}|\mathcal{H})$, is plotted relative to the deterministic decision rule model for each cue lead time. In A, the deterministic decision rule with α fixed to zero is well off the bottom scale of the graph and is not shown.

and prior entry to the observed sensory acceleration are investigated further in the remaining experiments.

3. Experiment 2

3.1. Introduction

Although Experiment 1 confirmed that exogenous cues produced sensory acceleration, it is possible that their effects are not due to attention, but instead due to sensory facilitation in their vicinity. To distinguish these mechanisms, attention was oriented in this second experiment with an endogenous cue, a central arrow located remotely from the targets (Posner, 1980), thus preventing sensory facilitation. Though the arrow was irrelevant for the task, it provided completely accurate location information about one of the two targets to maximize its capability to orient attention (Hughes, 1984; Jonides, 1981). Previous studies, as described above, are in conflict as to whether endogenous cues cause prior entry.

3.2. Observers

Nine graduate students at the University of Rochester, aged 21–32 years, six female, participated in the experiment. One observer reported being left-handed. All reported normal or corrected to normal vision, were paid for their participation, and were naïve to the purpose of the experiment. All observers had previously participated in Experiment 3.

3.3. Stimuli and procedure

The method was similar to that for Experiment 1 with the following exceptions. Instead of rings at the target location, a central arrow cue was used. A white ($84.2\,\mathrm{cd/m^2}$, $x = 0.286$, $y = 0.309$) arrow, whose tip extended 1.5° from the fixation point, was presented centered at the fixation point in a pseudorandom orientation. After a delay of 0, 100, 300, 600, 1000, or 1500 ms, the cued target was presented at a location whose angle relative to the fixation point matched the orientation of the arrow. The cue lead times were altered from Experiment 1 because the effects of endogenous attention develop more slowly than those of exogenous attention, increasing to a similar sustained level by 300–400 ms (Cheal & Lyon, 1991; Müller & Rabbitt, 1989). The stimulus time course is illustrated in Fig. 6.

3.4. Results

An average of 5.8% of the trials in the SJ block and 5.1% in the TOJ block for each observer were excluded from further analysis due to abnormally delayed reaction times, following the procedure described in Experiment 1. The PSSs were calculated as in Experiment 1 and are shown in Fig. 3B. For both the SJ and TOJ, the PSSs were negative and significantly different than zero at a cue lead time of 0 ms ($p < .05$). For the TOJ, the PSS increased to a positive sustained level, significantly different than zero ($p < .05$) for cue lead times of 300 ms and greater, while for the SJ, the PSS remained near zero at all cue lead times, significantly different than zero only at a cue lead time of 600 ms. The PSSs for the TOJ and SJ differed significantly ($p < .05$) from each other at the cue lead times of 300, 1000, and 1500 ms and differed marginally significantly ($p = .07$) from each other at cue lead times of 0 and 600 ms.

The results of the Bayesian inference tests are shown in Fig. 4B for the SJ and Fig. 5B for the TOJ. In contrast to Experiment 1, for both the SJ and TOJ, the triggered-moment and perceptual-moment models with α fixed to zero were more plausible than the models with α free to vary. For the TOJ, both models with α fixed to zero were also more plausible than the deterministic decision rule, which was more plausible with α free to vary than fixed to zero. For the SJ, as in Experiment 1, the triggered-moment model was more plausible than the perceptual-moment model at the

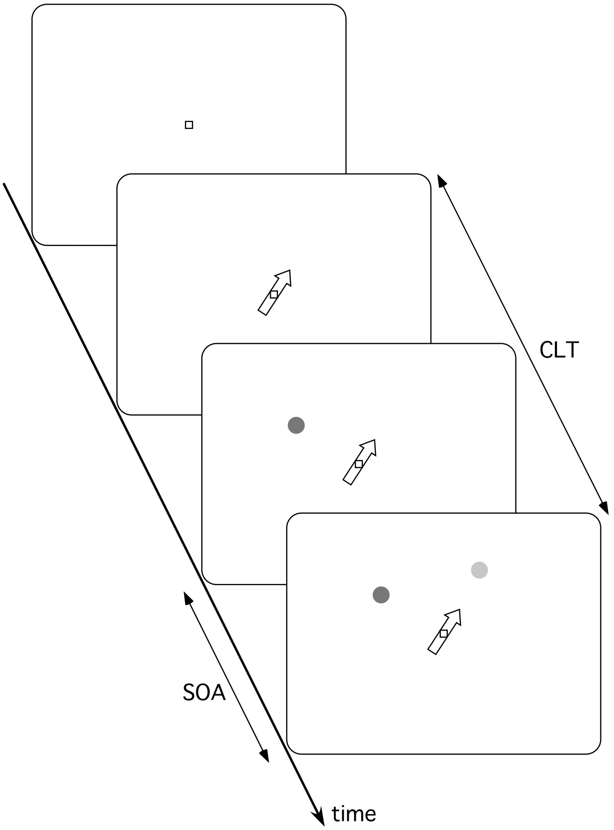

Fig. 6. An example stimulus frame time sequence for Experiment 2. The cue lead time (CLT) between the cue and the cued target and stimulus onset asynchrony (SOA) between the cued and uncued targets are shown. The illustrated SOA is negative because the uncued target was presented before the cued target. The figure is not to scale—for clarity, the sizes of the targets and arrow have been exaggerated relative to their distances.

short and long cue lead times, while the perceptual-moment model was more plausible at all cue lead times for the TOJ.

3.5. Discussion

The evidence does not support the notion that the central arrow cue caused sensory acceleration. Though changes in the PSS of the TOJ became significant after a cue lead time of 300 ms, consistent with the expected time course of endogenous attention, the effects were generally not present for the SJ. Although the deterministic decision rule model for the TOJ required a non-zero α, this can be explained as the result of a criterion shift or response bias. A non-zero α was not required in the triggered- or perceptual-moment models that explicitly account for response biases, nor for the SJ models. Therefore, the shifts in the PSS observed for the TOJ with the central arrow cue can be explained at least as well by a response bias as by a sensory acceleration. Although eye movements were possible at cue lead times of 300 ms and longer, foveal targets should be perceived more rapidly than peripheral targets (Rutschmann, 1966), potentially explaining any positive results, but not explaining the null results for the SJ.

