Does attention speed up processing?

Tünnermann, Jan; Petersen, Anders; Scharlau, Ingrid

Published in:
Journal of Vision

DOI:
10.1167/15.3.1

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Does attention speed up processing? Decreases and increases of processing rates in visual prior entry

Jan Tünnermann University of Paderborn, Paderborn, Germany

Anders Petersen University of Copenhagen, Copenhagen, Denmark

Ingrid Scharlau Leuphana University of Lüneburg, Lüneburg, Germany

Selective visual attention improves performance in many tasks. Among others, it leads to "prior entry"—earlier perception of an attended compared to an unattended stimulus. Whether this phenomenon is purely based on an increase of the processing rate of the attended stimulus or if a decrease in the processing rate of the unattended stimulus also contributes to the effect is, up to now, unanswered. Here we describe a novel approach to this question based on Bundesen's Theory of Visual Attention, which we use to overcome the limitations of earlier prior-entry assessment with temporal order judgments (TOJs) that only allow relative statements regarding the processing speed of attended and unattended stimuli. Prevalent models of prior entry in TOJs either indirectly predict a pure acceleration or cannot model the difference between acceleration and deceleration. In a paradigm that combines a letter-identification task with TOJs, we show that indeed acceleration of the attended and deceleration of the unattended stimuli conjointly cause prior entry.

Introduction

Selective visual attention is known to enhance the processing of information. In the mid-19th century, physiologist and physicist Hermann von Helmholtz demonstrated the influence of covert attention with a letter-identification task. On displays briefly exposed by an electric spark, observers were able to read letters at locations they covertly attended to at the expense of losing the ability to read letters at the point of fixation, despite the superior accuracy of the fovea (Wright & Ward, 2008, pp. 3–6).

Among the many effects of covert attention on subsequent processing that have been discovered, prior entry—the shorter perceptual latency of an attended stimulus—is one of both the oldest and least known. Its experimental investigation well predates the rise of experimental psychology (e.g., Bessel, 1838, or Mitchel, 1858; for the standard psychological explanation, see Boring, 1929, or Sanford, 1888; for a more thorough historical account, see Hoffmann, 2006). The term "prior entry" dates back at least to Titchener (1908), who included the law of prior entry in his fundamental laws of attention. He writes, "The stimulus, for which we are predisposed, requires less time than a like stimulus, to produce its full conscious effect. Or, in popular terms, the object of attention comes to consciousness more quickly than the objects that we are not attending to" (p. 251). Whether this means that the attended stimulus is processed faster or that the stimulus from which attention is drawn away is processed more slowly (each in comparison to a neutral condition in which attention is equally distributed) remained unclear until now despite the long tradition of prior-entry research. In the present paper, we isolate methodical reasons for this and approach the problem in a new way that finally provides an answer.

Prior entry has been extensively studied employing temporal order judgments (TOJ; see e.g., Klein, Schmidt, & Müller, 1998; Scharlau, 2007; Shore, Spence, & Klein, 2001; for a review, see Spence & Parise, 2010). In this paradigm, subjects judge the order of appearance for two targets. The targets are presented at different locations, and the time interval between their onsets is varied. Typically, this includes the stimulus onset asynchrony (SOA) of zero when the targets are presented simultaneously. Prior entry is then observed in the fact that depending on the SOA the order judgments differ from the actual order. Compared to an unattended stimulus, an attended stimulus

Citation: Tünnermann, J., Petersen, A., & Scharlau, I. (2015). Does attention speed up processing? Decreases and increases of processing rates in visual prior entry. *Journal of Vision*, *15*(3):1, 1–27, http://www.journalofvision.org/content/15/3/1, doi:10.1167/15.3.1.

doi: 10.1167/15.3.1 Received August 1, 2014; published March 2, 2015 ISSN 1534-7362 © 2015 ARVO

is perceived as appearing earlier. The effect is found in bimodal setups in which one modality is cued (Stone, 1926; Zampini, Shore, & Spence, 2005) or within one modality when attention is drawn to one location (e.g., by instruction, see Stelmach & Herdman, 1991) or a feature (Hikosaka, Miyauchi, & Shimojo, 1993b). A robust prior-entry effect is present in the visual domain—on which this study focuses—when peripheral cues are used (Shore et al., 2001).

Despite its prevalence in prior-entry research, the TOJ method faces several problems. It has been argued that not attention but response biases effectively cause prior entry (e.g., Frey, 1990; Jaśkowski, 1993; Schneider & Bavelier, 2003). When uncertain, subjects could select the target that is marked by the cue or the instruction in the typical two-alternative forced-choice response. Such and other nonattentional influences have been intensively studied (e.g., Scharlau, 2004; Scharlau & Neumann, 2003a; Shore et al., 2001) with the result that response biases and sensory priming (see Wiggs & Martin, 1998) contribute but cannot fully account for prior entry. Especially when exogenous cues are used, it is attention that mainly drives the effect. Due to the fact that these influences have been thoroughly investigated, they can be controlled or accounted for when TOJs are used to assess prior entry.

Besides these difficulties, fundamental limitations restrict the measurement of prior entry with TOJs in important ways. It frequently remains unclear at which level in processing or for the entry in which cognitive system or memory the stimulus arrival is compared. Titchener's (1908) definition refers to consciousness. TOJs probe at the level at which an order response can be generated, which may not agree with this definition, and more importantly, it depends on the precise TOJ task and the strategies subjects employ. Is it, for instance, sufficient to identify one target? Can the task be solved based on the stimulus location, or is it required to map stimuli to points in time? With regard to their relation to attention, memory systems at various levels have been extensively studied (see e.g., Chun & Turk-Browne, 2007). Prior entry has not been explicitly linked to any of them. In principle, it can occur in any such system. Thus, a method to investigate prior entry must either produce sufficiently general results or be explicit about the level at which prior entry is probed.

Most intriguingly, the fundamental question of whether prior entry arises from attention-based speed benefits for the attended target or if the processing of the unattended is slowed down remained unasked until recently (Weiß, Hilkenmeier, & Scharlau, 2013). Most likely, it has been ignored for so long because TOJs, the prevailing method in prior-entry research, are completely indifferent to this difference.[1] This is due to the fact that only a relative response is measured ("target A earlier than target B") whereas TOJs do not map to the absolute processing time or perceptual latency of any of these targets.

Despite the prevailing ignorance regarding the relativeness of TOJs, some researchers mention the problem in the passing. Spence, Shore, and Klein (2001, p. 823), for instance, comment on Stelmach and Herdman's (1991) temporal-profile model: "However, there is an implicit assumption in figure 14B that directing attention to a stimulus actually speeds up the perception of that stimulus (i.e., that it is perceived sooner after the stimulus onset than would have been in case had attention been directed elsewhere; see Stelmach et al. 1994, p. 108). Neither the present data, nor that reported by Stelmach & Herdman (1991, Stelmach et al. 1994) allow us to critically evaluate this claim." Then, referring to their figure 14C, they point out that a delay of the unattended stimulus equally explains the data.

Setting aside for the moment the TOJ paradigm, a prior-entry effect can also be found in other related attentional phenomena, some of which have been explicitly linked to prior entry whereas others are concerned with perceptual latency in general. Carrasco and McElree (2001) showed in research using reaction time tasks that focusing attention on a stimulus indeed accelerates its processing. Still, their data provide no direct evidence whether or to what degree deceleration of the unattended stimulus contributes to the net prior-entry effect in TOJs.

A different result was obtained by Spence, Nicholls, and Driver (2001) for modality-based attention in the presence of expectancy manipulations. In experiments that in an unpredictable sequence contained visual, auditory, or tactile stimuli, they found a disadvantage for targets in the unattended modalities. Reaction times for those targets were increased with regard to a neutral (divided attention) baseline condition. These decelerative components (costs) exceeded accelerative components (benefits) with regard to their contribution to the net reaction time effect. The benefits were even removed—whereas the costs remained—when the authors discarded trials that repeated the same modality from the previous trial, which constitute exogenous cues in addition to their expectancy manipulation. How these findings can be transferred to the domain of visual TOJs and prior entry remains unclear in the light of this complication and the fact that these were multimodal experiments. Adding to this, results from reaction time experiments and TOJs have been found to dissociate (e.g., see Jaśkowski & Verleger, 2000), and therefore, attentional mechanisms revealed by reaction time studies cannot be simply assumed for TOJs.

In a different line of research, prior entry has been discussed as a reason for order reversals in serial visual processing (Hilkenmeier, Scharlau, Weiß, & Olivers, 2012; Olivers, Hilkenmeier, & Scharlau, 2011). Such reversals occur when attention is drawn to the earlier of two targets that appear next to each other in a stream of distractors, all presented at the same location. The second target benefits from a "boost" initiated by the first target and thereby produces prior entry in a purely facilitatory manner. The underlying theory (Olivers & Meeter, 2008) also includes a "bounce," an inhibitory process initiated by a distractor if placed in between the targets. This, however, is a deceleration of the processing of the second target, which should effectively reduce prior entry. The results can be transferred to the TOJ paradigm only with reservations: The theory was developed to explain temporal attention using successive stimuli that are either targets or distractors at a single location. In the TOJ paradigm, however, stimuli consist of targets (with the exception of the cue) and are also spatially distributed. The interactions of boosts and bounces in this situation are unclear. Most likely, there would only be the purely facilitatory prior-entry component as there is no distractor to initiate a bounce. By contrast, for prior entry in the flash-lag paradigm (a mismatch between the perceived location of a moving and a briefly exposed stimulus), as investigated by Priess, Scharlau, Becker, and Ansorge (2012), acceleration as well as deceleration can contribute. It can either be that processing of the flash, which is assumed to attract attention, is accelerated or that processing the moving stimulus is slowed down.

One recent study directly addressed the role of deceleration in prior entry assessed by TOJs. Weiß et al. (2013) coupled TOJs with an additional latency measure. They used two stylized clocks on which rotating hands appeared separated by a variable time interval. In the attention condition, one clock was cued. Observers reported the order in which the hands appeared (traditional TOJ) and reported the position of the hands they perceived when they appeared. The latter measure was used to assess the perceptual latency for each stimulus (Carlson, Hogendoorn, & Verstraten, 2006). Weiß et al. indeed found that the clock from which attention was drawn away was slowed down. The processing rate of the attended stimulus was increased, but the decrease of the processing rate of the unattended target made a larger contribution to the net prior entry. This result, however, is based on converting the spatial misperception of the moving hands onsets into a measure of perceptual latency, which is still indirect and might be confounded by influences of attention on motion perception (see e.g., Müsseler, Stork, & Kerzel, 2002).

Electrophysiological investigation may provide insights into the timing of processes that ultimately lead to prior entry. Analysis of event-related potentials (ERPs) has already been used to assess the attentional influence of spatial cueing. Hillyard, Luck, and Mangun (1994), for example, showed that the amplitude of early ERP components is modulated by attention using spatially valid and invalid cues (peripheral and central) that preceded a single target. If attention reduces the perceptual latency, as claimed by the prior-entry hypothesis, not only amplitude modulation but also temporal shifts of the peaks of ERP components should be present, reflecting the attention-induced speed changes in processing.

However, studies that used TOJs and ERP recordings provide mixed results. Although the behavioral results of a visual TOJ task are in line with the literature, McDonald, Teder-Sälejärvi, Di Russo, and Hillyard (2005) found only amplitude enhancements and no shifts of the peak latencies of early ERPs. Evidence in favor of an influence of neural events during processing on the perception of stimulus timing was reported by Vibell, Klinge, Zampini, Spence, and Nobre (2007). In contrast to McDonald et al., they found shifts of peak latencies in ERP components (see Spence & Parise, 2010, for a discussion of reasons for these conflicting findings). Again, the effect could be driven either by a slowdown in the unattended as well as speedup in the attended modality or both.

Thus, it must be concluded that neither evidence from related phenomena, electrophysiological evidence, nor, finally, the study by Weiß et al. (2013), the only one that has explicitly targeted this question so far, are able to provide compelling evidence for pure acceleration, pure deceleration, or combinations of both. In the present study, we set out to find an answer for this fundamental question using a method based on stimulus identification (Bundesen, 1990) that is not subject to the relativeness of TOJs.

Methodology and paradigm

In this study, prior entry is assessed within the framework of the Theory of Visual Attention (TVA; Bundesen, 1990). TVA allows obtaining processing speed measurements for encoding stimuli into visual short-term memory (VSTM) based on data from an identification task. It provides an unspeeded, accuracy-based measure. It is immune to effects caused by motor components in contrast to reaction-time tasks. Furthermore, it does not involve motion or a temporal distribution of the targets.

The concepts used in prior-entry literature can be sharpened with the mathematical framework provided by TVA. In the prevalent literature on prior entry, terms such as speed, acceleration, and latency are often used without explicit definition and in many cases synonymously. In TVA, there is a well-defined concept

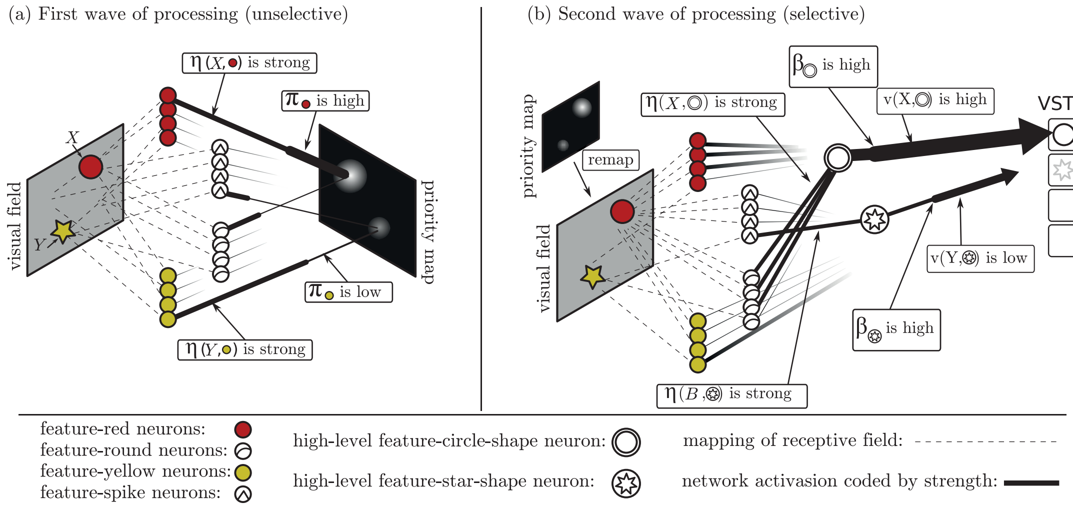

Figure 1. Illustration of the first (a) and second (b) wave of processing according to NTVA. In this example, observers are instructed to report the shape of the red object. The sensory evidence (η) depends on the input. Pertinence values (π_j) are tuned in favor of red objects and biases (β_i) for making shape categorizations. Dashed lines represent neurons remapped in the second wave. The width of solid lines indicates the activation (overall firing rate) of the networks that participate in signal propagation. To retain clarity, only some paths are labeled. For an animated version, see Movie file Figure1.mov in the supplementary materials.

of VSTM, and it provides an elaborate neural theory of encoding stimuli into this storage.

