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The influence of target discriminability on the time course of attentional selection

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Abstract

A wealth of neurophysiological data has demonstrated that visual attention can selectively enhance target representations early in the visual processing pathway. In addition, behavioural evidence tells us that the extent to which irrelevant items interfere with target processing depends on their featural similarity to the target. In this context, how does target discriminability influence temporal selection? We present results from an electrophysiology study that addresses this question by investigating the time course of the neural processes involved in target selection as target distinctiveness is varied. The results suggest that, in line with previous findings, making discrimination harder reduces the accuracy of target identification. We find that there are significant differences in the perceptual processing of the target in the two conditions, as indexed by early visual ERPs and the P3 ERP. We ground this and previous empirical evidence within a theoretical framework for understanding the mechanism of attentional selection represented in the ST^2 model, a neural network model of temporal attention and working memory. By simulating both experimental conditions, we show that the model provides a convincing explanation of the pattern of experimental results, in addition to informing questions about the nature and time course of attentional selection.

Keywords: Visual Masking; Event-Related Potential; Temporal Selection

Introduction

The deployment of endogenous attention allows the visual system to selectively enhance the neural representations of task-relevant features in the environment. Our understanding of the neurophysiology of vision in monkeys suggests that focal attention can modulate neural activity very early in the visual processing pathway. Studies of neural firing patterns in spatial selection tasks report correlates of endogenous attention in the primary visual cortex, when a salient feature must be discriminated and selectively enhanced in the presence of competing spatial distractors (Reynolds, Chelazzi, & Desimone, 1999). In humans, ERP studies of selective spatial attention have found that stimulus features at attended locations are enhanced as early as 70-80ms after onset (Hillyard & Anllo-Vento, 1998). But how does selective attention operate in time? Specifically, when the visual system is rapidly presented with successive fleeting stimuli at an already attended spatial location, how quickly can it discriminate a target embedded in a sequence of distractors, and generate a transient attentional enhancement? In this regard, previous behavioural research has found that the extent to which irrelevant distractors temporally interfere with target processing critically depends on how effectively the visual system is configured to distinguish between featural characteristics of targets and distractors (Visser, Bischof, & Di Lollo, 2004).

Visser et al. (2004) use two variants of a sequential stimulus presentation paradigm, previously used by Ward, Duncan, and Shapiro (1997) to study the well-known attentional blink phenomenon (Raymond, Shapiro, & Arnell, 1992). In the first variation, referred to in this paper as *Rapid Serial Visual Presentation* (RSVP), targets are inserted in a sequential stream of distractors presented at the same spatial location. In the second variation, referred to as *Onset* (termed the 'Skeletal' task by Ward et al. (1997)), no stream of distractors is used. Instead, targets are briefly presented and are followed by a backward visual mask. Though the attentional blink deficit is found in both variations, the authors find that the presence of distractors nevertheless influences the difficulty of target selection. Specifically, making the distractors featurally similar to targets reduces behavioural accuracy of target identification.

In this paper, we build upon this finding, and investigate how the time course of target processing is affected by target discriminability. Adapting an experimental paradigm similar to that used by Visser et al. (2004), we record EEG data to provide an index of the temporal dynamics of the underlying neural processing evoked by the presentation of a single target. Importantly, we compare the differences in the ERP signatures evoked by targets presented in the above conditions, and propose an explanation of these differences within the context of a theoretical framework. To this end, we employ the ST^2 model of temporal attention and working memory (Bowman & Wyble, 2007), which implements a two-stage neural network to model temporal visual processing. The model explains and predicts a broad set of experimental findings encompassing the attentional blink, repetition blindness, and RSVP in general. By following through a sequence of theoretically sound changes to the existing model, we enable it to simulate the Onset paradigm. The modifications are validated by comparing virtual ERP traces generated from the model to human ERP traces. As we shall see, the model provides a convincing explanation of the pattern of experimental results, in addition to informing questions about the cognitive equivalence of target processing in masking and RSVP experiments.