The results from the TOJ were smaller than had been reported for similar cues in previous studies. Stelmach and Herdman (1991) reported shifts in the PSS of about 40 ms for a cue lead time of 250 ms, while Shore et al. (2001) reported shifts of about 30 ms for a cue lead time of 405 ms. The main difference between the procedure of the present experiment and that of the previous studies is that in those studies, the target locations were confined to two locations, while in this experiment, the targets could occur in any location within an annulus centered at the fixation point.

One potential flaw of this experiment is the possible failure of the central arrows to orient attention to their targets. While exogenous cues automatically orient attention (see LaBerge, 1981) even when known never to indicate the location of a visual target (Remington, Johnston, & Yantis, 1992; though see Yantis & Jonides, 1990), endogenous cues require volitional effort from the observer to re-orient attention (Jonides, 1981). Differences in attentional allocation might, for example, explain the discrepancy between the results from the SJ and TOJ tasks in this experiment if the observers chose to distribute their attention broadly in the SJ task in which both targets must be detected but focused their attention in the TOJ task in which only the first target must be detected.

4. Experiment 3

4.1. Introduction

To reduce the possibility that observers could distribute their attention differently in the TOJ and SJ tasks, we wished to employ an attentional cue that was automatic yet did not introduce sensory stimulation at the target location. Recently (see Langton, Watt, & Bruce, 2000, for a review), researchers have found that reflexive covert shifts of visual attention to peripheral locations can be triggered by uninformative eye-gaze directions presented at fixation, both in cartoon faces (Friesen & Kingstone, 1998; Kingstone, Friesen, & Gazzaniga, 2000) and pictures of real faces (Driver et al., 1999; Hietanen, 1999; Langton & Bruce, 1999; Langton & Bruce, 2000). Reaction time is facilitated when a target is presented at the location where the eyes are looking. This facilitation effect occurs as early as 105 ms and disappears by 1005 ms (Friesen & Kingstone, 1998). Driver et al. (1999) found that the gaze direction caused faster discrimination of peripheral letters, even when the letters were four times as likely to occur in an opposite location. When the gaze cue conflicted with the target location probabilities in this manner, the gaze cue significantly facilitated discrimination time only at 300 ms, and not earlier or later, suggesting that gaze-directed shifts of attention were only automatic for a limited duration.

4.2. Observers

Ten graduate students at the University of Rochester, aged 21–32 years, seven female, participated in the experiment. One observer reported being left-handed. All reported normal or corrected to normal vision, were paid for their participation, and were naïve to the purpose of the experiment.

4.3. Stimuli and procedure

The method was similar to that for Experiment 2 with the following exceptions. Instead of a central arrow, a cartoon face, 4° in diameter, with the fixation point as its nose, was drawn to the screen with white eyes and no pupils. After 500–1000 ms, the two pupils, 0.3° in diameter, were presented within the eye whites, directing the gaze of the face towards the location where the cue target was presented after a cue lead time of 0, 100, 300, 600, 1000, or 1500 ms. The stimulus time course is illustrated in Fig. 7.

4.4. Results

An average of 6.2% of the trials in the SJ block and 5.5% in the TOJ block for each observer were excluded from further analysis due to abnormally delayed reaction times, following the procedure described in Experiment 1. The PSSs were calculated as in Experiment 1. The results were similar to those of Experiment 2 and are shown in Fig. 3C. The PSS for the TOJ was significantly different from zero ($p < .05$) at a cue lead times of 100 ms and longer and increased from to a sustained level by 300 ms. The PSSs determined by the SJ were small (less than 4 ms), and differed significantly from zero ($p < .05$) only at cue lead times of 300 and 1500 ms, ($p = .07$ and .06, respectively, at cue lead times of 600 and 1000 ms). The PSSs from the TOJ and SJ differed significantly from each other ($p < .05$) at cue lead times of 100 ms and longer.

The results of the Bayesian inference tests are shown in Fig. 4C for the SJ and Fig. 5C for the TOJ. These tests are very similar to those in Experiment 2. For both the SJ and TOJ, the most plausible models were those with α fixed to zero.

4.5. Discussion

The evidence did not support the existence of sensory acceleration for gaze-directed cues. The dynamics of the PSS results for the TOJ are typical of gaze-directed attention, beginning slightly earlier than would the effects of endogenous attention, but can be explained by changes in cognitive factors. The similarity of the results of Experiments 2 and 3, and the reported automaticity of the gaze-directed cues, suggest that it was not the lack of efficiency of the endogenous cues that caused the null results for the SJ, but the lack of an abrupt onset near the target location. If these cues caused any sensory acceleration, the effect is very small. The hypothesis that sensory facilitation, rather than prior entry, may be the leading cause of sensory acceleration is tested further in Experiment 4.

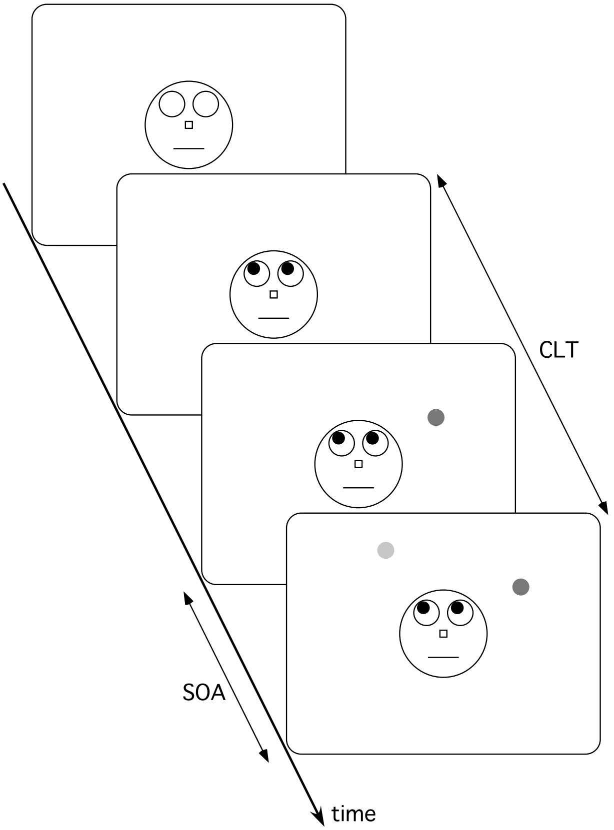

Fig. 7. An example stimulus frame time sequence for Experiment 3. The cue lead time (CLT) between the cue and the cued target and stimulus onset asynchrony (SOA) between the cued and uncued targets are shown. The illustrated SOA is negative because the uncued target was presented before the cued target. The figure is not to scale—for clarity, the sizes of the targets and the face have been exaggerated relative to their distances.