For the experiments reported in this study, we offer the reader a TVA-based analysis and interpretation. Furthermore, we discuss possible mechanisms in the framework of NTVA (a neural interpretation of TVA; Bundesen, Habekost, & Kyllingsbæk, 2005). But, importantly, the results presented in this paper remain valid with only a minimum of theoretical assumptions from the TVA framework. That is, we assume that the encoding times of visual stimuli follow a delayed exponential distribution. This well-motivated assumption is commonly made in models of encoding processes (e.g., Carrasco, McElree, Denisova, & Giordano, 2003; Colonius & Diederich, 2011; García-Pérez & Alcalá-Quintana, 2012; Shibuya, 1991). Hence, the non-TVA-minded reader may skip the following section and TVA-based discussions, merely accepting the assumption of exponentially distributed encoding times. However, we encourage the reader to take the TVA-based perspective because it provides a clear formal language and coherent theoretical background that has been applied to many other phenomena.

Theory of Visual Attention

TVA is a model in which objects in the visual field *race* for limited *slots* in VSTM (Bundesen, 1990; Shibuya & Bundesen, 1988). An object x is said to be encoded into VSTM if a categorization of the object is encoded into VSTM. During the processing, categorizations are established mutually independently and in parallel with a constant hazard rate, $v(x,i)$, where x is an object in the visual field, and i is a perceptual category (e.g., a certain color, shape, or spatial position). The time it takes to encode a category into VSTM is assumed to follow an exponential distribution. The slots in VSTM are used as an abstraction regarding the limitation of VSTM ($K = 3$–4 objects for normal subjects). According to NTVA (Bundesen et al., 2005), VSTM does not in itself represent the features of the encoded objects but rather functions as a pointer to their location. That is, feedback loops are used to sustain the activity in the neurons representing the features of the encoded objects. Visual representations can thus outlast the original sensory stimulation. To illustrate the NTVA interpretations of the underlying mathematics, we reference Figure 1 in the following explanations. The neurons should be considered an abstraction and simplification of the real neural networks involved. For instance, these abstract neurons can be dynamically remapped based on attentional weights. How the mechanisms are conceived in terms of real neural networks as well as evidence for their existence was presented by Bundesen et al. (2005).

To bias the competition for a slot in VSTM, a first wave of unselective processing is used to calculate an attentional weight, w_x, for every object in the visual field. Attentional weights are given by the *weight equation* of TVA:

$$w_x = \sum_{j \in R} \eta(x,j)\pi_j \tag{1}$$

where R is the set of all categories, $\eta(x,j)$ is the strength of sensory evidence that object x belongs to category j, and π_j is the pertinence value of category j, which reflects the current selection criterion. In NTVA, the first wave of processing is implemented by "feature-j neurons" with receptive fields that contract at random locations in the visual field (see Figure 1a) such that $\eta(x, j)$ equals the sum of the activations of all the feature-j neurons in whose receptive fields object x is presented. This activation is modulated by the pertinence value π_j and projected to a retinotopic area that constitutes a priority map, which is used to distribute resources in the second wave of processing (selective processing).

In the second wave of processing, the rates by which categorizations of objects race for access to VSTM are calculated. The rate of categorizing object x as having feature i is given by the *rate equation* of TVA:

$$v(x,i) = \eta(x,i)\beta_i \frac{w_x}{\sum_{z\in S} w_z} \tag{2}$$

where $\eta(x,i)$ is the strength of sensory evidence that object x belongs to category i, and β_i is the decision bias associated with category i. The last factor in the equation is the relative attentional weight of object x, which is the attentional weight of object x, w_x, divided by the sum of attentional weights across all objects in the visual field, S. On the neural level, the relative attentional weight of an object x determines the probability that a given neuron will represent object x in the second wave of processing. That is, the higher the relative attentional weight of an object, the more neurons will be allocated to process the object in the second wave of processing (see Figure 1b). In NTVA, $\eta(x,i)$ should be interpreted as the total activation of the set of all feature-i neurons when every feature-i neuron represents object x, and the decision bias in favor of category i is maximal (i.e., $\beta_i = 1$).

Because the experiments reported in this article only require participants to encode two targets, we may disregard the limitation of VSTM. In this special case, the probability that an object x is encoded in VSTM before time t is given by

$$F(t) = \begin{cases} 1 - e^{-v_x(t-t_0)} & \text{if } t > t_0 \\ 0 & \text{else} \end{cases} \tag{3}$$

where v_x is the total processing rate of object x, and t_0 is a threshold reflecting the minimum exposure duration required before the encoding process toward VSTM starts. The rate v_x is defined as the sum of the processing rates of all categorizations of object x, that is,

$$v_x = \sum_{i\in R} v(x,i) \tag{4}$$

where R is the set of all perceptual categories. Furthermore, the total processing capacity, C, is defined as the sum of processing rates across all perceptual categories, R, and all elements in the visual field, S, that is,

$$C = \sum_{x\in S}\sum_{i\in R} v(x,i) = \sum_{x\in S} v_x \tag{5}$$

Most importantly for the present study, the expected time of encoding an object x into VSTM, E_x, is given by the expected value of the exponential distribution added to the longest ineffective exposure duration:

$$E_x = t_0 + \frac{1}{v_x} \tag{6}$$

The parameters that describe this encoding have the following meaning: v_x, as we measure it here, is a *rate* in the form of categorized objects per second. Threshold t_0 is a *latency*, here measured in milliseconds, and the expected encoding time in VSTM, E_x, which combines v_x and t_0 (see Equation 6), reflects the *duration* of the encoding process as defined by TVA.

Combining TVA- and TOJ-based assessment of prior entry

In order to put to test whether prior entry is purely caused by shortening the encoding duration of the attended target or whether deceleration of the unattended target is also present, we embedded the TOJ task in a TVA-based letter-recognition task. The TOJ measures prior entry in the established way whereas TVA provides direct access to parameters related to processing speed.

In the TOJ paradigm, participants typically observe the appearances of two stimuli, such as distinct shapes, and indicate the order of stimulus arrival. The TVA-based methods present participants with symbols, mostly letters, for various durations, ranging from shortly presented and thus barely identifiable letters to letters presented for long durations, which are easily reported. Both paradigms rely on properly selected measuring points, and a certain level of difficulty to be sensitive. The resulting dual task (reporting letter identities and arrival orders) must be manageable for the participants, and the volatile impressions of temporal order and letter identities should not be lost until the result is reported.

The overall framework is straightforward: Two backward masked letters are presented at different locations. The task for participants is to enter both letters (letter identification) and hereafter report the order in which the letters appeared on the screen. This dual response is described in detail in the section on response collection.

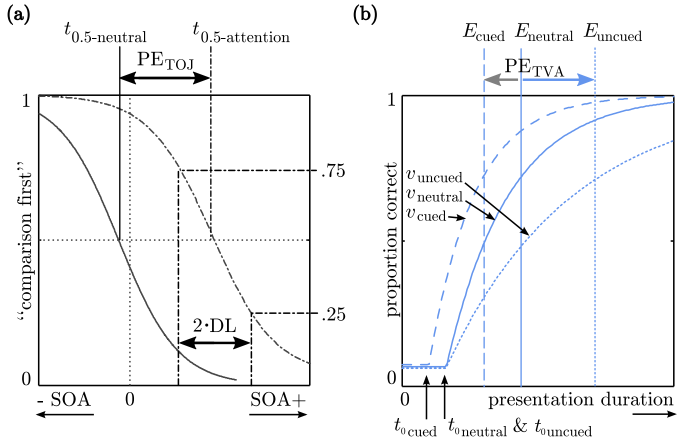

Figure 2. (a) Idealized psychometric functions of TOJ data. These functions of SOA show the relative frequency of the "comparison first" judgments that start at 1 for large negative SOAs, at which the comparison is preceding the standard with a large interval. The 0.5 intercepts are estimated for the control condition ($t_{0.5\text{–neutral}}$) in which no cue was present and the attention condition ($t_{0.5\text{–attention}}$) in which the comparison is cued. The difference of the 0.5 intercepts is the TOJ-based prior-entry estimate, PE_{TOJ}. The difference limen (DL) value is half the distance between the first and the third quartile. It is only illustrated for the attention condition. (b) Idealized psychometric functions of the exponentially distributed letter-identification data. The functions give the relative frequency of correctly reported letters dependent on the presentation duration. They take off at the t_0 thresholds with a slope determined by the v parameters. The corresponding expected value of VSTM arrival is marked for each curve, and the TVA-based relative prior entry, PE_{TVA}, is the difference between E_{uncued} and E_{cued}.

In agreement with the logic of classic TOJs, one letter is defined as the *comparison* stimulus and the other as the *standard* stimulus. In the attention condition, the comparison stimulus is preceded by a peripheral cue whereas the standard stimulus appears at an uncued location. The cue remains visible over the whole interval between cue onset and target onset (cue onset asynchrony, COA). Such a peripheral cue is known to attract exogenous attention to its location. The effect is transient with its effectiveness usually peaking between 100 ms and 200 ms (see Nakayama & Mackeben, 1989; for a more recent review of covert attention and its effects, see Carrasco, 2011). There is no cue in the control condition. For the TVA measurement, the interval from target onset to mask onset is independently varied for each target. At the same time, for the TOJ measurements, the targets are presented with a varying interval between their onsets.

To parameterize the paradigm, we use presentation durations $D = [17$ ms, 34 ms, 84 ms, 134 ms$]$ that work well for a TVA-based analysis of a two-letter recognition task. A tuple of durations, one for the comparison

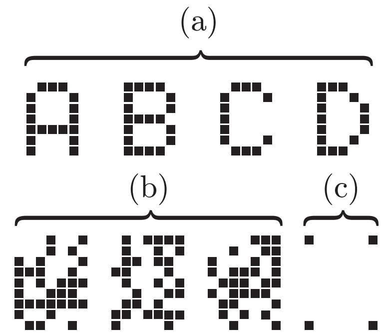

Figure 3. Stimuli used in the paradigm. The gray background is not shown here. (a) Four out of the 21 target letters. (b) Three examples of the 10 masks. (c) The cue.

and one for the standard stimulus, is thus taken from the set $D \times D$.

To determine five SOAs, the stimulus material was tested in a common TOJ task in which COA = 100 ms and no letter identification was required. The SOAs were tweaked until the data from pilot experiments were well predicted by a logistic psychometric function. This required adding a long positive SOA for the cue condition. As illustrated in Figure 2, the curve for the cue condition approaches zero at larger positive SOAs compared to the neutral condition. The final sets used in the combined paradigm were $\text{SOAs}_{\text{neutral}} = [-68$ ms, -34 ms, 0 ms, 34 ms, 68 ms$]$ and $\text{SOAs}_{\text{attention}} = [-68$ ms, -34 ms, 0 ms, 34 ms, 68 ms, 134 ms$]$.

With negative SOAs, the comparison stimulus leads; with positive SOAs, the standard stimulus is presented earlier than the comparison. In the trials with a cue, this means that sequences with negative SOAs are always of the order cue–comparison–standard. For a COA of 100 ms and a target SOA of +68 ms or +134 ms, the sequence is standard–cue–comparison. For the other positive SOAs, the cue also precedes the standard stimulus. See the subsection on design for a visualization of these alternatives.

Stimuli and presentation

For the TOJ task, there are no special requirements regarding the target appearance except that in a given trial there have to be at least two distinguishable stimuli. Here, 21 letters (A, B, C, D, E, F, G, H, J, K, L, M, N, O, P, R, S, T, U, W, X; easily confusable letters deleted) are used. Examples of this stimulus material are shown in Figure 3. The letters consist of little black squares on a 5×7 grid with an extension of about $0.8° \times 1.3°$ of visual angle. These can be masked with a pattern of randomly arranged black squares (on a 7×9 grid, shown in Figure 3b; $1.3° \times 1.8°$). These stimuli originate from Lunau and Olivers (2010), and pilot experiments confirmed that this kind

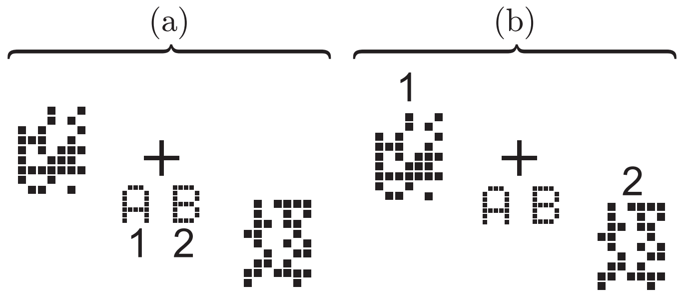

Figure 4. (a) Implicit order judgment deduced from the order in which letters have been reported. Order markers can be optionally toggled (“1–2,” “2–1”, “==”). (b) An explicit order judgment is required when no target was reported correctly. Order markers are then placed above the masks.

of letters works well for the TVA-based method. The cue consists of four black squares in the corners of the 7×9 grid (see Figure 3c). No mask is required for the cue because its encoding is not assessed with the TVA-based methods nor is its visibility critical for inducing prior entry (Scharlau & Neumann, 2003a). The background color is set to a light gray.

Two different letters are presented at two of six possible locations. These locations are centered at a distance of about 3.5° from the central fixation cross. After the corresponding durations, each stimulus is masked with a random pattern, which stays visible until the end of the trial.

Response collection

After deployment of the masks, the participants are first required to enter the letter identities they have recognized or guess on the letter identities that were not recognized (forced choice). Participants can enter (and, if necessary, alter) their response without a deadline, and after confirming with a key press, they are required to indicate the perceived order of the letters. This method guarantees that letter identification and temporal order judgment are made on the basis of the same visual information.

A small “1” and “2” are presented below the entered letters to indicate the perceived order (see Figure 4a). The default arrangement, of which the participants are aware, is that the first letter is marked with a “1” and the second with a “2” so that no adjustment is required when the letters are entered in perceived arrival order. If necessary, the markers can be toggled with the tab key to change the report of the perceived order or to indicate that the letters are perceived simultaneously (in this case two “equals” signs are presented below the reported letters).