Target processing in Onset and RSVP

We first present the behavioural and electrophysiological results for targets in Onset presentation and targets in RSVP.

Methods

Participants Twenty-two university students were paid to participate in the experiment. Two were excluded due to an excessive number of EEG artifacts, and a further three were excluded because of insufficient number of trials in the skeletal condition, leaving 17 participants for the behavioural and EEG analysis (mean age 22.2; SD 3.3). All were free from neurological disorders and had normal or corrected-to-normal vision.

Stimuli and Apparatus We presented alphanumeric characters in black on a white background at a distance of 100cm on a 21" CRT computer screen (1024x768 @ 85Hz) using the Psychophysics toolbox (Brainard, 1997) running on Matlab version 6.5 under Microsoft Windows XP. Stimuli were in Arial font and had an average size of 2.1° x 3.4° visual angle.

Procedure Participants viewed four blocks (3 RSVP/1 Onset, counterbalanced between subjects) of 100 trials. Within each block, there were 96 trials containing a single target and four trials consisting only of distractors. Five practice trials preceded the first block in both the RSVP and Onset conditions, which were not included in the final analysis. The underlying structure and timing of RSVP and Onset streams was the same; however, whereas in RSVP the target was embedded into a continuous stream of distractors, Onset streams contained only the target and a following distractor. The target for each trial was chosen at random from a list of 14 capital letters (B, C, D, E, F, G, J, K, L, P, R, T, U, V); distractors could be any digit except 1 or 0. The target item's position in the stream varied between position 10 to 54. The 'distractor only' trials were randomly inserted to make the occurrence of the target less predictable. Trials were randomly ordered and 50% of targets were followed by a blank in both RSVP and Onset trials to equate patterns within blocks. However, for the purposes of this paper, only data from the Onset masked and the RSVP masked conditions were analysed.

A fixation cross presented for 500ms preceded the first item of each stream. Items were presented at approx. 20 items per second (item duration 47.1ms; no inter-stimulus interval) to ensure participants' detection accuracy was not at ceiling. An RSVP stream consisted of 70 items. Each stream ended with a dot or a comma presented for 47.1ms. Following stream presentation, participants were asked to enter using a keyboard the final item followed by the target they saw, if any. The dot-comma task was included to ensure that participants maintained their attention on the stream till the end.

EEG recording EEG activity was recorded from Ag/Ag-Cl electrodes mounted on an electrode cap (FMS, Munich, Germany) using a high input impedance amplifier (1000MΩ, BrainProducts, Munich, Germany) with a 22-bit ADC. Electrode impedance was reduced to less than 25kΩ before data acquisition. The sampling rate was 2000Hz (digitally reduced to 1000Hz at a later stage) and the data was digitally filtered at low-pass 85Hz and high-pass 0.5Hz during recording. 20 electrodes were placed at the following standard locations according to the international 10/20 system: Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, C7, C8, Pz, P3, P4, P7, P8, Oz, O1, O2, T7 and T8. Electrooculographic (EOG) activity was bipolarly recorded from below and to the right side of the right eye.

EEG data analysis The EEG data was analysed using BrainVision Analyzer (BrainProducts, Munich, Germany), in conjunction with EEGLAB 6.01b (Delorme & Makeig, 2004) and custom MATLAB scripts. The data was referenced to a common average online and re-referenced to linked earlobes offline. Left mastoid acted as ground. Signal deviations in the EOG channel of more than 50μV within an interval of 100ms were identified as eye blink and movement artifacts. These were removed by rejecting data in the window of 200ms before and after an eye artifact. After artifact rejection, there were a total of 1517 trials where the target was seen in the RSVP condition (with an average of 89 trials per subject, and the smallest trial count being 52), and 560 trials where the target was seen in the Onset condition (with an average of 33 trials per subject, and the smallest trial count being 19). We verified that this large difference, due effectively to the experimental design, did not influence the statistical results. For each statistical comparison, this was done by redoing the statistical tests after randomly sampling trials from the RSVP condition for each subject, equal in number to Onset condition, and ensuring that the results did not change qualitatively.

