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The effect of load on spatial attention depends on preview: Evidence from a reading study

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ABSTRACT

The spatio-temporal distribution of covert attention has usually been studied under unfamiliar tasks with static viewing. It is important to extend this work to familiar tasks such as reading where sequential eye movements are made. Our previous work with reading showed that covert spatial attention around the gaze location is affected by the fixated word frequency, or the processing load exerted by the word, as early as 40 ms into the fixation. Here, we hypothesised that this early effect of frequency is only possible when the word is previewed and thus pre-processed before being fixated. We tested this hypothesis by preventing preview. We investigated the dynamics of spatial attention around the gaze location while the observer read strings of random words. The words were either always exposed (normal preview) or only exposed while being fixated (masked preview). We probed spatial attention when a target word with either high or low printed frequency – or low or high load, respectively – was fixated. The results confirmed that, early in a fixation, allocation of spatial attention 6 characters from the gaze was affected by the word's frequency but only when the word was exposed before being fixated, so that processing of the word could start before it was fixated. Our results indicate that the ongoing processing load of a word is modulated by its pre-processing and affects the dynamics of covert spatial attention around the word once it is fixated.

1. Introduction

Reading involves sequential eye movements, saccades, to bring words into the fovea one-by-one. In addition to, and to some extent independent of, these sequential shifts of overt attention, covert spatial attention is allocated to the line of text. As a result, the processing of a word's letters can occur before it is fixated, or the word can be fully processed even without it being fixated. Spatial attention is necessary for word recognition (Waechter, Besner, & Stolz, 2011) and it leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch, Kowler, & Dosher, 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995; Kowler, Anderson, Dosher, & Blaser, 1995); this makes reading a real-world framework within which to investigate the spatio-temporal distribution of spatial attention within a dynamic processing scenario (Fischer, 1999). Furthermore, manipulating the processing demand of a word in reading (e.g., by manipulating its printed frequency) enables the investigator to influence the processing load on the reader.

The effect of load on spatial attention has been investigated mainly in static viewing conditions where it has been shown that attention is more focussed when perceptual processing load is higher (e.g., Caparos & Linnell, 2009, 2010; Lavie, 1995; Linnell & Caparos, 2011; Madrid, Lavie, & Lavidora, 2011). Whether and how the focus of attention is affected by processing load over time is important for models of eye movement control in reading, as well as models of word processing, because the visibility of a given letter embedded in a line of text is suggested to be affected by (i) its distance from the gaze (which affects acuity), (ii) the number of letters or blank spaces that it is surrounded by (which affects crowding), and (iii) its proximity to the focus of attention (Grainger, Dufau, & Ziegler, 2016).

In our previous work (Ghahghaei, Linnell, Fischer, Dubey, & Davis, 2013), we directly investigated load effects in a more realistic task that required sequential eye movements and probed spatial attention during the course of a fixation in reading. We showed that word processing load affects the dynamics of spatial attention as early as 40 ms into a fixation when preview of the upcoming word was always available (i.e., words were not masked; Ghahghaei, Linnell, Fischer, Dubey, & Davis, 2013). Specifically, we examined spatial attention by measuring sensitivity around the gaze. Participants read sentences for comprehension as a primary task. In addition, they performed a secondary task which

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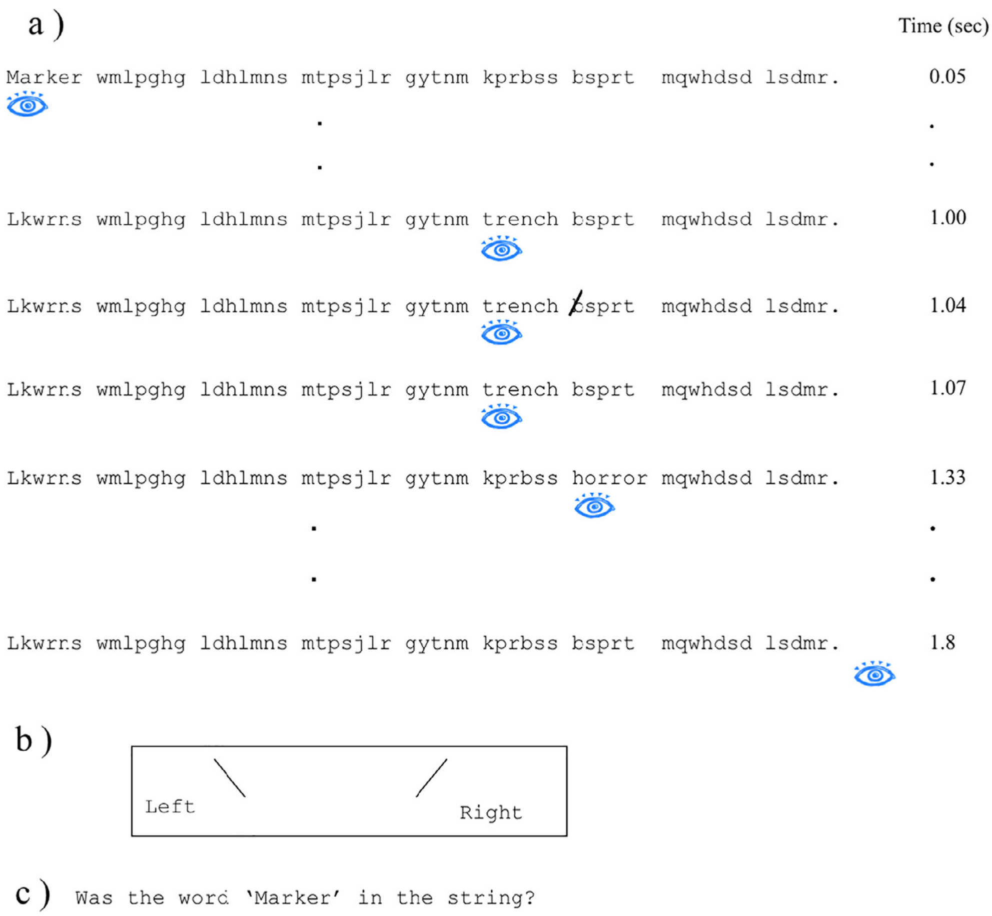