5. Experiment 4

5.1. Introduction

The purpose of this experiment is to determine whether sensory acceleration caused by exogenous cues depends on attention, or whether the observed effects are due to sensory interactions between the cue and target stimuli. While in Experiments 2 and 3 we used cues that oriented attention but did not spatially interact with the targets, in this experiment we employed cues that were abrupt onsets at the target location but that minimally captured attention.

Yantis and Johnson (1990) found that in displays containing multiple stimuli with abrupt onsets, only a limited number, approximately four, could be assigned a high priority. Other researchers have also found that attention can be only be allocated to a finite number of objects in other experimental paradigms (e.g., Pylyshyn, 1989; Pylyshyn & Storm, 1988). Therefore, by presenting a large number of cues, it should be possible to reduce the probability that attention is directed to any individual cued location. In this manner, it should be possible to reduce the attentional effects of exogenous cues while still retaining their abrupt onsets in the proximity of the target. If the effects of the cues on the SJ and TOJ were primarily due to their sensory facilitation rather than their capacity to capture attention, one would predict that increasing the number of cues should not have a significant effect on SJs or TOJs.

Since the variable number of cues adds an additional independent variable in this experiment, testing many different cue lead times as in the previous experiments would require too many trials for a single subject to accomplish in a reasonable time. Therefore, in Experiment 4A, a single cue lead time of 75 ms was used, corresponding to the maximum shift in the PSS observed in Experiment 1 for the TOJ and nearly the maximum for the SJ. To provide some indication of the dependence of the results on the cue lead time, we have also included Experiment 4B, which used a cue lead time of 150 ms, where the effects of the cue were weaker. This was a pilot experiment with a different subject pool, and a preliminary analysis of its results has been reported previously (Schneider & Bavelier, 2001).

5.2. *Observers*

Two different sets of 12 undergraduate students at the University of Rochester participated. All reported normal or corrected to normal vision, were paid for their participation, were naïve as to the purpose of the experiment, and had not participated in Experiments 1–3. In Experiment 4A, the observers ranged in age from 18–22 years and included 10 females. Two observers reported being left handed, and the others were right handed. In Experiment 4B, the observers ranged in age from 18–31 years and included eight females. One observer reported being of mixed handedness and the others were right handed.

5.3. *Stimuli and procedure*

The experimental parameters that follow are for Experiment 4A, with differences noted parenthetically for Experiment 4B. The method is similar to that of Experiment 1, but the number of the white ring-shaped exogenous cues varied among the trials—1, 2, 4, 6, 9, or 12 cues were presented (1, 2, 4, 6, 8, or 10 cues in Experiment 4B). One of the targets was presented within one of the cues, and the other target was presented at a location where no cue had been presented. The cues were presented at pseudorandom locations within an annulus ranging between 6.5° and 7.5° from the fixation point (6–8° for Experiment 4B), with their centers located at least 2.5° from each other and the uncued target (3° in Experiment 4B). The targets were separated by at least 7° (in Experiment 4B, although the targets could be separated by only 3°, to be consistent, only those trials in which the targets were separated by at least 7° were analyzed). All of the cues were presented 75 ms before the cued target (150 ms in Experiment 4B). The stimuli were displayed on a Sony GDM-FW900 23-inch monitor (Sony Electronics, New York, NY) with a refresh rate of 160.4 Hz (in Experiment 4B, the stimuli were displayed on the same monitor and as in Experiments 1–3). The stimulus time course is illustrated in Fig. 8.

5.4. Results

In Experiment 4A, an average of 5.7% of the trials in the SJ block and 5.5% in the TOJ block for each observer were excluded from further analysis due to abnormally delayed reaction times, following the procedure described in Experiment 1.

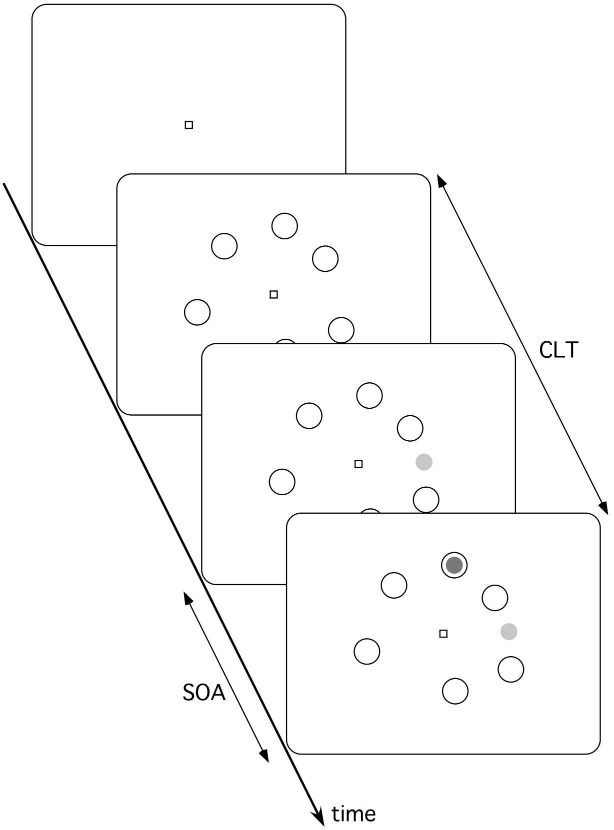

Fig. 8. An example stimulus frame time sequence for the six-cue condition in Experiment 4. The cue lead time (CLT) between the cue and the cued target, fixed to 75 ms in Experiment 4A and 150 ms in Experiment 4B, and stimulus onset asynchrony (SOA) between the cued and uncued targets is shown. The illustrated SOA is negative because the uncued target was presented before the cued target. The figure is not to scale—for clarity, the sizes of the targets and cues have been exaggerated relative to their distances.