ERPs were time locked to the onset of the target and extracted from -200ms to 1200ms with respect to target onset. The average activity at the P7 and P8 electrodes was used for analysis, as it contained both distinctive early ERP components and the P3 ERP. After segmentation, direct current drift artifacts were removed using a DC detrend procedure employing the average activity of the first and last 100ms of a segment as starting and end point, respectively. Following this, the baseline was corrected to the prestimulus interval (-200ms to time point 0) and segments were averaged to create ERPs. ERP component latencies were calculated using 50% area latency analysis (Luck & Hillyard, 1990). Statistical analysis was performed in MATLAB, and a 25Hz low pass filter was applied to enhance visualisation of ERP components.

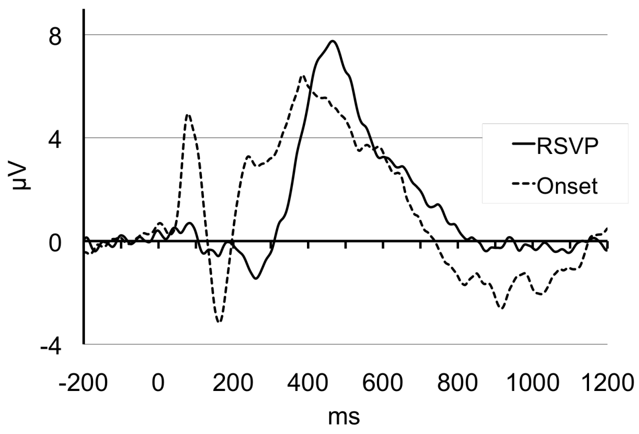

Figure 1: Human ERP for targets in RSVP and Onset presentation averaged across P7 and P8 electrode locations. ERPs are time-locked to target presentation time 'T'.

Computational modelling In order to simulate single target RSVP streams with 50ms presentation rate, the input patterns presented to the ST^2 model contained 40 items with the target appearing at position 14 of the stream. Each item was presented for 10 timesteps, which is equivalent to 50ms. Each item presented to the ST^2 model has a certain strength value. Distractors have a constant value of 0.526. To simulate the single target paradigm for Experiment 1, the target strength values iterate from 0.442 to 0.61 in steps of 0.014. This results in the ST^2 model simulating 13 trials for the single target paradigm, one simulated trial per target strength.

Results

Behaviour Overall, when compared to RSVP, Onset presentation makes targets easier to detect. Participants report 76% (SEM 0.03) of targets correctly if they are embedded in a regular RSVP stream, whereas in the Onset condition target accuracy is 86% (SEM 0.03). This difference is statistically significant: $F(1,16) = 7.87$, $MSE < 0.01$, $p = 0.01$, and corroborates a similar finding by Visser et al. (2004).

ERP early components Whether a target is presented in Onset presentation or RSVP has a strong effect on early processing. Figure 1 illustrates a highly significant difference

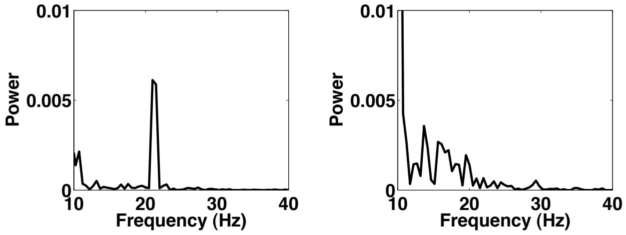

Figure 2: Fast fourier transform (FFT) of the ERP from the P7 and P8 electrode locations for the RSVP (left) and Onset (right) condition. The RSVP condition shows a peak in the FFT plot at the frequency of target presentation (approx. 21Hz), which is not present for Onset presentation.

in the P1 and N1 ERP early components between targets in RSVP and Onset presentation. The mean absolute value in the area from 0-200ms after target presentation is 3.3μV (SEM 0.27) for targets in Onset streams and 1.02μV (SEM 0.09) for targets in RSVP ($F(1,16) = 91.93$, $MSE = 0.479$, $p < 0.001$).