Fig. 1. A schematic representation of one trial in the masked-preview condition. a) Here the target word (trench) was low in frequency. Words were masked when not fixated. The probe occurred 6 characters from the gaze (here, on the right side) location, 40 ms after the beginning of the first fixation on the target word. The top end of the probe pointed either to the left or right (here, right). The probe disappeared after 30 ms. The string disappeared when the gaze passed an invisible boundary to the right of the last letter in the string or when the eye fixated the last word for 600 ms. In the normal-preview condition, the words were always exposed. b) The participant performed an unspeeded 2-AFC discrimination task (using a manual response) for the orientation of the probe.(c) Finally, the participant answered (with an oral response) an identification (Yes/No) question about the string he/she had just read.

consisted of *unspeeded* discrimination of the orientation of an attentional probe – a line tilted 22.5° to the right or left of the vertical meridian. The proportion correct on probe discrimination was the measure of spatial attention. (Note that unspeeded discrimination of the orientation of a probe has previously been shown to be sensitive to the profile of attention in a task requiring sequential eye movements; Gersch, Kowler, Schnitzer, & Dosher, 2008). The probe had higher contrast than the text and occurred on the line of text, 6 characters (2 visual degrees) to the left or right of the gaze location. It occurred with different temporal onsets from the start of the first fixation on the fixated word. The printed frequency of target words was modulated to be either high or low, resulting in low or high processing load for the fixated target, respectively. Our results showed that 40 ms into a fixation, there was an effect of the frequency of the fixated word on attention which disappeared by 110 ms into a fixation. This effect was significant 6 characters to the left (but not right) of the gaze location. This effect of frequency was only observed on the left side of the gaze presumably because of the asymmetry in the extent of the perceptual span; the perceptual span is a span within which useful information can be extracted and it extends roughly 5 characters to the left and 14 characters to the right of the gaze location in reading English texts for comprehension (McConkie & Rayner, 1975). This span is attentional rather than visual given that its direction depends on the direction of reading (e.g., Pollatsek, Bolozky, Well, & Rayner, 1981) and it cannot be explained by visual span (e.g., Legge et al., 2007) or crowding (e.g., Ghahghaei & Walker, 2016). In this situation, where less spatial attention is allocated to the left of the gaze than to the right of it, probes occurring on the left should be more sensitive to any effects of word frequency.

Ghahghaei et al. (2013) showed that the processing of the fixated word exerts a load on spatial attention mechanisms such that spatial attention was more focused around the gaze when the fixated word was low rather than high in frequency. There could be two different ways that the load exerted by the fixated word is related to its processing. On the one hand, it could be that the word's load is constant over the course of the fixation and depends on the word's overall processing demand. On the other hand, it is possible that the word's load varies over time and depends on the moment-to-moment processing demand that it exerts. If the former is the case then, throughout a fixation, spatial attention should be focussed more on a low- rather than a high-frequency word, regardless of how advanced the pre-processing of the word is before it is fixated. If the latter is the case then, early in a fixation, attention should be focussed more on a low-rather than a high-frequency word only if the word is sufficiently pre-processed before being fixated. An effect of pre-processing is in theory possible because information that is obtained during word preview has been shown to be integrated across the saccade to the word (e.g., Inhoff, Starr, & Shindler, 2000; Rayner & Clifton, 2009).

In addition to models of eye movement control in reading, other models of eye movement control in tasks like scene processing or visual search can benefit from including effects of load on the focus of attention. To build their visibility map, these models normally use a visual field that is constrained by visual acuity but not the availability of spatial attention during the course of the fixation (e.g., Ghahghaei & Verghese, 2015; Itti, Rees, & Tsotsos, 2005; Najemnik & Geisler, 2005; Renninger, Verghese, & Coughlan, 2007). These models will benefit from considering the availability of spatial attention – as it depends on the time elapsed since the last saccade in addition to when the upcoming saccade is made- and the ongoing processing load.

In the work reported here, we asked if an effect of frequency on spatial attention depends on whether the word has been pre-processed before being fixated. We did so by manipulating the validity of preview