In Experiment 4B, in approximately 23% of the trials, the two targets had been presented in locations less than 7° apart. In order to conform to the methodology of previous experiments, these trials were excluded from further analysis. Of the remaining trials, an average of 6.4% for the SJ block and 5.7% for the TOJ block for each observer were excluded from further analysis due to abnormally delayed reaction times.

The PSSs were calculated for the SJ and TOJ as in Experiment 1 and are shown in Fig. 9. For both Experiments 4A and 4B, the PSSs determined from both the SJ and TOJ were significantly different from zero ($p < .05$) at each number of cues. The PSSs for the TOJ were larger and significantly different than those for the SJ for four and more cues in Experiment 4A, and for all conditions in Experiment 4B ($p \leqslant .05$). In Experiment 4A, the PSS in the TOJ did not appear to strongly depend on the number of cues, while the PSS in the SJ decreased for more than two cues. In Experiment 4B, the PSS in both the SJ and TOJ decreased with an increasing number of cues. The rate of decrease for the PSSs for the SJ in Experiment 4A and both the SJ and TOJ in Experiment 4B seemed to decelerate towards an asymptote at a large number of cues. This baseline was approximately 20 ms for Experiment 4A, and 9 ms for Experiment 4B. In both experiments, the PSS for the SJ decreased approximately 10 ms as the number of cues increased.

As in the previous experiments, Bayesian inference tests were performed. At each number of cues for both the SJ and TOJ, the models that included a freely varying α were more plausible than the models with α fixed to zero. For the SJ in Experiment 4A, the perceptual-moment model was more plausible than the triggered-moment model for 1, 2, 4, and 6 cues, while the triggered-moment model was more plausible for 9 and 12 cues. Similarly in Experiment 4B, the perceptual-moment model was more plausible for 1, 2, and 4 cues, while the triggered-moment model was more plausible for 6, 8, and 10 cues.

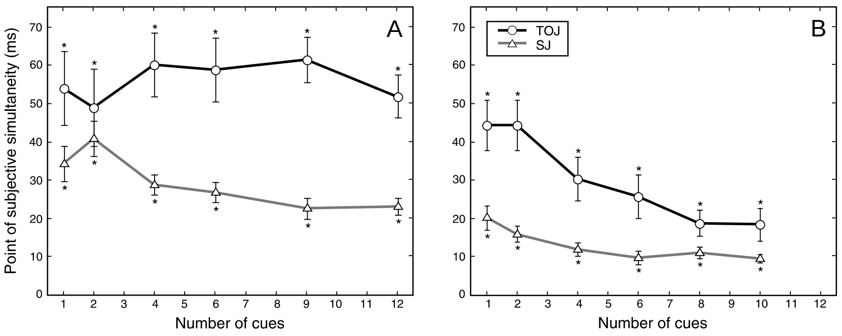

Fig. 9. Shifts in the points of subjective simultaneity (PSS) for the simultaneity (SJ) and order (TOJ) judgments caused by different numbers of exogenous cues in Experiments 4A, with a cue lead time of 75 ms, and 4B, with a different set of observers and a cue lead time of 150 ms. Error bars indicate the standard error of the weighted means, and asterisks mark the points that differ significantly from zero (two-tailed t test on the weighted means, $p < .05$).

5.5. Discussion

If attention can be construed as a limited resource, then as the number of cues presented increases, the amount of attention allocated to each cue should decrease. If observers assigned high priority to some subset of the cues, then as the number of cues increased, the probability that the target occurred at an attended location would decrease, increasingly diluting the average effects of attention. However, the PSS seemed to reach a non-zero baseline for large numbers of cues for both cue lead times. This indicates the presence of a non-attentional effect, as attention cannot be directed to so many cues at once. For a large number of cues, it may be that either no attention was allocated, or, more likely, that spatial attention had been maximally dispersed in the visual field, with all locations within that region receiving equal benefits of attention. In either case, since the unattended target was located in the same region of space as the cues, the difference in attentional allocation between the cued target and the uncued target ought to be quite small. Therefore, any difference between the cued and uncued targets must be due to effects other than attention. The data indicate positive sensory acceleration effects with a large number of cues, suggesting that an attention-independent component contributes to the effects of exogenous cueing.

A potential attention-dependent sensory acceleration is revealed by the decrease in the PSS with an increasing number of cues for the SJ. However, since the effects of exogenous attention would be expected to differ at cue lead times of 75 and 150 ms, and since the dependence of the PSS on the number of cues was of a similar size at both cue lead times, perhaps even this is not an attentional effect, but perhaps a contextual one. Whatever the case, the potential contribution of attention to apparent prior entry effects is small, at best.

6. General discussion

Our conclusions include three main points. The first point is that observations of shifts in the PSS due to attentional manipulation in a TOJ are not sufficient evidence to accept the prior entry hypothesis and conclude that attention accelerates sensory processing. Using a simple TOJ task, it is impossible to distinguish between attentional effects upon sensory mechanisms and those upon cognitive mechanisms. The SJ task may provide a more accurate probe of sensory effects. If the assumption is correct that temporal order and simultaneity decision are based only upon the difference in arrival times of the stimuli, then changes in an observer's criteria in the SJ task do not affect the estimate of the point of maximal simultaneity.

In the present study, the TOJ and SJ tasks could in some cases lead to different conclusions. The data from the TOJ tasks revealed shifts in the PSS with a time course consistent with the type of attentional cue used in each experiment. However, the data from the SJ tasks reveal significant shifts in the PSS only for the exogenous cues used in Experiments 1 and 4, and not the endogenous and gaze-direct cues used in Experiments 2 and 3. The model tests show that sensory acceleration is only necessary to explain the results of Experiments 1 and 4, with the additional effects observed in the other experiments for the TOJ task explainable by response biases or other changes in the decision criteria. Therefore, the second main point of our conclusions is that effects that must be attributed to sensory acceleration occurred only with exogenous cues—sensory changes near the target locations.