Instead of evoking P1/N1 early components, RSVP targets produce an ssVEP (steady state Visual Evoked Potential) wave (Di Russo, Teder-Sälejärvi, & Hillyard, 2003) oscillating at the same frequency as the presentation rate of items in the RSVP stream. As seen in Figure 2, each item is presented for 47.1ms (corresponding to the RSVP rate of roughly 20 items per second), resulting in a peak at approx. 21Hz in the FFT plot for the RSVP condition.

ERP P3 component The P3 component, which is depicted in Figure 1, temporally overlaps with the ssVEP evoked by the sequence of distractors preceding and following the target, and shows a different profile for Onset compared to RSVP targets. The 50% area latency of the P3 in the 200-600ms window is shorter for Onset (mean 422.24ms, SEM 21.49) than RSVP targets (mean 484.76ms, SEM 9.91). This difference is significant; $F(1,16) = 6.45$, $MSE = 5155.26$, $p = 0.02$. However, the difference in the mean amplitude of the P3 in the 200-800ms window is not significant (F ¡ 1).

The ST^2 model

The ST^2 model, as published in Bowman and Wyble (2007), can simulate the RSVP, but not the Onset condition. We briefly summarise its architecture. Refer to Bowman and Wyble (2007) for a full description of the model and the mathematical details of its neural network implementation, Neural-ST^2.

Stage 1 - Input & extraction of types The extraction of *types* (Chun, 1997), which represent featural and semantic properties of a stimulus, occurs in stage one. Input values, which simulate target letters and digit distractors, are fed into the input layer. Subsequent layers reflect forward and backward masking in early visual processing and the extraction of semantic representations. Both target and distractors generate activation at the task filtered layer (TFL), but a task demand mechanism operating at this layer ensures that only targets are selected for working memory encoding. Despite the fact that stimuli are presented serially during the AB task, processing within stage one may exceed the presentation time of sequentially presented items. Hence, these layers are parallel or simultaneous in nature, in that more than one node can be active at a time.

Stage 2 - working memory encoding An item is encoded into working memory by connecting its *type* in stage one to a working memory *token* in stage two, thereby representing episodic information and encoding serial order. This process is referred to as 'tokenisation'. If at the end of a trial, any type node of a target has a valid connection to a token, that target is considered to have a reportable representation in working memory. Winner-take-all inhibition between working memory tokens ensures that only one tokenisation process can be active at a time, thus serialising working memory encoding.

Temporal attention from the blaster Temporal attention is implemented by a mechanism termed the blaster, which is triggered by task-relevant items, as specified by an filter that is selective for targets. When active, the blaster provides a powerful enhancement to the later layers of stage one. This allows targets to become sufficiently active to initiate the tokenisation of recently presented targets. During tokenisation, the blaster is suppressed until encoding of the target has completed. The suppression prevents a second target from refiring the blaster while the first target is being tokenised.

Generating virtual ERP components

Different layers of the ST^2 model correspond to distinct stages of cognitive processing. By summing over simulated neural activation in specific layers of the model, we extract 'virtual ERP' (*vERP*) activity (Craston, Wyble, Chennu, & Bowman, 2009) reflecting particular stages of cognitive processing. In analogy with human ERP (*hERP*) components, we can compare how the resulting vERP components are modulated by the various experimental conditions.

In the model, the input and masking layers most closely resemble processes occurring in early visual cortex. We term the average activity at these layers the virtual SSVEP (*vSSVEP*), analogous to the human SSVEP wave. Similarly, the virtual P3 component (*vP3*) contains activation from later parts of Stage 1 (item layer and TFL), the nodes in stage two (tokens) and the binding link connecting the two stages.