If neither of the letters is correctly identified, the order cannot be deduced from the markers placed next to the reported letters. In these rare cases (17.5% in our experiments), the program requires the participants to toggle the markers next to the masks (see Figure 4b). This allows the report of the order or simultaneity even without identification of the letters. After the order response is adjusted, the participants confirm their response with a key press. There is no response deadline; just as with the letter identification, the order judgment is an unspeeded response. For the TOJ evaluation, this maker-based order judgment is translated into a binary “comparison first” decision in agreement with the logic of traditional TOJs.

	SOA						
Condition	68	34	0	34	68	134	Overall
Attention	32	64	272	64	32	32	496
Neutral	32	64	272	64	32	×	464
Overall	64	128	544	128	64	32	960

Table 1. Number of trials per SOA in the attention and control conditions.

Design

The proposed (durations × SOAs × cueing conditions) design has a trial distribution centered at SOA = 0 and includes an additional 134-ms SOA in the attention condition (see Table 1). More SOA = 0 trials are included because the TVA-based fitting is most stable when applied to data from trials with simultaneous presentation (see Appendix: Bootstrapping a TVA data set). The number of trials in each cell is equally distributed among the possible combinations of the two targets' presentation durations. The complexity in terms of temporal overlap that arises from the independent variation of display durations and SOA is expressed in Figure 5. The stimulus locations are selected randomly from the possible locations during the experiment.

Models for fitting TOJ and TVA data

In this section, we describe the models for fitting the TOJs and letter-identification judgments to obtain TOJ- and TVA-based prior-entry estimates.

Estimating the TOJ-based prior entry

The TOJ-based prior-entry estimate is obtained by fitting psychometric functions (Woodworth & Schlosberg, 1954) to the order-response data. The distributions of the attention and control conditions are approximated for each participant by logistic functions and logit analysis (Finney, 1971), which is used to obtain 0.5 thresholds $t_{0.5\text{–neutral}}$ and $t_{0.5\text{–attention}}$ for the

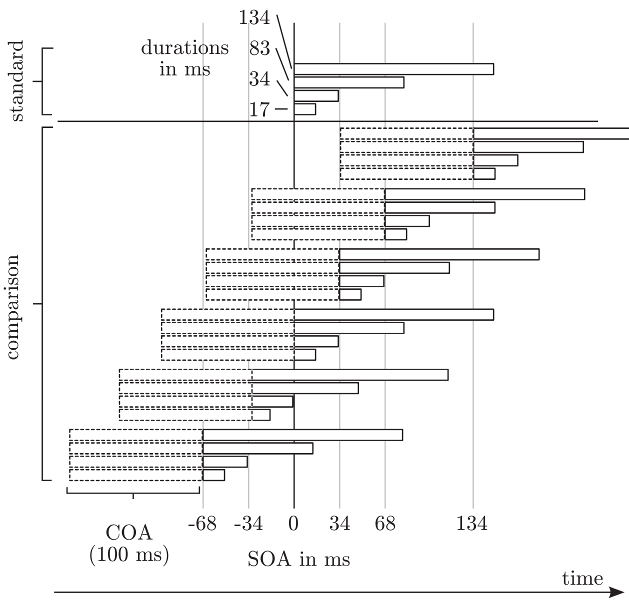

Figure 5. Temporal arrangement of stimuli. The standard stimulus is presented at time zero for one of the depicted durations. The comparison stimulus is presented for one of the depicted durations at one of the depicted relative times (SOA: Negative values mean "earlier than standard"). The comparison stimulus is cued in half of the trials; that is, it is preceded by the cue with an interval given by the COA.

control and attention conditions, respectively. Idealized psychometric functions of the TOJ, with the thresholds marked, are shown in Figure 2a. Based on these estimates, TOJ-based prior entry is calculated as the difference between the thresholds:

$$PE_{TOJ} = t_{0.5-\text{attention}} - t_{0.5-\text{neutral}} \tag{7}$$

For a comparison with the TVA-based estimates, we are interested in the size of prior entry, hence we follow a suggestion by Weiß and Scharlau (2011) on how to limit the interference by the unattended target (a more detailed discussion of this can be found in Appendix: Estimating the size of prior entry with TOJs).

You may note that $t_{0.5\text{–neutral}}$ is not zero in the illustration in Figure 2a but shifted to the negative. This results from the use of the "simultaneous" judgment. A substantial amount of presentations with SOAs at the point of subjective simultaneity (and SOAs close to it), which equals objective simultaneity in the neutral condition, are judged as "simultaneous." This leads to fewer order responses, and thus the psychometric functions are shifted downward, shifting their x-intercepts to the left. The psychometric functions of the TOJ provide a further parameter: the *difference limen* (DL) is half the distance between the first and the third quartile (see Figure 2a). It measures the dispersion of the psychometric function and thus describes the discrimination performance. A smaller DL indicates better discrimination precision. The value of DL approaches zero when the psychometric function approaches a vertical line (i.e., that of a perfect discriminator).

Estimating the TVA-based prior entry

The original TVA model described by Bundesen (1990) assumes that the time it takes for an object to be encoded into VSTM follows a delayed exponential distribution (see Equation 3). Recently, Dyrholm, Kyllingsbæk, Espeseth, and Bundesen (2011) extended the TVA model to account for trial-by-trial variability in the VSTM capacity parameter K and the longest ineffective exposure duration parameter t_0. We performed a massive bootstrapping of one participant's data to assess the stability of these models in our experimental paradigm because it contains multiple onsets of targets, masks, and the cue, which have not yet been extensively studied with TVA methods. For the reasons of varying interference as described above, the bootstrapping was done separately for each combination of attention manipulation (cued, neutral, and uncued) and order-judgment type ("comparison first," "standard first," and "simultaneous"). The bootstrapping revealed that the original TVA model gives the most stable parameter estimates for the data from our paradigm. Furthermore, only the SOA = 0 ms trials (simultaneous presentation) allow stable estimates with the TVA-based analysis (see the Appendix: Bootstrapping a TVA data set for more details on the bootstrapping).

Because the experimental paradigm employs a forced-choice letter report, we accounted for guessing by including a high-threshold guessing model (e.g., see Petersen, Kyllingsbæk, & Bundesen, 2012): Let P_A and P_B be the probabilities of correctly encoding target A and B, respectively (see Equation 3). The adjusted probability of correctly encoding target A (or target B if we interchange target A and target B) is then given by

$$P_A^{\text{adj}} = P_A + (1 - P_A)\left(\frac{P_B}{N-1} + (1 - P_B)\frac{2}{N}\right) \tag{8}$$

where N is the number of different response letters ($N = 21$ in our case). That is, if target B is encoded but target A is not, participants guess on the identity of target A among the remaining $N - 1$ alternatives (the two letters were always different). If, however, none of the targets are encoded, participants make two random guesses on the identities of target A among N alternatives.

TVA parameters v and t_0 are obtained for each participant and condition by a maximum-likelihood procedure employing the Nelder-Mead algorithm (Lagarias, Reeds, Wright, & Wright, 1998). The expected encoding times in VSTM, E_{cued}, E_{neutral}, and

E_{uncued}, are calculated from the estimated parameters according to Equation 6. Figure 2b shows idealized plots of the model with the corresponding expected encoding times marked. The TVA-based relative prior-entry estimate is then obtained as

$$\mathrm{PE}_{\mathrm{TVA}} = E_{\text{uncued}} - E_{\text{cued}} \tag{9}$$

In contrast to the TOJ-based analysis, the expected encoding times in VSTM can be used to quantify the reduction of the encoding duration for the attended stimulus ($E_{\text{neutral}} - E_{\text{cued}}$) and the increase in encoding duration for the unattended stimulus ($E_{\text{uncued}} - E_{\text{neutral}}$), both of which are of interest to this study.

Experiment 1

Participants

Twenty-five volunteers participated in a session, which lasted about 1 hr. Ten of these participants produced their data in the COA = 100 ms block of Experiment 2, which was identical to this experiment. These data were included in the evaluation of Experiment 1. The authors also participated in the experiments and are identified in all subject-level plots by their initials. All participants had normal or corrected-to-normal vision and were granted 6 € per hour (except for the authors).

Procedure

The general procedure followed the framework described in Methodology and paradigm. A COA of 100 ms was used in the first experiment, that is, the location of the comparison stimulus was cued with this interval prior to target presentation.

Results

The data recorded for each participant were fitted with the models described in the section Models for fitting TOJ and TVA data. Plots of the fitted curves have been included in the Appendix: Individual fits for Experiments 1 and 2. The estimated parameters were submitted to statistical tests. An alpha level of 0.05 was used for all tests. We used Holm–Bonferroni corrected one-tailed t tests whenever multiple comparisons were made.[2]

As Figure 6a indicates, the estimated encoding time in VSTM of the cued target ($M = 52.91$ ms) is significantly reduced by about 10 ms compared to the neutral control condition ($M = 61.54$ ms), $t(24) = 5.58$,

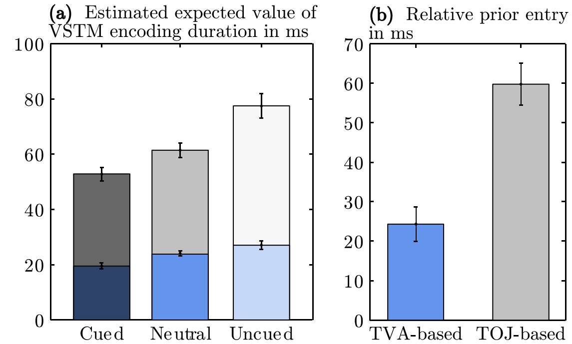

Figure 6. (a) Estimated encoding time in VSTM from Experiment 1 averaged over participants. The blue portions of the bars show the contributions of the t_0 parameter, and the gray portions correspond to $(1/v)$. (b) TVA- and TOJ-based prior-entry estimates.

$p < 0.001$. The uncued target (throughout the article, "uncued" refers to the target that appears at a location other than the cued location, that is, from which attention is drawn away, whereas in the "neutral" baseline condition with "neutral" targets, there is no cue at all) arrived about 16 ms later ($M = 77.39$ ms) than targets from the neutral condition, $t(24) = 4.95$, $p < 0.001$. The same pattern is present in the underlying v and t_0 parameters (see Table A2 for statistical details).

When the v values are used to calculate the overall processing rates C_{neutral} ($M = 59.76$ Hz, $SD = 20.09$) of the control condition and $C_{\text{attention}}$ ($M = 58.26$ Hz, $SD = 19.33$) of the attention condition (where $C_{\text{neutral}} = 2 \cdot v_{\text{neutral}}$ and $C_{\text{attention}} = v_{\text{cued}} + v_{\text{uncued}}$, according to Equation 5), their magnitudes do not differ significantly, $t(24) = 0.68$, $p = 0.49$, 95% confidence interval (CI) [−3, 6]. This suggests that there is no substantial overall increase of available processing resources caused by the deployment of attention in this experiment.

Figure 6b shows that the magnitudes of prior entry measured with the TVA-based ($M = 24.63$ ms, $SD = 18$) and TOJ-based ($M = 59.62$ ms, $SD = 26.29$) methods differ significantly, $t(24) = 6.15$, $p < 0.001$. This dissociation is assessed in Experiment 2 and addressed later in the General discussion.

Discussion

The results of Experiment 1 suggest that attention indeed slows down the processing of the unattended stimulus and speeds up the processing of the attended stimulus, which conjointly leads to prior entry. The relative prior entry measured by the TVA-based method is about 26 ms with 16 ms caused by the slowdown of the unattended target being the larger contribution.

That the decrease in processing rate of the unattended stimulus contributes more to prior entry than the increase in processing rate of the attended stimulus is in line with the results of Weiß et al. (2013). Importantly, looking at the processing rates, the overall rate C appears to be conserved under the attentional manipulation. That is, the stimulus processing rate v of the cued target is increased by the same amount by which the rate of the uncued target is reduced, compared to the neutral control condition. Due to the exponential processing model of TVA, this redistribution of resources leads to a greater reduction in the encoding duration for the unattended stimulus compared with the increase in encoding duration for the attended stimulus.

In addition to the effect on the processing rates v, cueing was found to also modulate t_0 in this experiment. Whereas this does not have a clear interpretation within the current theoretical framework of TVA, modulations of t_0 have previously been reported in the literature (Vangkilde, Bundesen, & Coull, 2011). Experiment 2 will address this effect further.

To sum up, we found strong evidence that selective speedups and slowdowns in visual processing conjointly produce prior entry in our setting. Resources are redistributed, which, due to the exponential processing model of the encoding durations of the two targets, results in a larger contribution from the decrease in processing rate of the unattended stimulus compared with the increase in the processing rate of the attended stimulus. A substantial mismatch of the size of TVA-based prior entry and its traditional TOJ-based measure as well as an unexpected effect of cueing on the threshold t_0 remain unexplained. As the measured effects are evoked by the presence of attention, a gradual modulation of it may allow further insights into the underlying mechanisms. This is the rationale behind the second experiment.

Experiment 2

This experiment investigates the magnitude differences of TVA- and TOJ-based prior entry and the t_0 effect revealed in the first experiment. Conditions with additional COAs are added to the setup of the first experiment. This modulates the amount of attention present at the location of the comparison stimulus when it appears (e.g., see Olivers, 2007).

For TOJs, the specific time course of prior entry depends on the interval between the attention-guiding stimulus and the target (Hikosaka, Miyauchi, & Shimojo, 1993a; Scharlau, Ansorge, & Horstmann, 2006; Scharlau & Neumann, 2003b). Typically, the magnitude of prior entry rises with the COA until it peaks between 100 and 200 ms and declines for larger COAs. The range in which the attentional facilitation peaks is often only broadly delimited. Scharlau et al. (2006) concluded a range between 135 and 272 ms; however, using COAs of 50, 100, and 200 ms, we expect the TOJ-based prior entry to increase proportionally with these COAs. Within the framework of the TVA, such a COA-dependent effect could occur when the relative attentional weights depend on the COA in a similar manner.

If the TVA-based prior entry depends on the COA in a similar fashion, the size discrepancy between it and the TOJ-based prior entry could be an additional (possibly linear) upscaling for the perceived temporal interval based on actual VSTM arrival times. Furthermore, for the unexpected effect in t_0, it is then of interest whether its contribution is proportional to the measured prior entry (i.e., it also depends on the COA) or if it always has a fixed contribution to the effect.

Participants

Fourteen volunteers participated in two or three sessions with different COAs. Four participants who already had participated in Experiment 1 (identical to one condition of Experiment 2) participated in the remaining two conditions only. All participants had normal or corrected-to-normal vision and were paid 6 € per hour.