The third main point is that the effects of exogenous cues seem to include both attention-dependent and attention-independent components. An attention-dependent component ought to decrease as the number of cues increases, as did the PSS in Experiment 4. It is also possible that this effect is not due to attention but merely an undetermined sensory phenomenon, such as lateral inhibition or some other mechanism that might reduce the salience of each of multiple stimuli compared to a single stimulus. If the effect were purely attentional, then the difference in attentional resources allocated to the cued and uncued targets should decrease to zero for a large number of cues, as the attended area grows to encompass the uncued target location. But the effect was observed to reach a positive asymptote after about six cues. That the PSS is still positive when attention was maximally dispersed is indicative of an attention-independent component. Further support for an attention-independent component is evident in Experiment 1 in which the exogenous cues produced a significant perceptual latency reduction even when simultaneous with the target stimuli, too soon for attention to be engaged.

The mechanism of the attention-independent effects produced by the exogenous cues is not clear. One possibility is that sensory facilitation could lower the response thresholds of neural populations coding for the same retinotopic location. Alternatively, the visual system might be prone to confuse or be unable to encode the correct identities and timings of multiple events occurring within a small time and distance interval. Cai and Schlag (2001) demonstrated an example of an identity misbinding, showing that color of one object among a rapidly presented sequence could apparently be mistakenly allocated to a subsequently presented object with a different shape in an adjacent location. This is similar to the illusory conjunctions discovered in visual search experiments (e.g., Cohen & Ivry, 1989; Treisman & Schmidt, 1982). A time compression between the onsets of the cue and its target might also be sufficient to explain even the largest observed sensory acceleration effects, which were approximately 40 ms for a cue lead time of 75–125 ms. Such a time compression might be a natural consequence of the mechanisms the brain uses to measure the onset time of a stimulus. Allik and Pulver (1994) showed that TOJs seemed to be based on a low-pass temporal filter of the stimuli with a time constant of about 33 ms. Depending on the neural response profiles of two stimuli and the spatial precision of this temporal filter, one stimulus could influence the measurement of the onset of neighboring subsequent stimuli. A neural model, supported by recordings of neural activity might account for both the attentional and non-attentional effects of exogenous cues.

The lack of sensory acceleration effects for endogenous attentional cues is consistent with the lack of reported latency changes in the physiological literature for such cues. In monkey physiology experiments, sustained attention is usually oriented by instructions and by requiring the monkeys to perform a task at the attended location. Single unit recordings in areas MT (e.g., Treue & Maunsell, 1996; Treue & Maunsell, 1999), V2 and V4 (e.g., Luck, Chelazzi, Hillyard, & Desimone, 1997; McAdams & Maunsell, 1999) show attentional gain changes, but the onset times of the responses do not appear to be affected by attention. In some cases attentional gain changes were evident early in the stimulus response, with the attended response beginning at the same time as the unattended response but increasing somewhat more steeply. In other cases, response profiles were initially identical and diverged only after the peak response.

In humans, a number of researchers (e.g., Gomez Gonzalez, Clark, Fan, Luck, & Hillyard, 1994; Luck et al., 1994; Mangun, Hansen, & Hillyard, 1987; Mangun & Hillyard, 1991) have shown that endogenous attention affects the amplitudes but not the latencies of evoked response potential (ERP) components generated in extrastriate cortex. Any conclusions drawn from ERP latencies must be qualified by their interpretation difficulties since ERPs are composed of signals from a number of sources that may combine in complex ways (see e.g., Foxe & Simpson, 2002). Likewise, endogenous attention modulates the amplitude but not consistently the phase of the steady state visual evoked responses (VEPs) to oscillating stimuli (Morgan, Hansen, & Hillyard, 1996; Müller et al., 1998).

In fact, to our knowledge only two studies has reported physiological attentional latency modulations. Di Russo and Spinelli (1999) found that a slowly color-changing peripheral cue superimposed on an oscillating grating modulated the phase of the VEP, corresponding to a latency decrease of 14 ms relative to the condition when the cue was located in the opposite hemifield. The attentional cue was unusual because, although it consisted of abrupt color changes at the target location, the cue did not modulate VEP latencies in the absence of instructions to attend to it. In response to transient changes in the grating, the cue shortened the peak ERP latencies of the N60 and P100 components by 7 and 10 ms, respectively, and lengthened the latency of the P200 component by 5 ms. The second study reporting attention-dependent changes in physiological latencies is the recent study by Schuller and Rossion (2001) who reported that valid reflexive gaze-cues reduced the peak latencies of the P1 and N1 occipito-parietal ERP components compared to invalid cues. The latency of the P1 component was reduced by 2–6 ms, and the latency of the N1 component was reduced by 6–18 ms.

The general lack of reported ERP latency effects caused by endogenous attention is not due to the impossibility of recording ERP latency effects in general. For example, stimuli with lower luminance have been found to have longer perceptual latencies (e.g., Roufs, 1963; Roufs, 1974; Rutschmann, 1973; Wilson & Anstis, 1969). Both Johannes, Munte, Heinze, and Mangun (1995) and Wijers, Lange, Mulder, and Mulder (1997) observed that luminance and isoluminance, respectively, modulated the latency of early ERP components, but neither found any early interactions with the amplitude modulations caused by attention.

There is no relevant single-unit data to bear on the question of whether exogenous cues reduce latencies. Few physiological experiments have been performed using exogenous cues because of the difficulty in distinguishing the activity generated by the cue from that of the target. Several studies have used long cue lead times to avoid this problem. For example, Seidemann and Newsome (1999) used an exogenous cue with a cue lead time of 700 ms and reported that the time courses of the responses to attended and unattended stimuli in area MT in the monkey were initially similar but diverged after about 250 ms. Several studies indicated changes in the amplitudes but not in the latencies of human ERP components elicited by target stimuli that followed exogenous cues by no less than 600 ms (Eimer, 1994; Hillyard, Luck, & Mangun, 1994; Mangun, 1995; Miniussi, Wilding, Coull, & Nobre, 1999). Using a long cue lead time for exogenous attention is not ideal because the effects of endogenous and exogenous cues are indistinguishable after 600 ms (Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). To probe the unique effects of exogenous attention, the cue lead time must be much shorter. Another approach is to attempt to mathematically separate the effects of the cue and target. van der Lubbe and Woestenburg (1997), Bruin, Kenemans, Verbaten, and Van der Heijden (1998), and Hopfinger and Mangun (1998) employed various filtering techniques, but none observed any changes in the latencies of early ERP components with cue lead times as short as 100, 140, and 34 ms, respectively.