Modelling the Onset condition

By making a number of theoretically justified changes to the architecture of the model, we now replicate our behavioural and EEG data for Onset presentation.

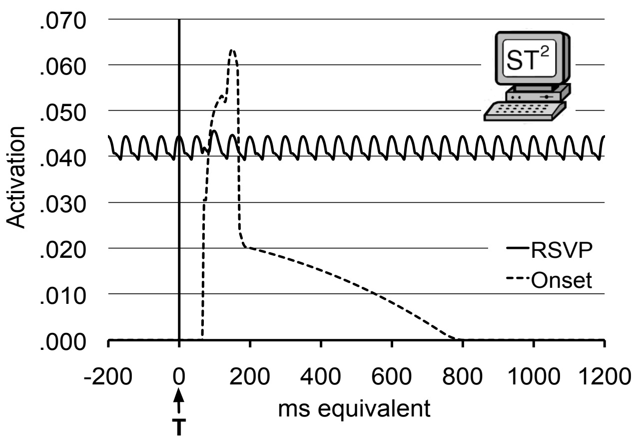

Figure 3: Virtual EEG activity from input and masking layers of the ST^2 model simulate the ssVEP for the RSVP condition and early components for the Onset condition. ERPs are time-locked to target presentation time 'T'.

Step 1: Simulating early visual processing

Manipulation In Onset presentation, the stream contains just the target and the distractor following the target. All other distractors are replaced by blank intervals. In order to simulate such a stream in the ST^2 model, we modify the array of values that serve as input to the model. All distractors - except the one following the target - are set to a value of zero, equivalent to no activation.

Results The modification of the input array has a strong effect on virtual ERP traces resembling early visual processing. For targets in RSVP, the model shows a continuous *virtual ssVEP* wave oscillating at the frequency of target presentation (Figure 3), replicating the pattern of human data observed in Figure 2. The first item of the RSVP stream causes an increase of activation in early layers of the model, and subsequent stimuli excite early layers and suppress previous stimuli due to masking, producing a sustained oscillation that lasts until the end of the RSVP stream. In effect, the cumulative effect of early visual processing in the model manifests as the virtual ssVEP, instead of as distinctive early virtual ERP components.

In contrast, in Onset presentation, there are no distractors and hence there is no activation preceding the target. Presentation of the target creates a strong burst of activation at early layers of the ST^2 model. As there is no forward masking, the activation evoked by the Onset target at early layers is higher than in regular RSVP. The distractor following the target in Onset presentation then produces a second large burst of activation, as it is not constrained by backward masking. All of this activation at early layers occurs between the model equivalent of 100 and 200ms following target presentation. There is a qualitative match between the virtual ERP from the ST^2 model (Figure 3) and the human early ERP components for

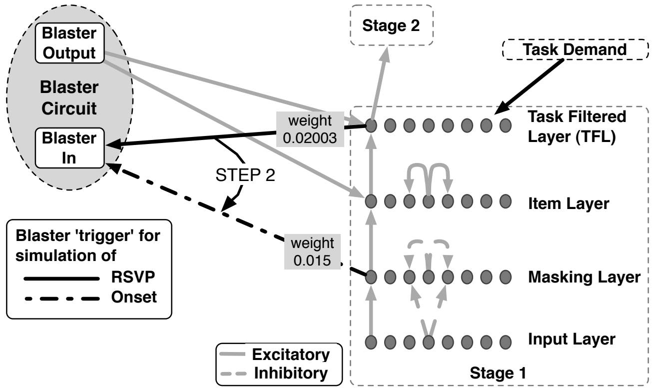

Figure 4: Step 2 of simulating Onset presentation: The connection that triggers the blaster is moved from the TFL to the masking layer.

Onset presentation from Figure 1.