Procedure

This experiment consisted of three blocks with COAs of 50, 100, and 200 ms, each set up according to Methodology and paradigm. The COA = 100 ms block was identical to Experiment 1. The order in which these blocks were conducted was alternated to prevent a systematic influence of improvement by learning. For participants for whom the COA = 100 ms condition was already available from Experiment 1, the remaining two conditions were conducted in alternating order. Due to the long overall time of the experiment (3 hr plus), participants were allowed to take long breaks and continue the experiment whenever they wanted.

Results

The following sections describe the statistical analysis of the estimated TVA parameters and the comparisons between TVA- and TOJ-based prior-entry estimates.

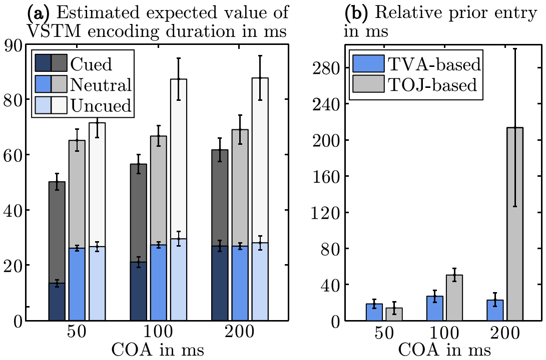

Figure 7. (a) Estimated encoding times in VSTM for the different COAs. The blue portions of the bars show the contributions of the t_0 parameter, and the gray portions correspond to the value of $(1/v)$. (b) Magnitudes of relative TVA-based and TOJ-based prior entry for different COAs.

TVA-based estimates

The estimated expected VSTM encoding durations (see Figure 7a) were submitted to a two-way (COA × Cueing condition) repeated-measures ANOVA, which revealed a main effect of cueing condition, $F(2, 52) = 19.39$, $p < 0.001$, and COA, $F(2, 52) = 9.4$, $p < 0.001$, and an interaction of cueing condition and COA, $F(4, 52) = 5.93$, $p < 0.001$. Post hoc tests at the individual COAs showed significant contributions from both an acceleration of the encoding of the attended stimulus and a deceleration of the encoding of the unattended stimulus in all of the conditions ($E_{\text{cued}} < E_{\text{neutral}} < E_{\text{uncued}}$; see Tables A1, A3, and A4 for detailed statistics).

Concerning the v parameters, there is a main effect of cueing condition, $F(2, 52) = 10.29$, $p < 0.001$, according to a (COA × Cueing condition) repeated-measures ANOVA. Post hoc tests at the individual COAs (see Tables A1, A3, and A4) did not reach significance in all conditions in contrast to Experiment 1 (which only had the COA = 100 ms condition, but more participants were included in the evaluation).

For all COAs, the overall processing rates in the neutral and attention conditions do not differ significantly: For COA = 50 ms, C_{neutral} is 61.95 Hz (SD = 19.07) and $C_{\text{attention}}$ is 63.05 Hz (SD = 20.49), the difference being within the 95% CI [–8.25, 6.05]. For COA = 50 ms the values are C_{neutral} = 63.05 Hz (SD = 22.65) and $C_{\text{attention}}$ = 58.52 Hz (SD = 18.70) and 95% CI [–1.28, 10.44] on the difference; and for COA = 200 ms, C_{neutral} = 59.73 Hz (SD = 21.03) and $C_{\text{attention}}$ = 58.16 Hz (SD = 15.84) and 95% CI [–6.22, 9.36] on the difference.

For the t_0 parameter, a repeated-measures ANOVA (COA × Cueing condition) revealed that Experiment 2 replicated the main effect of cueing condition observed in Experiment 1, $F(2, 52) = 10.95$, $p < 0.001$. The ANOVA also revealed a significant main effect of COA, $F(2, 52) = 8.77$, $p < 0.05$, and a significant interaction of COA and Cueing condition, $F(4, 52) = 6.8$, $p < 0.001$. Figure 7a (lower part of the bars) shows that the impact of the cue on t_0 is large for COA = 50 ms, medium for COA = 100 ms (both significant, see Tables 2 and 4) and that there is no effect on t_0 for COA = 200 ms (Table A5).

Comparison with TOJ-based estimates

The results of the TVA- and TOJ-based prior-entry estimation are shown in Figure 7b. As expected, the magnitude of the TOJ-based prior entry (PE_{TOJ}) depends on the COA, increasing strongly with larger COAs. The TVA estimates, however, seem to be independent of the COA. This is supported by statistical analysis: A two-way repeated-measures ANOVA reveals a main effect of COA, $F(2, 26) = 4.31$, $p < 0.05$, a main effect of prior-entry measurement type (TOJ or TVA), $F(1, 26) = 5.78$, $p < 0.05$, and an interaction of both, $F(2, 26) = 4.2$, $p < 0.05$. Pairwise t tests on the three TVA conditions showed no significance although the TOJ conditions differ significantly from one another (see Table A5).

Visual assessment of the plots in Figure A4 suggests that the discrimination performance in the TOJ is especially weak (shallow curves) in the COA = 200 ms condition. Thus, the DL estimates (see Figure 2a) were submitted to a two-way ANOVA. A main effect of COA was found, $F(2, 26) = 7$, $p < 0.05$. Cueing condition, $F(2, 26) = 0.3$, $p = 0.59$, and its possible interaction with COA, $F(2, 26) = 2.59$, $p = 0.09$, did not reach significance. Post hoc comparisons of the different COA conditions were conducted: The difference in DL is significantly larger for the COA = 200 ms condition compared with the COA = 50 ms condition, $t(13) = 2.99$, $p < 0.05$, and compared with the COA = 100 ms condition, $t(13) = 2.61$, $p < 0.05$. The difference of DL between the COA = 50 ms condition and the COA = 100 ms condition is not significant, $t(13) = 0.77$, $p < 0.45$.

Discussion

Contributions from deceleration and acceleration of the processing rates v were confirmed as a cause of prior entry in the second experiment for all COAs. The overall processing rates C are similar in all cueing and COA conditions, indicating that the same resources were accessed in all conditions. However, the TVA-based prior-entry effect was not modulated by varying the amount of attention allocated to a location at target appearance via the cueing interval. TOJ-based prior entry, by contrast, was strongly driven by the cueing interval. Especially its magnitude for COA = 200 ms is rather large and subject to high variance (see Figure 7b). Thus, the difference of TVA- and TOJ-based prior entry cannot be explained by a simple scaling between the actual and the perceived intervals. The dissociation that shows up in the second experiment suggests a more fundamental difference between what the two methods measure.

Before further discussion of this dissociation, the likelihood and influence of eye movements, which were not controlled during the experiments, should be addressed. In our experiments, saccades initiated by target onsets are very unlikely to influence target identification as saccade latencies are larger than 200 ms (Tam & Ono, 1994): The majority of the SOAs in our experiment are below or equal to 68 ms, and the longest target duration is 134 ms, resulting in a maximum of only 202 ms from a target onset until both targets are masked (see Figure 5). In contrast, saccades initiated by the cue onsets in the COA = 200 ms condition may be executed before the presentation of the masks and thereby facilitate encoding of the cued targets. However, no such advantage was found when comparing the estimated encoding time for the cued targets in the COA = 200 ms condition with the estimated encoding time in the COA = 50 ms and COA = 100 ms conditions in which the cued targets could not benefit from eye movements due to saccade latencies (see Figure 7). Furthermore, during the instruction, participants were made aware of the fact that eye movements do not help in the task and must be avoided. Thus, it is unlikely that eye movements are a problem in our data.

Understanding the dissociation between the TVA- and TOJ-based measurements is important as otherwise the finding that a decrease and an increase of processing rates conjointly cause prior entry may not be transferable to the mechanisms that apply in traditional TOJs. One important ingredient for an explanation could be the task difficulty, which appears to be increased for the TOJ task at the large COA. A similar case in which DL increased with the COA was found by Scharlau and Neumann (2003b). Their interpretation, that "Apparently, temporal order judgment becomes increasingly difficult as the prime [a visually backward-masked cue, J.T.] and the target are separated by larger temporal intervals and become distinctive perceptual events" (p. 198) could explain the drop in discrimination performance at the large COA in the present study. Similarly, in our paradigm, the mask onsets are additional perceptual events, and thus might cause the relatively low discrimination performance, which is also found in the other COA conditions. We pursue this interpretation further in the General discussion and suggest a processing model that offers an explanation for the TVA–TOJ dissociation.

For the TVA-based measurement, the performance appears to be unaffected by the COA. The overall processing rate, which can be regarded as a measure of performance in the task, is similar at all COAs. In order to emphasize the different behavior of the curves in terms of prior-entry magnitude and overall performance in the TOJ and the letter-recognition task, the independent VSTM-encoding probabilities of the two targets can be combined. The resulting joint probability that one target is perceived before the other depending on the SOA is the same probability that is assessed in the traditional TOJ. The transformation is outlined in the following; however, it may be skipped without loss of continuity.

Let variable $\Delta t = \mathrm{SOA} + t_0^A - t_0^B$ represent the difference between when stimulus A and stimulus B start their race toward VSTM. If $\Delta t < 0$, the probability of encoding stimulus A before stimulus B is given as a function of v_A, v_B, and Δt:

$$P_A(v_A, v_B, \Delta t) = 1 - e^{-v_A|\Delta t|} + e^{-v_A|\Delta t|}\left(\frac{v_A}{v_A + v_B}\right) \text{ for } \Delta t < 0 \quad (10)$$

where $1 - e^{-v_A|\Delta t|}$ is the probability that stimulus A is encoded before stimulus B starts to race. Alternatively, if stimulus A is not encoded before stimulus B starts to race (given by the probability $e^{-v_A|\Delta t|}$), the probability of encoding stimulus A before B is given by Luce's choice axiom $[v_A/(v_A + v_B)]\left(= \int_0^\infty v_A e^{-v_A t} \cdot e^{-v_B t} dt\right)$. If instead $\Delta t \geq 0$,

$$P_A(v_A, v_B, \Delta t) = e^{-v_B|\Delta t|}\left(\frac{v_A}{v_A + v_B}\right) \quad \text{for } \Delta t \geq 0 \quad (11)$$

That is, stimulus B is not encoded before stimulus A starts to race (given by the probability $e^{-v_B|\Delta t|}$), and stimulus A is encoded before stimulus B when they both race simultaneously (given by the probability $v_A/[v_A + v_B]$). The "comparison first" function for the attention condition is then given by

$$CF_{\text{attended}}(\mathrm{SOA}) = P_A\left(v_c, v_u, \mathrm{SOA} + t_0^c - t_0^u\right) \quad (12)$$

where the subscripts c and u refer to the cued and uncued targets, respectively. Similarly, the "comparison first" function for the control condition is given by

$$CF_{\text{neutral}}(\mathrm{SOA}) = P_A(v_n, v_n, \mathrm{SOA}) \quad (13)$$

where n refers to targets from the (no-cue) control condition.

Figure 8 shows exemplary plots for two participants in which the TVA-based order judgment curves and the actual TOJ-based curves have been overlayed for all COAs. First of all, it can be seen that the TVA-based curves resemble proper psychometric functions as produced by TOJs. AQ, like many other participants

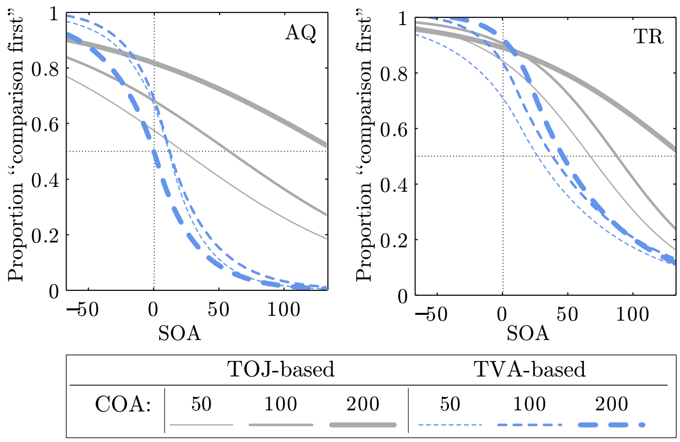

Figure 8. Plots of the TVA-based "comparison first" probabilities and TOJ-based fits of the actual "comparison first" judgments (only the attention conditions are shown). As the TVA-based order judgment is binary, the actual TOJ data have been adjusted by disregarding the simultaneity responses.

(see Figure A4), has rather weak performance in the TOJs whereas TR is the participant with the lowest average DL across all conditions (and thus a strong participant). The figure shows the large discrepancy between the magnitudes of prior entry measured by each method in the positions of the x-intercepts, which are shifted by the influence of the cue. For TR, there appears to be a small magnitude dependency with regard to the COA. This is only seen for some participants (e.g., not for AQ), so if such a dependency exists, the effect is probably too small in comparison to the noise between blocks and thus not visible in the statistical analysis. By contrast, the COA dependency is strong for the TOJ and is found in all participants.

Interestingly, García-Pérez and Alcalá-Quintana (2012) recently proposed a psychometric model for TOJs that overcomes the relativeness problem by assuming exponentially distributed arrival times at the order comparator. These are the exact same assumptions as made by our TVA-based model for TOJs, which, in addition, are backed up by a consistent theoretical and neurophysiological framework (NTVA). The basic mathematical model by García-Pérez and Alcalá-Quintana (although being extended by additional components to model simultaneity perception) are equivalent to the equations we derived from TVA above (see Equations 10 through 13). Fitting such functions directly to TOJ data is promising for future TOJ-based investigations. This approach can avoid the relativeness problem with regard to the processing rates of the stimuli, as shown by García-Pérez and Alcalá-Quintana. Combined with the TVA-based theoretical background we elaborate in the present study, results from TOJs can be connected to the body of empirical findings already accounted for by TVA.

Besides the magnitude discrepancy, the curious t_0 effect was targeted with the second experiment. The development with regard to the COA is interesting: In contrast to the resource redistribution reflected in the changes of the v parameters (while at the same time C is conserved), the t_0 effect appears to be a direct consequence of the cue. It shows up in Experiment 2 as a purely facilitatory effect at the cued location. Not only is the uncued target unaffected, but it also depends on the cueing interval being stronger for short COAs. Note that in Experiment 1 with COA = 100 ms, there was a very small latency increase of the uncued target, which just reached significance. The purely facilitatory effect found in Experiment 2 agrees with what head-start models predict (see General discussion section on speedup and slowdown). Thus it is possible that such mechanisms play a role in certain situations. If the encoding process itself is relatively short (a large C parameter in terms of TVA), it might be the factor that mainly determines the VSTM arrival and thereby the order judgment. Many TOJ paradigms use very simple stimuli, such as discs or squares, for which a short encoding duration can be expected.