In conclusion, attentional cues of all sorts caused behavioral effects in temporal order judgment experiments that mimic those that would be produced by the sensory acceleration predicted by the prior entry hypothesis, but attention is more likely to have produced the effects by influencing the decision process. When the attentional cues were located remotely from the targets, effects consistent with sensory acceleration did not occur in simultaneity judgment experiments, or generally in physiological experiments that have been reported in the literature. Attentional cues located near the targets were found to cause sensory acceleration, but the majority of the effect was found to be independent of attention. In short these findings confirm that attended stimuli are consistently reported as perceived before unattended ones, but they reveal that this effect is more likely to arise from the influence of attention upon cognitive factors or the presence of attention-independent sensory facilitation, rather than through an attention-mediated acceleration of perceptual processing.

Acknowledgments

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Appendix A

A.1. Decision mechanism

The decision mechanism has been modeled using Sternberg and Knoll's (1973) general independent-channels model. In this model, relative temporal judgments between two stimuli, S_1 and S_2 with onset times t_1 and t_2, are made by a central decision mechanism that consists of a simple decision rule operating on the difference between their central arrival times, U_1 and U_2. Transmission through the nervous system is thought to cause these central arrival times to be delayed and dispersed relative to the stimuli onset times by variable factors R_1 and R_2. For simplicity, these delays are implemented as normally distributed random variables, although in reality they must be positive and likely have a somewhat different structure. The central arrival times of the two stimuli are then $U_1 \equiv t_1 + R_1$ and $U_2 \equiv t_2 + R_2$, and the difference between their arrival times is $\Delta U \equiv U_2 - U_1 = \Delta t + \Delta R$, where $\Delta t \equiv t_2 - t_1$ and $\Delta R \equiv R_2 - R_1$.

Now let S_1 be affected by a process that reduces its transmission delay relative to S_2 by a time α, the sensory acceleration parameter, such that $\langle R_1 \rangle = \langle R_2 \rangle - \alpha$. Since the difference of two normal distributions is also normally distributed, ΔR is normally distributed, and

$$\Delta U \sim \mathcal{N}(x, \mu, \sigma) \equiv \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{-(x-\mu)^2/2\sigma^2},$$

with a mean $\mu = \Delta t + \alpha$ and a variance σ^2 that consumes all of the variability arising from transmission dispersion as well as the mechanism that measures the difference in central arrival times. The relationship among these variables is illustrated in Fig. 10.

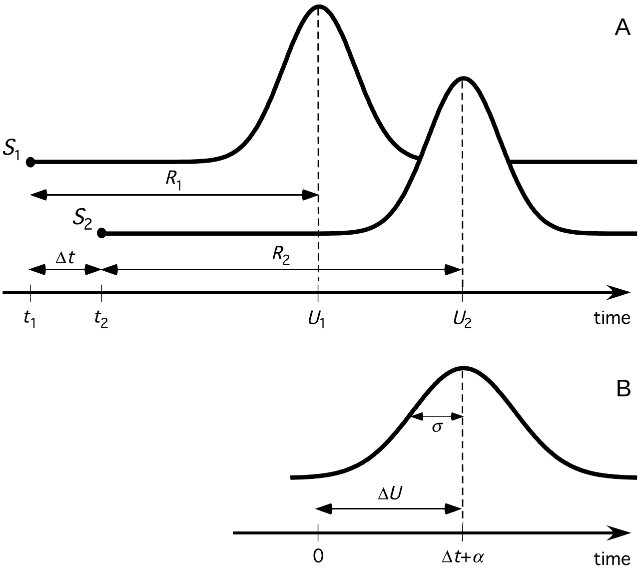

Fig. 10. (A) The distributions of the arrival times, U_1 and U_2, of two stimuli S_1 and S_2, at the central decision mechanism. S_1 has an onset time t_1, and its arrival time is delayed through transmission by a variable time R_1. S_2 is onset at t_2, and its arrival time delayed by R_2. (B) U_1 is accelerated by a time α through some process such that $\langle R_1 \rangle = \langle R_2 \rangle - \alpha$. The distribution of the difference in arrival times, ΔU, has a mean $\Delta t + \alpha$ and a total variance σ^2.

Sternberg and Knoll (1973) presented a number of different models of the decision rule employed by the central mechanism. The attention-switching models (their Models 4 and 5) have had some success (e.g., Allan, 1975), but they will not be considered since they make an assumption that is violated within the visual domain (see e.g., Baron, 1973), that only a single stimulus can be attended at once. Instead we will investigate in detail models based on their deterministic decision rule (Model 1), triggered-moment model (Model 3), and perceptual-moment model (Model 2). To be able to apply these models to behavioral data, we have introduced decision criteria and response bias parameters that Sternberg and Knoll had ignored for clarity.

Deterministic decision rule. The deterministic decision rule is applicable only for the TOJ, and not for the SJ. The model assumes that observers are able to precisely measure the central arrival times of two stimuli, and respond with the correct arrival order. Since each arrival time is affected by variable transmission delays, as described above, the order of central arrival times may not correspond to the order of onset times of the stimuli. The decision mechanism permits the observer to set criteria that may favor one stimulus over the other. For instance, an observer may respond that the attended stimulus occurs first ("$t_1 < t_2$") if it appears at least by a time τ before the unattended stimulus. The decision rule, illustrated in Fig. 11, is

$$P(\text{“}t_1 < t_2\text{”}) = \begin{cases} 1 & \text{if } \Delta U \geqslant \tau \\ 0 & \text{if } \Delta U < \tau, \end{cases} \tag{A.1}$$

which can be calculated,

$$P(\text{“}t_1 < t_2\text{”}) = P\{\Delta U \geqslant \tau\} = \int_{\tau}^{\infty} \mathcal{N}(x, \Delta t + \alpha, \sigma)\, dx = 1 - \Phi(\tau, \Delta t + \alpha, \sigma), \tag{A.2}$$

where

$$\Phi(x, \mu, \sigma) \equiv \int_{-\infty}^{x} \mathcal{N}(y, \mu, \sigma)\, dy$$