In summary, virtual ERP activation associated with early visual processing shows a distinct activation for Onset targets and an oscillatory pattern for RSVP targets, thus qualitatively replicating the human ERP. Furthermore, the timing of the Onset vERP activation occurs within a similar time window as the P1/N1 wave observed for Onset targets in the human ERP.

Step 2: Simulating the P3

Manipulation Replication of behavioural accuracy and the virtual P3 component requires theoretically justified changes to the architecture of the ST^2 model. Onset targets appear on a previously blank screen, whereas in RSVP, the target has to be selected from a continuous stream of distractors. In terms of the ST^2 model, we hypothesise that the difference between target detection in these conditions influences the way in which the blaster is triggered:

- In RSVP, the system cannot distinguish targets from distractors until they have reached the TFL. There, the task demand mechanism acts as a filter, selectively enhancing targets and inhibiting distractors.
- In Onset presentation, there are no distractors preceding the target, hence, the system can assume that the first item that is 'presented' to the input layer is the target. Accordingly and as seen in Figure 4, we propose that in Onset presentation, the blaster is triggered as soon as activation reaches the masking layer. Moving this connection from the TFL to the masking layer also requires a modification of the weight value of that connection (see Figure 4), because activation levels in the TFL and masking layers differ[1].

[1]Compared to the TFL, activation values at the masking layer are higher in absolute terms. Hence, we reduce the weight values between masking layer and blaster, to prevent the blaster circuit from being overcharged by the input from the masking layer.

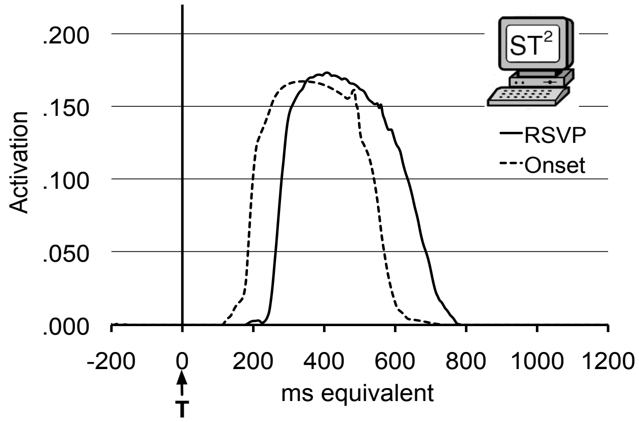

Figure 5: After Step 2: Virtual P3 for the RSVP and Onset condition. The RSVP vERP is baseline corrected to -200 to 0ms with respect to target onset to account for distractor related activity, which is absent in the Onset condition. ERPs are time-locked to target presentation time 'T'.

Results Activation propagates through the ST^2 model with a temporal lag from one layer to the next. Hence, if the blaster is triggered from the masking layer, the blaster fires at an earlier time point relative to target onset than if activation has to propagate to the TFL before the blaster can be triggered. Consequently, the blaster's output is also shifted earlier in time. The first consequence of this change is a shift in latency of the virtual P3 for Onset compared to RSVP targets, as seen in Figure 5. With the change in model architecture to reflect processing of Onset targets, the blaster is triggered earlier, and thus initiates the target's tokenisation and virtual P3 earlier than in the RSVP condition.

The change in model architecture means that the blaster now fires for all Onset targets. This correctly increases the accuracy of the ST^2 model at encoding Onset targets relative to RSVP targets (100% vs 77%). Although the simulated accuracies are not the same as that observed in human behaviour, the changed model replicates the qualitative difference between the two experimental conditions. Furthermore, the same change in the model that simulated the behavioural effect also produces a latency difference in the virtual P3: The 50% area latency of the vP3 in the 200-600ms window is shorter for Onset (365ms) than for RSVP targets (430ms). This pattern replicates the significant latency difference observed in human P3 data.