To summarize the results and implications from the second experiment, the main findings of Experiment 1 have been confirmed: Deceleration of the unattended and acceleration of the attended stimulus, driven by a redistribution of resources, produce the net prior-entry effect. Intriguingly, the variation of the strength of attention at the target location by block-wise altering the cueing interval did not affect, or only weakly affected, the TVA-based prior entry whereas it strongly modulated the TOJ-based effect. Furthermore, a reduction of the discrimination performance in the TOJ was observed at large COAs. Finally, the t_0 effect is most likely a direct and local consequence of the cue that leads to a purely facilitatory latency reduction as suggested by head-start models.

General discussion

The motivation of this study was the missing answer for the missing question of whether and to what degree the otherwise intensely investigated prior-entry effect arises from speeding up the attended or slowing down the unattended stimulus. The present study addressed this fundamental question, and we provide evidence that indeed both speeding up and slowing down cause part of the effect. The mechanism that drives the changes in transmission speed is a redistribution of processing resources. Such a redistribution in combination with the exponential processing model of TVA leads to a larger contribution of the slowing down of the unattended stimulus in the net effect. This is well in line with the results obtained by Weiß et al. (2013), the only other study that directly addressed the same question.

Of course, the claim to have answered such a fundamental question deserves qualification. Our results stem from the application of a TVA-based method, and a large part of this study is concerned with the struggle to relate the measurements to TOJs, a traditional method for measuring prior entry. Thus, we should either argue that the TVA-based method is a true measure of prior entry in its own right and the results of TOJs are somehow distorted, or the argument should show that the differences between both methods can be explained and the main finding transfers to TOJs. The latter argument can only be pursued in a rather speculative manner by describing mechanisms that, at the same time, agree with our TVA- and TOJ-based findings. Indeed, we believe that such an agreement can be achieved with a well-motivated model, which we describe later in the section on Prior entry and processing time. At this point, we will justify that the TVA-based measurement indeed is a true measure of prior entry.

Most definitions of visual prior entry, among them Titchener's (1908), which we quoted in the Introduction, include two important components: stimuli that are perceptually similar and attention that is allocated to a subset of them. In this situation, the otherwise similar stimuli arrive at different times at a central instance. The attended stimulus enters prior to the unattended stimulus. Both the TVA- and TOJ-based paradigms allow the use of perceptually similar stimuli. The only attributes that differ substantially are the spatial location in both paradigms and the time of presentation in the TOJ paradigm. Thus, the perceptual similarity can be equally achieved in both paradigms. Regarding the second component (i.e., the possibility to guide attention toward stimuli), the TOJ is inferior to the TVA-based method. The reason for this is the presence of a temporal asynchrony, which is a fundamental part of TOJs. No matter by which means attention is directed in the first place, the onset of the first target is likely to induce an attention shift toward its location. In situations in which the unattended target appears before the attended target, it may alter the effect of the cue. Such interference problems, as discussed in the TOJ literature (e.g., Scharlau et al., 2006; Weiß & Scharlau, 2011), distort the measured size of prior entry. Similarly, it is hard to account for spatially unspecific temporal attention, which is modulated by the sequentially occurring events. This adds another factor that interferes with intended attention manipulation in TOJs.

Furthermore, the presence of spatially and temporally distributed stimuli in the display and the requirement to map spatial positions to the order impression when entering the response present a more complicated task to participants. More possibilities for strategic adjustments are provided to the observer who has to deal with this task, for instance, determining either what came first or what came second or inferring the order from apparent motion illusions.

The degree to which a stimulus has to be processed is not well defined in TOJs. In most cases, the task can be solved by determining the order of the onsets at the locations and later establishing the correspondence between order and identity, which then is reported. If the first (or last) target has to be reported, it is even sufficient to register only its identity. Therefore, the precise degree of processing may differ significantly for different experiments or even for different strategies of the participants. By contrast, the TVA-based method explicitly probes at the well-defined level at which a stimulus has been sufficiently processed so that its identity can be reported.

Thus, the TVA-based method is a valid measure of prior entry as commonly defined. In many practical and theoretical aspects, it is equally suited if not superior to TOJs.[3] The prevalence of TOJs in prior-entry research is likely to be a reason why the important question we address in this study came up only recently.

Speedup and slowdown

The fact that our results show that both acceleration and deceleration of stimulus encoding contribute to prior entry is highly interesting for the discussion of models that aim to explain why prior entry arises in temporal order judgments: The existence of processing-speed differences, their interdependence based on sharing common resources, and the indication of head-start components (the t_0 effect) confronts such models with challenges beyond those of common TOJs. Some aspects of prevailing models agree well with our findings whereas others are in conflict.

Prevailing models of prior entry can be organized in two different classes. One class, the *independent-channels models*, was introduced by Sternberg and Knoll (1973). It conceives prior entry as a result of differentially speeded independent processes. We dub a second class *head-start models* as these describe prior-entry as a consequence of attention triggering a critical process earlier for the cued target. This critical process allows the transfer or integration of information to start earlier than in conditions in which attention is not directed.

For the independent-channels models, Sternberg and Knoll (1973) formalized the pivotal idea of prior entry, which is that "arrival latencies depend on stimulus attributes and possibly also on adjustable decision criteria" (p. 635). Stimuli are processed independently until they reach a common stage at which their arrival is compared. Due to attention, the cued stimulus proceeds faster relative to the uncued one and arrives earlier at the comparator. The difference between the arrival latencies is then the prior entry. This model is very general and not limited to attention. Whenever there is a factor (e.g., stimulus luminance) that increases or decreases the speed in one channel, prior entry is the result.

Thus, the notion that both acceleration and deceleration of stimulus encoding contribute to prior entry does not disagree with TOJ models such as those generalized by the independent-channels models in general because their predictions are indifferent to this difference. In fact, many aspects of what we found agree well with the independent-channels models. Speedup acts on one channel and slowdown on the other. Possibly, an additional head-start component (the t_0 effect) acts on the channel in which the attended stimulus is processed.

However, Sternberg and Knoll (1973) introduced the *assumption of selective influence*, which demands that a factor only acts on processes within one of the channels. This has implications with regard to our question: If there is attentional speedup and slowdown, these must be modeled as two independent factors.

Strictly speaking, however, the assumption does not hold with respect to our finding that the overall processing rate is invariant under the cueing manipulation, that is, $C_{\text{attention}}$ and C_{neutral} do not differ. In other words, in terms of attention, it is impossible to selectively influence one channel by, for example, speeding up its processing without slowing down the processing in the other channel. Therefore, in a strict sense, the independent-channels models as posed by Sternberg and Knoll (1973) are not valid to describe attentional effects on the encoding latencies that lead to prior entry.

A popular instance of an independent-channels model is Stelmach and Herdman's (1991) temporal-profile model. In this model, each encoding process is characterized by a temporal impulse function that, after peaking, declines. Attention toward a stimulus leads to a brisker profile of its impulse function, so that it peaks at earlier times, mimicking the processing speed advantage for the attended stimulus. The peak latencies are compared to produce a tentative order judgment. However, the output of this comparator does not always determine the response. Stelmach and Herdman propose a second comparator that estimates the certainty of the order impression based on the overlap of the profiles. A large overlap reflects a high uncertainty and weak order impression resulting in "simultaneous" or "uncertain" responses. The overlap is determined by the shape of the impulse: Brisker impulses and farther horizontal shifts of one curve with respect to each other lead to less overlap and thus a stronger order impression. For further demonstrations and discussion of consequences of the temporal-profile model, we refer to Weiß and Scharlau (2011). Stelmach and Herdman's model can represent both acceleration and deceleration by sharpening or, respectively, weakening the impulse profiles, which results in a relative prior entry.

For this model, our results imply a dependence between the shapes of the impulse profiles: Compared to a neutral condition, the reduction in the width of the attended stimulus' impulse should be accompanied by an increase of the width of the impulse evoked by the unattended target. If a temporal profile that behaves as predicted by Stelmach and Herdman (1991) can ever be measured directly, it would provide the possibility of validating our finding. Moreover, it may be possible to make use of their predictions based on their simultaneity detector, which evaluates the overlap of the two profiles. The dependence our results imply for the profiles should be reflected in this overlap. Whether behavioral consequences can be measured with sufficient precision, however, requires further investigation.

In contrast to the independent-channels models, head-start models do not allow for a combination of acceleration and deceleration leading to prior entry. The asynchronous-updating model, for instance, is based on the idea that a process can only encode features of an object into more durable internal representation (i.e., the internal model), once attention is assigned to the object's location (Neumann & Scharlau, 2007). When attention is shifted toward this location in advance, the transfer to the internal model can start earlier. The perceptual-retouch model (Bachmann, 1984; Kirt & Bachmann, 2013) assumes that a fast process of specific encoding must integrate with temporally trailing nonspecific activity. A cue triggers the nonspecific activity earlier to the benefit of the target, which becomes conscious earlier.

The asynchronous-updating model and perceptual-retouch model have been discussed as mechanisms that explain prior entry (Scharlau, 2007). According to these models, the targets must initiate the attention shift or the nonspecific activity themselves in conditions that contain no cue. When a cue is present, prior entry by facilitation results from the head start of the cued target.

Thus, the asynchronous-updating model and the perceptual-retouch model do not fully agree with our findings: They explain prior entry by pure facilitation caused by the cue-induced early attention shift or nonspecific activity. We argue that, in terms of TVA, this must result in a pure speedup by attention. The uncued target should not be processed less efficiently than a target of the neutral condition because, according to the head-start models, both initiate the attention shift toward them or the nonspecific activity themselves. Only the cued target has an advantage due to the cue. With TVA, the v parameters of the cued and uncued targets combined ($C_{\text{attention}}$) should exceed the sum of two neutral targets (C_{neutral}) based on the enhancement of the cued target. In our experiments, however, we found the contrary, that $C_{\text{attention}}$ and C_{neutral} are equal. Regarding the two targets, this suggests that instead of a head start of one as the consequence of attention at its location, rather the distribution of the processing resources is affected. Resources that facilitate the cued target have to be withdrawn from the unattended one.

Interestingly, we found an unexpected effect in the TVA parameter t_0. Contrary to what we argued before, this indeed indicates a head-start component that resembles the mechanisms of these models. The effect has no clear interpretation in terms of TVA yet, but it implies that processing of the attended stimulus starts earlier, not only in comparison to the unattended, but also in comparison to the neutral condition. Thus it reflects pure facilitation. Furthermore, this effect strongly depends on the cueing interval as predicted by such models. Its time course—being most effective at a cueing interval of 50 ms and a decline afterward—agrees better with the perceptual-retouch model (e.g., see Bachmann & Sikka, 2005; also see Scharlau et al., 2006, for a discussion of the time courses of rivaling head-start models). However, v is required to be very large (and hence the $1/v$ contribution to the encoding duration very small), for the t_0 effect to be the main influence on order judgment. A rather large v is not too far-fetched for typical TOJs as usually simple shapes, which can be easily discriminated, are used as targets.[4]

TVA appears to be a suitable framework for assessing prior entry and discriminating between head-start components and processing-speed-related components. An unsolved problem is that the temporally distributed presentation of stimuli, such as the peripheral cue that precedes the targets, is not considered in the original version of TVA.

How can the cue-induced redistribution of processing resources be accounted for in the NTVA framework? TTVA (temporal theory of visual attention; Petersen et al., 2012) has been developed to model data from the attentional dwell time paradigm, in which two spatially and temporally distributed postmasked targets are shown. A functional blindness for the second target occurs when it is presented 200–500 ms after the first. Because the impact on the second target in the dwell-time task is similar to that of the cue on the uncued stimulus in our paradigm, we suggest that the responsible mechanism is closely related. According to Petersen et al. (2012), the deficit in target report in the dwell-time paradigm is caused by feature-target neurons being locked by the first target and thereby unavailable for the second target. This explanation is based on the idea that positive feedback loops are required to sustain an object's representation in VSTM for a while, and neurons that participate in this loop are unavailable for processing the second target (see Figure 9). Only after neurons have been gradually released from this loop, this impairment disappears, usually at an SOA of about 900 ms or greater.

In the cueing situation in our paradigm, the cue may lock resources in the same way, which are then unavailable for the uncued stimulus (see Figure 10). The cued stimulus, however, can take over these resources because it is presented at the same location. The cue and the target share features, such as color, onset, etc., so the overlap of low-level resources activated by the cue and required for the target is substantial. The unavailability of resources for the uncued target results in its slowdown while the cued target is in possession of just these resources. This mechanism shifts the resources in favor of the attended stimulus, withdrawing them from the unattended. Moreover, we did not find any significant effect of the COA on the magnitude of the TVA-based prior entry. The difference in the processing rates v of the cued and uncued target is similar at the COAs that were tested. In this range, the dwell-time effect is also relatively strong as its decline has barely started (see Petersen et al., 2012). This suggests that, for the range we tested, resources have already been locked by the cue at COA $= 50$ ms and are not (or not sufficiently) released until COA $= 200$ ms. Thus, there is no substantial effect of the COA on the strength of the cue.

These mechanisms so far still adhere to the concept of the original TVA that the race of all stimuli starts at the same time after the resources have been assigned. To explain the effect on t_0 of presenting a cue, this assumption must be relaxed. The cue, when it is presented close enough to the letter, could initiate the calculation of the attentional weight prior to the presentation of the letter. Thus, when the letter is presented at the cued location, less time is needed to calculate attentional weights, and the stimulus may enter with a head start into the race. Whether this interpretation agrees with all aspects of the theory and how it can be tested in experiments must be the subject of future research. Given the dynamic input for real-world vision, it is highly desirable to accurately model the processing of spatially and temporally distributed stimuli.

Prior entry and processing time

In this section, we discuss the magnitude difference we find (in the COA $= 100$ ms and COA $= 200$ ms conditions; see Experiment 2) for the TOJ-based prior entry while the TVA-based estimate remains the same

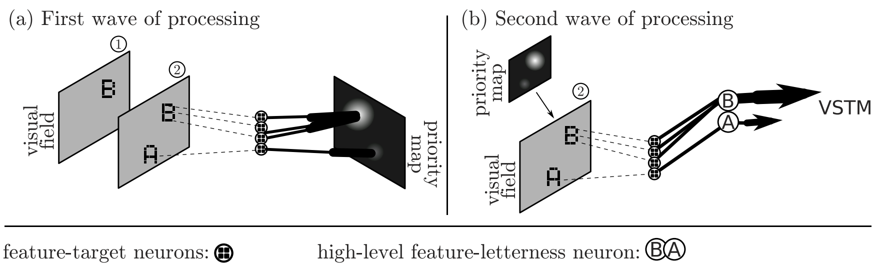

Figure 9. Illustration of the first (a) and second (b) wave of processing according to TTVA. At arrival of the target with identity *A* at Time 2 in the display, most of the target-specific neurons are still engaged in active feedback loops for the target with identity *B*, which arrived at Time 1 until it is transformed into a VSTM-independent representation (e.g., verbal). Note that the situation has been simplified by leaving out the masks. For a full account including masks, see Petersen et al. (2012).

for all COAs. For COA = 100 ms and COA = 200 ms, the TOJ-based prior entry appears substantially larger than the TVA-based prior entry. This means that for $PE_{TVA} < SOA < PE_{TOJ}$, the correct order at the level of VSTM can be turned into the wrong order at the level of TOJs. We shall explain a mechanism that makes such inversions possible and leads to a COA-dependent scaling of the TOJ-based prior-entry effect, which does not affect the TVA-based prior entry.