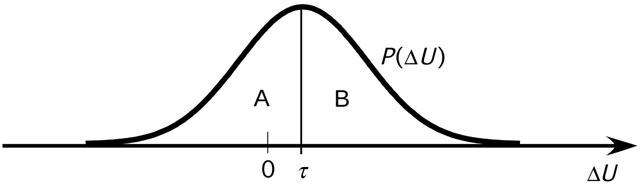

Fig. 11. The action of the deterministic decision rule, a simple model for a temporal order judgment. The decision mechanism operates on the distribution of the difference in arrival times ΔU of two stimuli, S_1 and S_2. If $\Delta U \geqslant \tau$ in region B, then the observer responds that S_1 occurred first. If $\Delta U < \tau$ in region A, then the observer responds that S_2 occurred first. If the decision criterion $\tau = 0$, the observer is unbiased with no preference for either stimulus.

is the cumulative normal distribution function. When rewritten in terms of the error function,

$$\Phi(\tau, \Delta t + \alpha, \sigma) = \sigma\sqrt{\frac{\pi}{2}}\,\mathrm{erfc}\left(\frac{\Delta t + \alpha - \tau}{\sigma\sqrt{2}}\right),$$

it is immediately obvious that the parameters τ and α are degenerate and cannot be distinguished experimentally.

A.1.1. Triggered-moment model

The triggered-moment and perceptual moment models assume that a determination of successiveness is required before a determination of temporal order can be made. Under the triggered-moment model, a moment of time with duration $\tau > 0$ exists initiated by a triggering stimulus such that all subsequent stimuli occurring within the moment will be perceived as simultaneous (“$t_1 = t_2$”) with it. The decision rule for a SJ, illustrated in Fig. 12, is

$$P(\text{“}t_1 = t_2\text{”}) = \begin{cases} 1 & \text{if } |\Delta U| \leqslant \tau \\ 0 & \text{if } |\Delta U| > \tau, \end{cases} \tag{A.3}$$

which can be calculated,

$$\begin{aligned} P(\text{“}t_1 = t_2\text{”}) = P\{|\Delta U| \leqslant \tau\} &= \int_{-\tau}^{\tau} \mathcal{N}(x, \Delta t + \alpha, \sigma)\,dx \\ &= \Phi(\tau, \Delta t + \alpha, \sigma) - \Phi(-\tau, \Delta t + \alpha, \sigma). \end{aligned} \tag{A.4}$$

Note that identical simultaneity criteria, τ, for the two stimuli are not theoretically required. For instance, it could be the case that the duration of the simultaneity window following an attended stimulus is $\tau + \varepsilon$, while the duration following an unattended stimulus is $\tau - \varepsilon$. The psychometric function that results with these durations and a sensory acceleration α is indistinguishable from the case with identical durations τ and a sensory acceleration $\alpha - \varepsilon$. If the duration of the simultaneity moment can be assumed to be independent of the order of the stimuli, then the

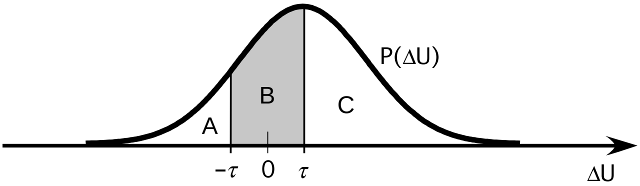

Fig. 12. The action of the triggered-moment decision rule on the distribution of the difference in arrival times ΔU of two stimuli, S_1 and S_2. For the simultaneity judgment, an observer reports that S_1 and S_2 were simultaneous if $|\Delta U| \leqslant \tau$ in region (B). Otherwise, if $|\Delta U| > \tau$ in regions A or C, the observer reports S_1 and S_2 as successive. For the order judgment, if $\Delta U > \tau$ in region C, then the observer responds that S_1 occurred first. If $\Delta U < -\tau$ in region A, then the observer responds that S_2 occurred first. If $|\Delta U| \leqslant \tau$ in region B, then the observer cannot determine the order and responds with probability β that S_1 occurred first. If $\beta = \frac{1}{2}$, the observer is unbiased.

durations are identically τ, and the maximum probability of reporting "$t_1 = t_2$" occurs at $\Delta t = \alpha$.

When making a TOJ, the observer reports "$t_1 < t_2$" if $\Delta U > \tau$ and "$t_1 > t_2$" if $\Delta U < -\tau$. According to this model, observers are unable to determine the order of the stimuli unless they have first determined them to be successive. When forced to make a determination of their order, the observer will make a random or biased guess. If $-\tau \leqslant \Delta U \leqslant \tau$, the observer cannot determine the order and reports "$t_1 < t_2$" with probability β. The observer is unbiased if $\beta = \frac{1}{2}$, and the resulting model corresponds exactly to Model 3 in Sternberg and Knoll (1973). The decision rule, illustrated in Fig. 12, is

$$P(\text{“}t_1 < t_2\text{”}) = \begin{cases} 1 & \text{if } \Delta U > \tau \\ \beta & \text{if } |\Delta U| \leqslant \tau \\ 0 & \text{if } \Delta U < \tau, \end{cases} \tag{A.5}$$

which can be calculated,

$$\begin{aligned} P(\text{“}t_1 < t_2\text{”}) &= P\{\Delta U > \tau\} + \beta P\{|\Delta U| \leqslant \tau\} \\ &= \int_{\tau}^{\infty} \mathcal{N}(x, \Delta t + \alpha, \sigma)\, dx + \beta \int_{-\tau}^{\tau} \mathcal{N}(x, \Delta t + \alpha, \sigma)\, dx \\ &= 1 + (\beta - 1)\Phi(\tau, \Delta t + \alpha, \sigma) - \beta\Phi(\tau, \Delta t + \alpha, \sigma). \end{aligned} \tag{A.6}$$

A.1.2. Perceptual-moment model

The perceptual-moment model is similar to the triggered-moment model in that two stimuli will be perceived as simultaneous if they occur within a specified moment of perceptual time. However, in the perceptual-moment model, the moments of time occur at clocklike fixed intervals, independently of any stimuli that may occur. Two stimuli will be perceived as simultaneous only if they happen to arrive within the same perceptual moment. The probability of two stimuli separated by Δt occurring within a perceptual moment of length τ is $1 - \frac{|\Delta t|}{\tau}$. The decision rule for the SJ is

$$P(\text{“}t_1 = t_2\text{”}) = \begin{cases} 1 - \frac{|\Delta U|}{\tau} & \text{if } |\Delta U| \leqslant \tau \\ 0 & \text{if } |\Delta U| > \tau. \end{cases} \tag{A.7}$$