In summary, after making the described changes to the ST^2 model, we have enabled it to simulate the Onset condition in terms of its qualitative relationships to the RSVP condition, with respect to both behavioural and EEG data. It should be noted that we have investigated a further change to the model architecture, described in Craston (2009), which involves a slight reduction in the task demand at the end of Stage 1, in order to produce a better fit to the behavioural accuracies and ERP patterns observed in the human data. Though we have omitted it here for the sake of parsimony, this additional step would be of interest if it could be demonstrated that the P3 had a statistically lower mean amplitude and/or longer duration in the Onset condition compared to the RSVP condition.

Discussion and Conclusions

Our experimental results inform behavioural research into the interaction between targets and distractors in RSVP paradigms. Visser et al. (2004), whose work this paper builds upon, find that target identification accuracy deteriorates as distractors become more similar to targets. They explain their findings using a variant of the two-stage theory of temporal visual processing (Chun & Potter, 1995), and surmise that a broadly tuned 'input filter' at the end of the parallel first stage allows target-like distractors to *contingently capture* attention and processing resources in the serial second stage.

The pair of experimental conditions we have described in this paper lie at opposite ends of the range of target discriminability manipulations employed by Visser et al. (2004), thereby emphasising differences in the ERPs between them. In the Onset condition, targets are detectable simply by their visual onset. In contrast, in the RSVP condition, letter targets are visually very similar to digit distractors, and must be processed categorically before they can be discriminated. We were interested in characterising the differences in the time course of target processing in this pair of conditions, and have done so by comparing the corresponding ERPs. It should be noted that our findings do not conflict with those reported by Vogel, Luck, and Shapiro (1998), who observed early components in response to the visual onset of a probe flash (which is similar to our Onset condition) within an RSVP stream.

Further, we have grounded our findings within the well-established ST^2 framework that implements the two-stage theory. By extending the framework to simulate the Onset condition, we propose a mechanistically explicit explanation of how the visual system, and especially the triggering of transient attentional enhancement, might be differentially configured in response to the demands of target discrimination. In particular, the extension of the model instantiates our hypothesis that temporal selection happens earlier in the Onset condition, and that the task demand at the end of Stage 1 does not need to perform any discrimination to detect targets. Finally, as discussed next, this investigation informs the choice of experimental paradigm for studying the attentional blink phenomenon, and the interpretation of EEG data collected therefrom.

Is Onset presentation an equal substitute for RSVP?

Despite its common application in experiments designed to study temporal visual processing, the RSVP paradigm has a number of practical disadvantages. Due to the fast presentation rate, RSVP streams contain a large number of distractors, and have a typical duration of 2-3 seconds. Furthermore, the rapid presentation of items is often taxing for participants, especially in long experiments. This situation arises when conducting EEG or Magnetoencephalography (MEG) experiments, where, in order to increase the signal-to-noise ratio by averaging, each condition is presented several times. Hence, as experimental time in an EEG/MEG laboratory is costly, there is a major incentive to minimise the duration of the experiment.

In comparison, the Onset task 'minimises demands both on selective attentional processing and on location switching mechanisms' (Ward et al., 1997), while nevertheless seeming to reveal the attentional limitations underlying the AB. Thus, due to simpler and shorter experiments, the Onset paradigm seems ideal for studies employing MEG or EEG to study the AB. Indeed, as a previous study investigating the AB by means of MEG and the Onset paradigm states: 'an AB effect is observed whether targets are embedded in a 20-item RSVP stream or just presented on their own followed by masks (Duncan, Ward, & Shapiro, 1994; Ward et al., 1997). In order to save measurement time, we decided to employ this abbreviated version for our study' (Kessler et al., 2005). However, from the results presented in this paper, we argue that there are considerable differences in target processing between Onset presentation and RSVP. Though our experiment employed only a single target, we believe that these results inform and are directly relevant to dual target RSVP studies. Consequently, direct comparisons between EEG/MEG data collected using these two paradigms should be interpreted with caution.

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