Similar dissociations have been discussed with regard to TOJs and reaction-time tasks (see, e.g., Jaśkowski, 1993; Neumann & Niepel, 2004), and different reasons have been suggested. They are based on the idea that the responses are differentially triggered by information processed on different routes or at different critical decision thresholds. In the context of this study, different decision thresholds could be similarly involved.

We suggest that for each experimental block with its specific task difficulty, such a threshold could be shifted for TOJs. That is, at larger COAs, when the order judgment is more difficult (Scharlau & Neumann, 2003b), the system accumulates more evidence before accepting a judgment. According to the model by Sternberg and Knoll (1973; see Figure 9), such additional processing increases the magnitude of prior entry. In

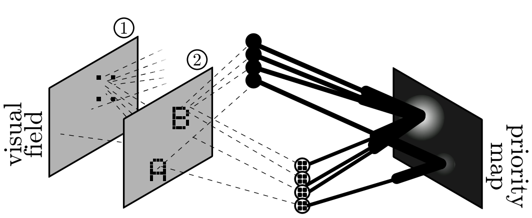

Figure 10. Illustration of a possible first wave of processing in the presence of a cue. The situation is basically the same as in the dwell-time paradigm (see Figure 9a) except that the cue locks the resources, and we assume that a target in the same location (*B* at Time 2 in this figure) takes over "feature-target neurons" from the cue that appeared at Time 1. The result is a second wave as in Figure 9b with an advantage for letter *B* that results in earlier VSTM arrival compared with letter *A*.

their electrophysiological study, Vibell et al. (2007) found prior entry to be larger at later compared to earlier ERP components. They concluded that, "This suggests that the prior-entry effects increase as neural processing proceeds from perceptual to later cognitive and motor-related processes" (p. 117). Thus, the measured size may strongly depend on the level of processing that is required until the participant is sufficiently certain to perform the judgment. The role of task difficulty in this mechanism is supported by the fact that the discrimination accuracy (measured via DL) is reduced for large COAs (see Experiment 2). For the DL values, we did not find a main effect of cueing, which adds further support for an explanation based on a strategic adjustment within an experimental block as opposed to a direct consequence of the cue, which would leave the performance in the neutral no-cue trials unaffected.

Such a variable criterion in stimulus identification can be realized with counting models (Townsend & Ashby, 1983), which have recently been applied in the context of TVA by Kyllingsbæk, Markussen, and Bundesen (2012). Instead of relying on single categorizations, which occur with a certain hazard rate, these models count tentative categorizations, each of which is made at a constant Poisson rate. Each response category is associated with such a counter. In the model used by Kyllingsbæk et al., the categorization with the highest count of tentative categorizations is selected and reported at the end of processing. Here we instead assume that a certain threshold of tentative categorizations exists that must be passed to select and report a certain categorization, reflecting the variable decision criterion. There are independent counters for letter identification and TOJ operating at different thresholds. Mathematically, the processing time of a categorization is then described by the Erlang distribution (convolution of k Poisson processes) with a mean of k/v, where k is the number of tentative categorizations required to pass the threshold and make that categorization, and v is the processing rate associated with the categorization or judgment. Hence, the expected encoding time in VSTM is given by $E_x = t_0 + k/v_x$ and $PE_{TVA} = E_{uncued} - E_{cued} = (t_{0\text{-uncued}} +$

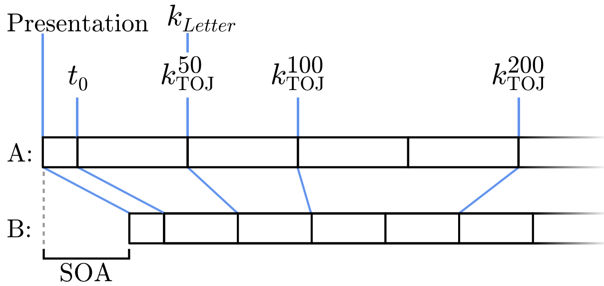

Figure 11. Illustration shows the timeline of tentative categorizations for a stimulus A and a stimulus B, for which the encoding rate for stimulus A, v_A, is lower than the encoding rate for stimulus B, v_B. The different criteria are marked with the corresponding k thresholds and are located at t_0+k/v_A for stimulus A and at $SOA+t_0+k/v_B$ for stimulus B. In this example, the time of the final categorizations are in the order of the physical presentation for $k_{Letter}=k_{\mathrm{TOJ}}^{50}=1$ and $k_{\mathrm{TOJ}}^{100}=2$, but reversed for $k_{\mathrm{TOJ}}^{200}=4$.

$k/v_{\mathrm{uncued}}) - (t_{0\text{-cued}} + k/v_{\mathrm{cued}})$. Further, we assume that in all three COA conditions only one tentative categorization is needed in order to make a letter categorization, $k_{Letter}=1$, whereas the number of tentative categorizations needed in order to make a TOJ increases with the COA (i.e., the difficulty in making a TOJ). That is, we assume that only one tentative categorization is needed in the COA = 50 ms condition, $k_{\mathrm{TOJ}}^{50}=1$, whereas two and four are needed in the COA = 100 ms condition, $k_{\mathrm{TOJ}}^{100}=2$, and COA = 200 ms condition, $k_{\mathrm{TOJ}}^{200}=4$, respectively (see Figure 11).

In Figure 12 it can be seen that the TVA-based (k-model) prior-entry estimate behaves more like the TOJ-based estimate when we apply the outlined task difficulty model on the subject level. The degree of similarity of the patterns obviously depends on the values chosen for k or, more specifically, the function that maps a k value to a COA (we used a linear mapping only for simplicity). However, the goal of this exercise was not to fit our data. It rather shows that such a scaling behavior can be modeled based on a theoretically valid assumption without affecting the way in which processing resources are initially distributed.

To summarize, the dissociation of TVA- and TOJ-based prior-entry estimates could be explained by strategic criterion changes[5] with regard to the COA in the TOJ task, which do not apply for the letter-identification task. In future work, this can be verified by showing that a reduction of the temporal complexity in the stimulus display (e.g., by avoiding the cue or the mask onsets) minimizes the effect. Similarly, increasing the letter-identification task complexity (e.g., by adding noise) should lead to a similar upscaling of TVA-based prior-entry estimate.

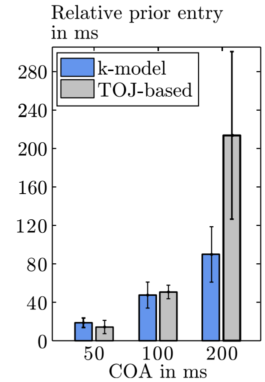

Figure 12. The plot shows that a linear increase in the number of tentative categorizations with COA leads to COA-dependent scaling similar to that observed in the TOJs.

For the present study, it should be noted that the proposed explanation does not require any adjustment of the attentional weights to account for the dissociation. Thus, when we measure the increase and decrease in encoding durations at the level of VSTM, this remains true also for the order judgments even when the prior-entry effect is scaled by the suggested mechanisms.

Conclusion

In the present paper, we reported a new TVA-based assessment of the phenomenon of prior entry in a common setup that also allows classic TOJ-based investigation. Our experimental results show that the total amount of processing resources is conserved even under the attention manipulation, but they are shifted toward the attended stimulus. Prior entry is thus caused by a prolongation of the encoding time of the unattended stimulus and a reduction of the encoding time of the attended stimulus. This is revealed by TVA-based assessment of the expected encoding times in VSTM, which show that the cued stimulus arrives earlier and the uncued stimulus later than stimuli from a neutral control condition. These results are in line with Weiß et al. (2013), who found a similar pattern with a fundamentally different method for probing arrival latencies. Haider, Häusser, and Carandini (2013) showed in a recent study in mice that visual stimulation resulting in inhibition at the cortical level may have been underestimated and more important in spatially selective processing than previously assumed. Furthermore, inhibition at the cortical level is likely to be modulated by attention. Thus, the decrease in processing rate that we found in relation to prior entry may well support such cortical inhibitions.

In this study, we combined the TVA-based measurements with TOJs to connect our findings to the

existing prior-entry knowledge, which mainly stems from TOJs. This revealed certain discrepancies between both methods. However, the TVA-based method itself is not prone to several factors that critically influence TOJs, such as interferences in the temporally distributed presentation (i.e., in some situations, the uncued target can draw attention away from the cue), hard-to-control interactions with temporal attention, or response biases in the subjective order judgments. Therefore, the TVA-based method appears highly useful as an assessment tool for prior entry and perceptual latencies in general.

Keywords: cueing, prior entry, TOJ, TVA, visual attention

Acknowledgments

The authors gratefully acknowledge the funding by the German Research Foundation under the grant SCHA 1515/1-2 within the ECRP II Programme of the European Science Foundation and SCHA 1515/5-1. Anders Petersen was supported by a grant from the Center of Excellence Program at the University of Copenhagen. We also thank the Paderborn Center for Parallel Computing for providing computational resources.

Commercial relationship: none.
Corresponding author: Jan Tünnermann.
Email: jeti@mail.upb.de.
Address: University of Paderborn, Paderborn, Germany.

Footnotes

[1] Formally, let the effect when a process A with duration $T_A \cdot s$ finishes earlier than a process B with duration T_B be regarded as a *prior entry by speedup*, where $s < 1$ is a factor representing the speedup; this can always be expressed as a *prior entry by slowdown* with durations of A and B being T'_A and $T_B \cdot 1/s$, respectively, and $1/s > 1$ representing the equipotent slowdown when $T'_x = T_x \cdot s$. In TOJs, this is a valid case because no assumptions or measurements are made regarding the magnitude of T_x, the absolute processing time of stimulus x. The argument can be generalized to allow for a combination of slowdown and speedup that results in the same relative prior entry using process durations $T_A \cdot s \cdot \alpha$, $T_B \cdot \alpha$, and $T'_x = T_x \cdot 1/\alpha$, where $0 < \alpha < 1$ is a free parameter.

[2] The reader may note the following issues that could compromise the reliability of the statistical analyses performed for this study: (a) Two dependent variables, TOJ- and TVA-based prior entry, were measured on partially overlapping data (see Methodology and paradigm). Furthermore, TVA estimate E is a compound parameter that is constructed from the parameters t_0 and v, which are estimated for the observed curves. In the statistics, however, the parameters are treated as independent measurements. (b) Experiment 1 is identical to one condition of Experiment 2. As the experiments were time-consuming (Experiment 2 lasted for 3 to 4 hr) only the remaining conditions (COA = 50 ms and COA = 200 ms) were conducted for participants who already produced a COA = 100 ms data set in Experiment 1. Inversely, all COA = 100 ms data from Experiment 2 were included in the analysis of Experiment 1. (c) Data collection for Experiment 2 originally finished after eight participants. However, as large unexpected individual differences were observed with regard to COA, a further six participants performed the experiment. These problems mainly increase the probability of type I errors. To deal with the situation as well as possible, we show all subject-level plots in Appendix: Individual fits for Experiments 1 and 2 (See Figure A3 and Figure A4, respectively).

[3] The difficulties in the evaluation of our data mentioned in Footnote 2 originate mainly from the efforts to obtain TVA as well as TOJ parameters in the same paradigm. The TVA-based method alone is highly usable and even has found its way into clinical research (see e.g., Finke et al., 2010). However, one goal of the present study is to compare TVA-based estimates with traditional TOJ-based estimates of prior entry from responses that are ideally based on the same information. Therefore the combined paradigm is used here.

[4] This is rather curious. TOJs mean to investigate systematic influences on the processing duration of stimuli. However, very simple stimuli are typically used, which are likely to be processed quickly. This substantially limits the differences that can be found.

[5] Importantly, this strategic adjustment is different from criterion changes that result in response biases as found, for example by Shore et al. (2001). In our model, what is adjusted is a threshold of information accrual. It is completely unspecific with regard to cued or uncued locations as it affects all processes.

References

Bachmann, T. (1984). The process of perceptual retouch: Nonspecific afferent activation dynamics in explaining visual masking. *Perception & Psychophysics, 35,* 69–84.

Bachmann, T., & Sikka, P. (2005). Perception of successive targets presented in invariant-item streams. *Acta Psychologica, 120,* 19–34.

Bessel, F. W. (1838). Untersuchungen über die Wahrscheinlichkeit der Beobachtungsfehler [Investigations regarding the probability of errors in observations]. *Astronomische Nachrichten, 15,* 369–404.

Boring, E. G. (1929). *A history of experimental psychology*. New York: D. Appleton-Century.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97,* 523–547.

Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. *Psychological Review, 112,* 291–328.

Carlson, T. A., Hogendoorn, H., & Verstraten, F. A. J. (2006). The speed of visual attention: What time is it? *Journal of Vision, 6*(12):6, 1406–1411, http://www.journalofvision.org/content/6/12/6, doi:10.1167/6.12.16. [PubMed] [Article]

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research, 51,* 1484–1525.

Carrasco, M., & McElree, B. (2001). Covert attention speeds the accrual of visual information. *Proceedings of the National Academy of Sciences, USA, 98,* 5363–5367.

Carrasco, M., McElree, B., Denisova, K., & Giordano, A. M. (2003). Speed of visual processing increases with eccentricity. *Nature Neuroscience, 6,* 699–700.

Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology, 17,* 177–184.

Colonius, H., & Diederich, A. (2011). Computing an optimal time window of audiovisual integration in focused attention tasks: Illustrated by studies on effect of age and prior knowledge. *Experimental Brain Research, 212,* 327–337.

Dyrholm, M., Kyllingsbæk, S., Espeseth, T., & Bundesen, C. (2011). Generalizing parametric models by introducing trial-by-trial parameter variability: The case of TVA. *Journal of Mathematical Psychology, 55,* 416–429.