Calculating the probabilities requires a convolution of the decision function and the latency distribution, and

$$\begin{aligned} P(\text{“}t_1 = t_2\text{”}) &= \int_{-\tau}^{\tau} \left(1 - \frac{|x|}{\tau}\right) \mathcal{N}(x, \Delta t + \alpha, \sigma) dx \\ &= \frac{\sigma^2}{\tau}(\mathcal{N}_+ + \mathcal{N}_- + -2\mathcal{N}_0) + \frac{1}{\tau}(\xi_+\Phi_+ + \xi_-\Phi_- - 2\xi_0\Phi_0), \end{aligned} \tag{A.8}$$

where the simplifying notation have been defined: $\mathcal{N}_{\{+,-,0\}} \equiv \mathcal{N}(\{\tau, -\tau, 0\}, \Delta t + \alpha, \sigma)$, $\Phi_{\{+,-,0\}} \equiv \Phi(\{\tau, -\tau, 0\}, \Delta t + \alpha, \sigma)$, and $\xi_{\{+,-,0\}} \equiv \{\tau, -\tau, 0\} - \Delta t - \alpha$.

The decision rule for the TOJ is

$$P(\text{“}t_1 < t_2\text{”}) = \begin{cases} 1 & \text{if } \Delta U > \tau \\ \frac{|\Delta U|}{\tau} + \beta\left(1 - \frac{|\Delta U|}{\tau}\right) & \text{if } 0 \leqslant \Delta U \leqslant \tau \\ \beta\left(1 - \frac{|\Delta U|}{\tau}\right) & \text{if } -\tau \leqslant \Delta U < 0 \\ 0 & \text{if } \Delta U < \tau. \end{cases} \tag{A.9}$$

Therefore,

$$\begin{aligned} P(\text{“}t_1 < t_2\text{”}) &= \int_{\tau}^{\infty} \mathcal{N}(x, \Delta t + \alpha, \sigma)\, dx + \frac{1}{\tau}\int_{0}^{\tau} x\mathcal{N}(x, \Delta t + \alpha, \sigma)\, dx \\ &\quad + \beta \int_{-\tau}^{\tau} \left(1 - \frac{|x|}{\tau}\right)\mathcal{N}(x, \Delta t + \alpha, \sigma)\, dx \\ &= 1 + \frac{\beta - 1}{\tau}(\sigma^2\mathcal{N}_+ + \xi_+\Phi_+) + \frac{\beta}{\tau}(\sigma^2\mathcal{N}_- + \xi_-\Phi_-) \\ &\quad - \frac{2\beta - 1}{\tau}(\sigma^2\mathcal{N}_0 + \xi_0\Phi_0). \end{aligned} \tag{A.10}$$

A.2. Model comparison

The comparison among the various models was performed using a Bayesian method of model comparison (MacKay, 1992). The plausibility of a hypothesis $\mathcal{H}$ in light of the experimental data $\mathcal{D}$ is:

$$P(\mathcal{H}|\mathcal{D}) \propto P(\mathcal{D}|\mathcal{H})P(\mathcal{H}). \tag{A.11}$$

Assuming no a priori preference for a particular hypothesis, $P(\mathcal{H})$ is constant, and we can rank the models by evaluating the evidence,

$$P(\mathcal{D}|\mathcal{H}) = \int P(\mathcal{D}|\mathbf{w}, \mathcal{H})P(\mathbf{w}|\mathcal{H})\, d\mathbf{w}, \tag{A.12}$$

where the integration ranges over the entire parameter space for the model parameters $\mathbf{w}$. Since there is no a priori reason to prefer any particular parameter values, the prior distribution of the parameters, $P(\mathbf{w}|\mathcal{H})$, is assumed to be uniform over some reasonable range. The evidence is proportional to the multidimensional integration of the likelihood function, $\mathcal{L} \equiv P(\mathcal{D}|\mathbf{w}, \mathcal{H})$, over the hyper-rectangular region defined by this prior distribution. The plausibility of a hypothesis depends on the joint data from all observers, which for independent observers is simply the product of the probabilities from each observer.

The data set for each observer samples the psychometric function with n_i independent repetition trials for each of the m different SOA values. If X_{ij} represents the binary response on the jth repetition of the ith SOA value and is encoded as

$$X_{ij} = \begin{cases} 1 & \text{if “}t_1 < t_2\text{” for TOJ or “}t_1 = t_2\text{” for SJ} \\ 0 & \text{otherwise,} \end{cases} \tag{A.13}$$

then X_{ij} is a Bernoulli random variable, and the likelihood function is

$$\mathcal{L} = \prod_{i=1}^{m} \prod_{j=1}^{n_i} p_i^{X_{ij}} (1 - p_i)^{n_i - X_{ij}}, \tag{A.14}$$

where $p_i \equiv P\{X_{ij} = 1 | \Delta t_i, \mathbf{w}\}$ is the response probability given by the model in Eqs. (A.2), (A.4), (A.6), (A.8) or (A.10) for the ith SOA value.

A.3. Model fitting

For a given model, the most likely parameters $\hat{\mathbf{w}}$ may be found by maximizing the posterior probability of the parameters, given by Bayes' rule as

$$P(\mathbf{w}|\mathcal{D}, \mathcal{H}) = \frac{P(\mathcal{D}|\mathbf{w}, \mathcal{H}) P(\mathbf{w}|\mathcal{H})}{P(\mathcal{D}|\mathcal{H})}. \tag{A.15}$$

The evidence $P(\mathcal{D}|\mathcal{H})$ is not relevant for the choice of $\mathbf{w}$, and thus, assuming a uniform distribution for the prior probability of the parameters $P(\mathbf{w}|\mathcal{H})$, maximizing the posterior probability is equivalent to finding the parameters $\mathbf{w}$ that maximize the likelihood function $\mathcal{L} \equiv P(\mathcal{D}|\mathbf{w}, \mathcal{H})$. Assuming the logarithm of the likelihood function can be approximated by a normal distribution at its maximum, the variances of the most likely model parameters can by obtained from the covariance matrix $\mathbf{A}^{-1}$, where $\mathbf{A} \equiv -\nabla^2 \log \mathcal{L}$ is the Hessian.

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