Finke, K., Dodds, C. M., Bublak, P., Regenthal, R., Baumann, F., Manly, T., & Müller, U. (2010). Effects of modafinil and methylphenidate on visual attention capacity: A TVA-based study. *Psychopharmacology, 210,* 317–329.

Finney, D. (1971). *Probit analysis* (3rd ed.). Cambridge: Cambridge University Press.

Frey, R. D. (1990). Selective attention, event perception and the criterion of acceptability principle: Evidence supporting and rejecting the doctrine of prior entry. *Human Movement Science, 9,* 481–530.

García-Pérez, M. A., & Alcalá-Quintana, R. (2012). Response errors explain the failure of independent-channels models of perception of temporal order. *Frontiers in Psychology, 3,* 94.

Haider, B., Häusser, M., & Carandini, M. (2013). Inhibition dominates sensory responses in the awake cortex. *Nature, 493,* 97–100.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993a). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33,* 1219–1240.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993b). Voluntary and stimulus-induced attention detected as motion sensation. *Perception, 22,* 517–526.

Hilkenmeier, F., Scharlau, I., Weiß, K., & Olivers, C. N. L. (2012). The dynamics of prior entry in serial visual processing. *Visual Cognition, 20,* 37–41.

Hillyard, S. A., Luck, S. J., & Mangun, G. R. (1994). The cuing of attention to visual field locations: Analysis with ERP recordings. In H. J. Heinze, T. F. Münte, & G. R. Mangun (Eds.), *Cognitive electrophysiology* (pp. 1–25). Boston: Birkhäuser.

Hoffmann, C. (2006). *Unter Beobachtung: Naturforschung in der Zeit der Sinnesapparate [Under observation: Natural science at the time of the sensoria]*. Göttingen: Wallstein.

Jaśkowski, P. (1993). Selective attention and temporal-order judgment. *Perception, 22,* 681–689.

Jaśkowski, P., & Verleger, R. (2000). Attentional bias toward low-intensity stimuli: An explanation for the intensity dissociation between reaction time and temporal order judgment? *Consciousness and Cognition, 9,* 435–456.

Kirt, T., & Bachmann, T. (2013). Perceptual retouch theory derived modeling of interactions in the processing of successive visual objects for consciousness: Two-stage synchronization of neuronal oscillators. *Consciousness and Cognition, 22,* 330–347.

Klein, R. M., Schmidt, W. C., & Müller, H. J. (1998). Disinhibition of return: Unnecessary and unlikely. *Perception & Psychophysics, 60,* 862–872.

Kyllingsbæk, S. (2006). Modeling visual attention. *Behavioral Research Methods, 38,* 123–133.

Kyllingsbæk, S., Markussen, B., & Bundesen, C. (2012). Testing a Poisson counter model for visual identification of briefly presented, mutually confusable single stimuli in pure accuracy tasks. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 628–642.

Lagarias, J. C., Reeds, J. A., Wright, M. H., & Wright, P. E. (1998). Convergence properties of the Nelder-Mead simplex method in low dimensions. *SIAM Journal of Optimization, 9,* 112–147.

Lunau, R., & Olivers, C. N. L. (2010). The attentional blink and lag 1 sparing are nonspatial. *Attention, Perception, & Psychophysics, 72,* 317–325.

McDonald, J. J., Teder-Sälejärvi, W. A., Di Russo, F., & Hillyard, S. A. (2005). Neural basis of auditory-induced shifts in visual time-order perception. *Nature Neuroscience, 8,* 1197–1202.

Mitchel, O. (1858). On personal equation. *Monthly Notices of the Royal Astronomical Society, 18,* 261–264.

Müsseler, J., Stork, S., & Kerzel, D. (2002). Comparing mislocalizations with moving stimuli: The Fröhlich effect, the flash-lag, and representational momentum. *Visual Cognition, 9,* 120–138.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29,* 1631–1647.

Neumann, O., & Niepel, M. (2004). Timing of "perception" and "perception" of time. In C. Kaernbach, E. Schröger, & H. Müller (Eds.), *Psychophysics beyond sensation* (pp. 245–269). Mahwah, NJ: Lawrence Erlbaum.

Neumann, O., & Scharlau, I. (2007). Experiments on the Fehrer–Raab effect and the "Weather Station Model" of visual backward masking. *Psychological Research, 71,* 667–677.

Olivers, C. N. L. (2007). The time course of attention: It is better than we thought. *Current Directions in Psychological Science, 16,* 11–15.

Olivers, C. N. L., Hilkenmeier, F., & Scharlau, I. (2011). Prior entry explains order reversals in the attentional blink. *Attention, Perception, & Psychophysics, 73*, 53–67.

Olivers, C. N. L., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological Review, 115,* 836–863.

Petersen, A., Kyllingsbæk, S., & Bundesen, C. (2012). Measuring and modeling attentional dwell time. *Psychonomic Bulletin & Review, 19,* 1029–1046.

Priess, H.-W., Scharlau, I., Becker, S. I., & Ansorge, U. (2012). Spatial mislocalization as a consequence of sequential coding of stimuli. *Attention, Perception, & Psychophysics, 74,* 365–378.

Sanford, E. C. (1888). Personal equation. *The American Journal of Psychology, 2,* 3–38.

Scharlau, I. (2004). Evidence against response bias in temporal order tasks with attention manipulation by masked primes. *Psychological Research, 68,* 224–236.

Scharlau, I. (2007). Perceptual latency priming: A measure of attentional facilitation. *Psychological Research, 71,* 678–686.

Scharlau, I., Ansorge, U., & Horstmann, G. (2006). Latency facilitation in temporal-order judgments: Time course of facilitation as a function of judgment type. *Acta Psychologica, 122,* 129–159.

Scharlau, I., & Neumann, O. (2003a). Perceptual latency priming by masked and unmasked stimuli: Evidence for an attentional interpretation. *Psychological Research, 67,* 184–196.

Scharlau, I., & Neumann, O. (2003b). Temporal parameters and time course of perceptual latency priming. *Acta Psychologica, 113*, 185–203.

Schneider, K. A., & Bavelier, D. (2003). Components of visual prior entry. *Cognitive Psychology, 47,* 333–366.

Shibuya, H. (1991). Comparison between stochastic models for visual selection. In J.-P. Doignon & J.-C. Falmagne (Eds.), *Mathematical psychology: Current developments* (pp. 337–356). New York: Springer.

Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: Measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 591–600.

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science, 12,* 205–212.

Spence, C., Nicholls, M. E., & Driver, J. (2001). The cost of expecting events in the wrong sensory modality. *63*(2), 330–336.

Spence, C., & Parise, C. (2010). Prior-entry: A review. *Consciousness and Cognition, 19,* 364–379.

Spence, C., Shore, D. I., & Klein, R. M. (2001). Multisensory prior entry. *Journal of Experimental Psychology: General, 130*, 799–832.

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 539–550.

Stelmach, L. B., Herdman, C. M., & McNeil, K. (1994). Attentional modulation of visual processes in motion perception. *Journal of Experimental Psychology: Human Perception and Performance, 20*(1), 108–121.

Sternberg, S., & Knoll, R. L. (1973). The perception of temporal order: Fundamental issues and a general model. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 629–685). New York: Academic Press.

Stone, S. (1926). Prior entry in the auditory-tactile complication. *The American Journal of Psychology, 37,* 284–287.

Tam, W. J., & Ono, H. (1994). Fixation disengagement and eye-movement latency. *Perception & Psychophysics, 56,* 251–260.

Titchener, E. (1908). *Lectures on the elementary psychology of feeling and attention.* New York: MacMillan.

Townsend, J. T., & Ashby, F. G. (1983). *The stochastic modeling of elementary psychological processes.* Cambridge: Cambridge University Press.

Vangkilde, S., Bundesen, C., & Coull, J. T. (2011). Prompt but inefficient: Nicotine differentially modulates discrete components of attention. *Psychopharmacology, 218,* 667–680.

Vibell, J., Klinge, C., Zampini, M., Spence, C., & Nobre, A. (2007). Temporal order is coded temporally in the brain: Early event-related potential latency shifts underlying prior entry in a cross-modal temporal order judgment task. *Journal of Cognitive Neuroscience, 19,* 109–120.

Weiß, K., Hilkenmeier, F., & Scharlau, I. (2013). Attention and the speed of information processing: Posterior entry for unattended stimuli instead of prior entry for attended stimuli. *PloS one, 8,* e54257.

Weiß, K., & Scharlau, I. (2011). Simultaneity and temporal order perception: Different sides of the same coin? Evidence from a visual prior-entry study. *The Quarterly Journal of Experimental Psychology, 64,* 394–416.

Wiggs, C. L., & Martin, A. (1998). Properties and mechanisms of perceptual priming. *Current Opinion in Neurobiology, 8,* 227–233.

Woodworth, R. S., & Schlosberg, H. (1954). *Experimental psychology*. New York: Holt, Rinehart and Winston.

Wright, R., & Ward, L. (2008). *Orienting of attention*. Oxford: Oxford University Press.

Zampini, M., Shore, D. I., & Spence, C. (2005). Audiovisual prior entry. *Neuroscience Letters, 381,* 217–222.

Appendix

Bootstrapping a TVA data set

In order to determine which of the two TVA models (exponential or ex-Gaussian) produces a more reliable fit, we performed a massive bootstrapping of one participant's data as suggested by Kyllingsbæk (2006). The data were rearranged to create nine subsets, one for each combination of attention and order condition, because these are subject to varying interference (see section on estimating the TOJ-based prior entry). The number of bootstraps per condition was set to twice the number of targets of that condition (which can be deduced from Table 1; note that control trials contain two equal no-cue targets, and attention trials contain one cued and one uncued target, yielding twice as many neutral targets as cued and uncued targets). The resampled data were fitted with the traditional exponential TVA model (as described in Bundesen, 1990) and the ex-Gaussian model proposed by Dyrholm et al.

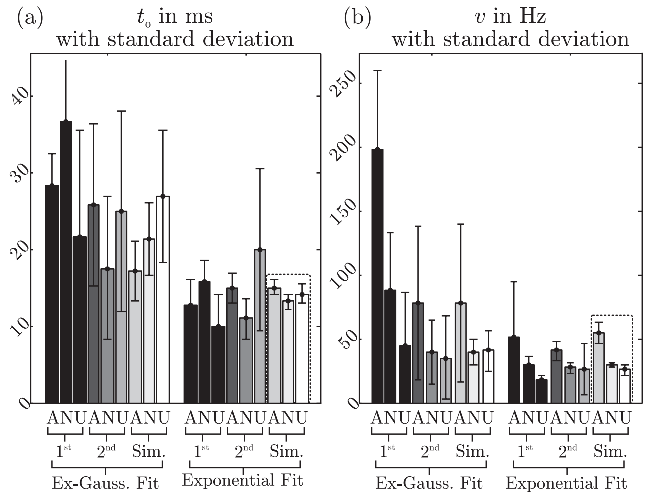

Figure A1. Results from bootstrapping a data set using the ex-Gaussian and exponential TVA models for parameter estimation. Chart (a) shows the estimates of t_0 and (b) those of v. Conditions are labeled with "Attended" (A), "Neutral" (N), and "Unattended" (U). First (1st), second (2nd), and simultaneous (Sim.) refer to stimulus arrival. The most stable estimates are in the simultaneous conditions fitted with the exponential model (marked with dotted boxes).

(2011); both models were fitted with the program provided by Dyrholm et al. The computational resources to perform the resulting 7,672 fits were provided by the Paderborn Center of Parallel Computing. The mean and standard deviations were calculated for the v and t_0 parameters for each of the nine subsets (see Figure A1).

The result of the bootstrapping shows that the exponential model is more stable for the data from our paradigm. Furthermore, the smallest error bars are found for the simultaneous conditions that cover a

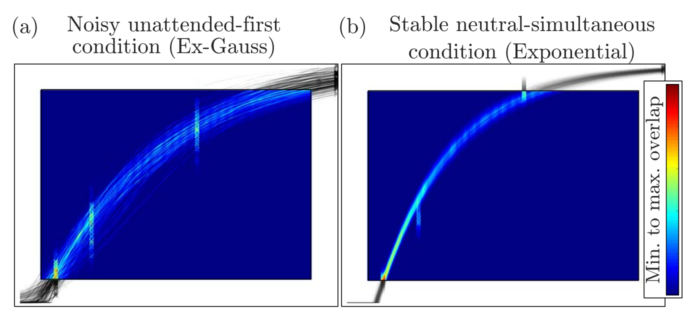

Figure A2. Heat maps of accumulated plots of estimates and data points of the bootstraps; a noisy (a) and a stable (b) condition (see Figure A1). Red colors correspond to many curves or data points overlapping (i.e., a stable model). The curves in the outer part (white background) are not colored, as this is where the curves converge, forcing a high overlap that would make the visualization insensitive in the interesting area where the curves show their actual shapes.

substantial amount of the trials (more than half; see Table 1). The reason for the extremely large error bars in the asynchronous trials of the ex-Gaussian fits can be seen in Figure A2a: The curves are more divergent, and some of the bootstraps lead to curves with a very steep slope (v values up to 475.4 Hz) and a late threshold (t_0 values up to 36.8 ms). The corresponding visualization of one of the simultaneous subsets is shown in Figure A2b. As a conclusion, we only include simultaneous trials in the TVA-based analysis of data recorded with this paradigm and use the exponential model, which appears more stable in this situation.

Estimating the size of prior entry with TOJs

With TOJs, prior entry can be estimated by fitting psychometric functions (see, e.g., Scharlau, 2007; Stelmach & Herdman, 1991; Weiß & Scharlau, 2011). Weiß and Scharlau argued that if one is concerned with the size of prior entry, it is very important to estimate it from trials in which interference by the unattended target—which is a natural part of the TOJ paradigm—is minimized. A direct way to do so would be to use only the conditions in which the comparison stimulus is indeed the first stimulus. Unfortunately, these conditions contain only half of the psychometric function and, in trials with attention attracted by the cue, only the less interesting half. This can be seen in Figure 2a: We would have to estimate the parameters of the psychometric function from the left part, which does not contain much information because the judgment probability is close to one. Weiß and Scharlau as well as Scharlau et al. (2006) suggested that the appropriate way is to estimate the parameters from the psychometric function that is derived from the trials in which the observer sees the comparison stimulus appearing first. As this occurs across the full range of SOAs, it results in a complete psychometric function. The "standard first" judgments are disregarded in this estimation as they contain a large amount of trials in which the unattended target appears quickly after the cue but before the attended target appears at the cue's location. These are high-interference trials: The unattended target can withdraw attention from the cued location when it is presented briefly after the cue and before the cued target; this interference reduces the efficiency of the cue. In our paradigm, such interference is possibly enhanced in trials in which the mask onset of the unattended stimulus also occurs before the cued target is shown as can be seen in Figure 5. Consequently, we use only the "comparison first" judgments in the TVA-based analyses of this study.

Individual fits for Experiment 1

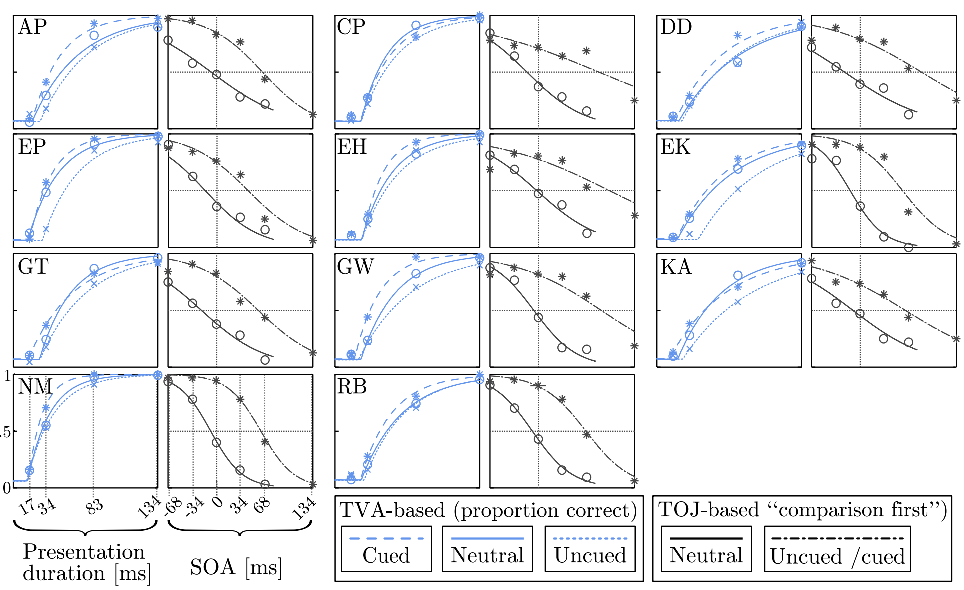

Figure A3. Plots of observed data and fitted curves for participants who only participated in Experiment 1 (COA = 100 ms). Plots of Experiment 1 data from participants who also took part in Experiment 2 are presented in the Appendix: Individual fits for Experiment 2 as COA = 100 ms conditions.

Individual fits for Experiment 2

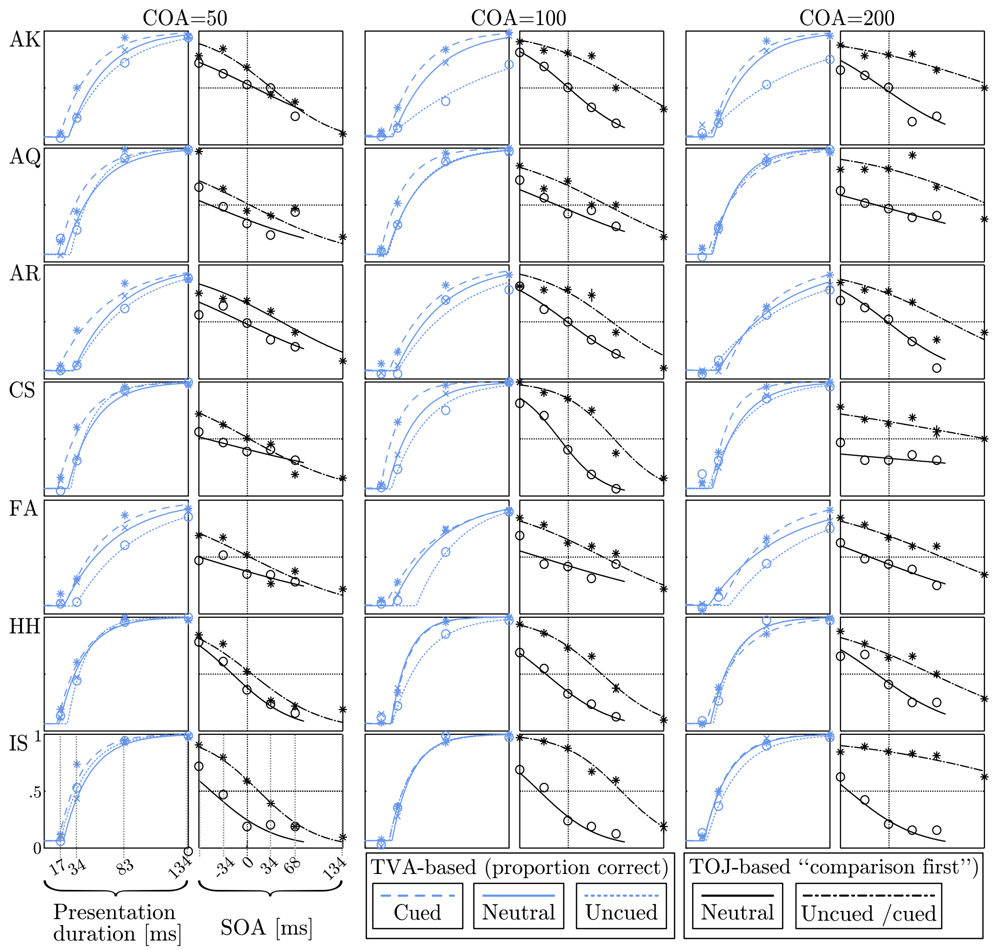

Figure A4. Plots of observed data and fitted curves for Experiment 2.

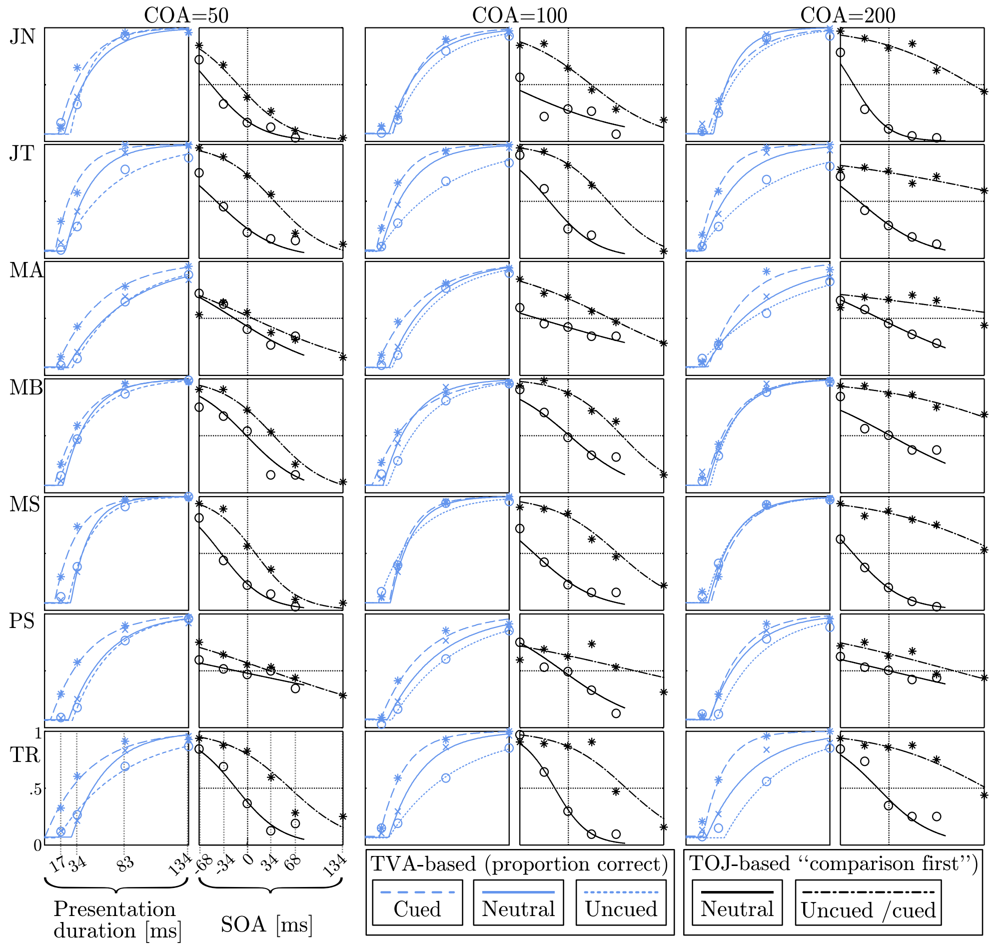

Figure A4. Plots of observed data and fitted curves for Experiment 2 (continued).

Statistics Overview

This section contains tabular overviews of means, standard deviations, and post hoc test statistics, which are referred to in the main text. Furthermore, we report the corresponding t values and 95% CIs on the difference of the means.

				Compared to neutral			Compared to uncued		
	Condition	M	SD	t	P^*	95% CI	t	P^*	95% CI
t_0	cued	12.45 ms	4.87	5.45	<0.001	[−14.99, −6.48]	8.19	<0.001	[−15.01, −8.74]
	neutral	23.18 ms	3.96				0.64	=1.06	[−4.98, 2.69]
	uncued	24.32 ms	6.14						
v	cued	32.86 Hz	8.91	1.46	=0.34	[−0.9, 4.66]	1	=0.34	[−3.07, 8.39]
	neutral	30.98 Hz	9.54				0.29	=0.39	[−5.07, 6.63]
	uncued	30.91 Hz	13.4						
E	cued	45.33 ms	10.4	7.93	<0.001	[−17.09, −9.77]	5.81	<0.001	[−26.25, −12.03]
	neutral	58.76 ms	13.95				2.17	<0.05	[−11.40, −0.01]
	uncued	64.47 ms	18.86						

Table A1. Descriptive and post hoc test statistics overview for the TVA parameters in the COA = 50 ms condition from Experiment 2. *Notes*: P^* are the p values of a one-tailed t test adjusted by Holm-Bonferroni correction for multiple comparisons.

				Compared to neutral			Compared to uncued		
	Condition	M	SD	t	P^*	95% CI	t	P^*	95% CI
t_0	cued	19.75 ms	6.01	4.53	<0.001	[−6.25, −2.34]	4.18	<0.001	[−11.19, −3.8]
	neutral	24.04 ms	4.48				2.06	<0.05	[−6.41, 0]
	uncued	27.24 ms	8.14						
v	cued	34.70 Hz	13.25	3.05	<0.01	[1.62, 8.42]	5.79	<0.001	[7.75, 16.34]
	neutral	29.68 Hz	10.20				5.10	<0.001	[−4.18, 9.87]
	uncued	22.66 Hz	7.9						
E	cued	52.91 ms	12.44	5.58	<0.001	[−11.68, −5.37]	6.65	<0.001	[−32.1, −16.88]
	neutral	61.43 ms	13.14				4.95	<0.001	[−22.62, −9.31]
	uncued	77.39 ms	22.23						

Table A2. Descriptive and post hoc test statistics overview for the TVA parameters in the COA = 100 ms condition from Experiment 1. *Notes*: P^* are the p values of a one-tailed t test adjusted by Holm-Bonferroni correction for multiple comparisons.

				Compared to neutral			Compared to uncued		
	Condition	M	SD	t	P^*	95% CI	t	P^*	95% CI
t_0	cued	19.30 ms	6.87	4.39	<0.01	[−8.31, −2.82]	2.72	=0.05	[−13.55, −1.55]
	neutral	24.87 ms	4.19				0.92	=0.94	[−6.66, 2.7]
	uncued	26.85 ms	9.38						
v	cued	35.58 Hz	12.35	2.18	=0.12	[0.04, 8.06]	4.23	<0.01	[6.18, 19.07]
	neutral	31.53 Hz	11.33				3.94	<0.01	[3.87, 13.29]
	uncued	22.95 Hz	9.21						
E	cued	51.07 ms	12	4.7	<0.01	[−13.27, −4.92]	4.46	<0.01	[−40.93, −14.22]
	neutral	60.17 ms	12.87				3.55	<0.01	[−29.73, −7.24]
	uncued	78.65 ms	26.05						

Table A3. Descriptive and post hoc test statistics overview for the TVA parameters in the COA = 100 ms condition from Experiment 2. *Notes*: P^* are the p values of a one-tailed t test adjusted by Holm-Bonferroni correction for multiple comparisons.

	Condition	M	SD	Compared to neutral t	P^*	95% CI	Compared to uncued t	P^*	95% CI
t_0	cued	24.51 ms	7.38	0.03	$=0.69$	[−3.13, 3.2]	0.41	$=1$	[−6.65, 4.53]
	neutral	24.47 ms	4.67				0.44	$=1.06$	[−6.51, 4.31]
	uncued	25.57 ms	9.09						
v	cued	34.33 Hz	9.37	1.41	$=0.34$	[−2.36, 11.29]	2.88	<0.05	[2.63, 18.36]
	neutral	29.87 Hz	10.51				3.4	<0.05	[2.21, 9.86]
	uncued	23.83 Hz	11.53						
E	cued	55.7 ms	15.91	2.64	<0.05	[−13.75, −1.38]	3.69	<0.01	[−36.99, −9.67]
	neutral	63.26 ms	17.88				3.73	<0.01	[−24.91, −6.62]
	uncued	79.03 ms	27.74						

Table A4. Descriptive and post hoc test statistics overview for the TVA parameters in the COA = 200 ms condition from Experiment 2. *Notes*: P^* are the p values of a one-tailed t test adjusted by Holm-Bonferroni correction for multiple comparisons.

	Condition	M	SD	Compared to COA = 100 t	P^*	95% CI	Compared to COA = 200 t	P^*	95% CI
PE_{TVA}	COA = 50 ms	19.14 ms	12.32	1.68	$=0.17$	[−19.28, 2.4]	1.06	$=0.3$	[−12.72, 4.33]
	COA = 100 ms	27.58 ms	23.13				1.08	$=0.3$	[−4.23, 12.72]
	COA = 200 ms	23.33 ms	23.66						
PE_{TOJ}	COA = 50 ms	14.63 ms	26.18	5.33	<0.001	[−51.04, −21.6]	2.2	<0.05	[−394.44, −3.29]
	COA = 100 ms	50.95 ms	27.16				1.87	<0.05	[−350.17, 25.09]
	COA = 200 ms	213.49 ms	325.37						

Table A5. Descriptive and post hoc test statistics overview for the TVA- and TOJ-based prior-entry estimates for the COA = 50, 100, and 200 ms conditions in Experiment 2. *Notes*: P^* are the p values of a one-tailed t test adjusted by Holm-Bonferroni correction for multiple comparisons.