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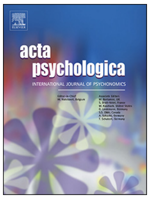

# Attentional competition across saccadic eye movements[☆]

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## ABSTRACT

Human behavior is guided by visual object recognition. For being recognized, objects compete for limited attentional processing resources. The more objects compete, the lower is performance in recognizing each individual object. Here, we ask whether this competition is confined to eye fixations, periods of relatively stable gaze, or whether it extends from one fixation to the next, across saccadic eye movements. Participants made saccades to a peripheral saccade target. After the saccade, a letter was briefly presented within the saccade target and terminated by a mask. Object recognition of the letter was assessed as participants' report. Critically, either no, two, or four additional non-target objects appeared before the saccade. In Experiment 1, presaccadic non-targets were task-irrelevant and had no effects on postsaccadic object recognition. In Experiment 2, presaccadic non-targets were task-relevant and, here, postsaccadic object recognition deteriorated with increasing number of presaccadic non-targets. As suggested by Experiment 3 and a mathematical model, this effect was due to a slowing down but also a delayed start of visual processing after the saccade. Together, our findings show that objects compete for recognition across saccades, but only if they are task-relevant. This reveals an attentional mechanism of task-driven object recognition that is interlaced with active saccade-mediated vision.

## 1. Introduction

Human goal-directed behavior heavily relies on the ability to recognize objects in the environment using vision. The capacity for visual object recognition, however, is severely limited (for reviews, see Bundesen, 1990; Desimone & Duncan, 1995; Schneider, 1995). Objects in the visual field must compete for limited attentional processing resources (e.g., neurons, Bundesen, Habekost, & Kyllingsbaek, 2005). Therefore, as more and more objects are present in the visual field, each object receives a smaller share of the processing resources, and object recognition suffers. To deal with this problem, visual attention biases the allocation of processing resources in favor of the current task, so that currently important objects receive more resources and better processing than unimportant ones (Bundesen, 1990; Desimone & Duncan, 1995).

There is extensive evidence that objects compete for object recognition within eye fixations (e.g., Duncan, 2006; Poth, Petersen, Bundesen, & Schneider, 2014; Shibuya & Bundesen, 1988; Vangkilde, Bundesen, & Coull, 2011), the periods in which the eyes remain relatively stable (Findlay & Gilchrist, 2003; Land & Tatler, 2009). However, a fundamental hallmark of human vision is thereby neglected: the active sampling of the visual environment using rapid saccadic eye movements (for recent reviews, see Gegenfurtner, 2016; Rolfs, 2015; Schütz, Braun, & Gegenfurtner, 2011). Visual acuity is highest only at the center of gaze, which falls on the central fovea of the eye's retina (e.g., Cowey & Rolls, 1974; Curcio & Allen, 1990). Therefore, humans make saccadic eye movements that move the fovea from one object to the next, so that the object is sampled in detail in the next fixation (e.g., Findlay & Gilchrist, 2003; Land & Tatler, 2009). It is unclear whether attentional competition between objects is constrained to a given eye fixation, or whether objects from one fixation can compete with and thus impair the processing of objects in the next fixation (Schneider, 2013).

One may hypothesize that there is no such transsaccadic attentional competition and assume that successive eye fixations are entirely distinct visual processing episodes. This *visual separation hypothesis* has intuitive appeal, because the retinal image is blurred and visual information uptake is suppressed during saccades, which indeed separates one fixation from the next (Krock & Moore, 2014; Wurtz, 2008). Moreover, only a limited number of objects shown before a saccade can

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be reported after the saccade in accordance with a spatial cue (Irwin, 1992; Irwin & Gordon, 1998). This has led to the proposal that only those objects survive the saccade that are represented in limited-capacity visual working memory (VWM; or a similar transsaccadic memory, respectively, for reviews, see Irwin, 1996; Mathôt & Theeuwes, 2011). The competition between objects takes place before their encoding into VWM, and must hence rely on object representations created prior to VWM encoding (Bundesen, 1990; Bundesen et al., 2005). Therefore, if only representations in VWM survive the saccade, the competing representations outside VWM should be lost across the saccade, so that there is no transsaccadic competition.

What argues against the visual separation hypothesis is evidence that visual object information outside VWM partially persists across the saccade (Irwin, 1992; Irwin, Brown, & Sun, 1988). This persistence may be largely bound to the retinal locations of objects (Irwin et al., 1988) which are moved by the saccade. However, because the competition for object recognition concerns all visually available objects in the visual field (Bundesen, 1990; or at least great parts thereof, Bundesen et al., 2005; Desimone & Duncan, 1995), this persisting object information may compete with the actual objects in the next fixation. As a result, object recognition in the next fixation should suffer per se from the object available in the previous fixation.

Furthermore, it has been suggested that the competition for object recognition can extend across changes and interruptions of visual input, such as those imposed by saccades, but only if the objects are relevant to the task at hand (Schneider, 2013). This *task-driven competition hypothesis* is directly based on Schneider's (2013) theory of “Task-dRiven visual Attention and working Memory (TRAM)”. According to TRAM, objects from the previous fixation that are task-relevant but have not been fully processed will be protectively maintained and shielded against being wiped-out by the saccade, and enter the competition for object recognition in the next fixation. As a result, object recognition in this fixation should suffer from all task-relevant objects of the previous fixation (except for those for which correspondence between the fixations can be established, see also Poth, Herwig, & Schneider, 2015; Poth & Schneider, 2016b).

Here, we investigated the question of whether objects compete for object recognition across saccadic eye movements. In three experiments, participants made saccades to peripheral saccade target objects and then reported a letter that became visible within these objects after the saccade. The letter was presented for a number of different durations and terminated by a mask (see also Poth et al., 2015, Poth and Schneider, 2016a, b). This procedure of limiting presentation durations allowed us to investigate object recognition performance in purely visual terms, without imposing requirements on reaction times (including saccadic reaction times) that might engage additional motor processes (e.g., Finke et al., 2005). Different durations were used because attentional competition between objects should be visible most strongly at intermediate presentation durations, while there might be floor and ceiling effects for very short and long presentation durations, which depend on the individual (e.g., Shibuya & Bundesen, 1988).

Experiment 1 investigated whether recognition of a postsaccadic object suffers from attentional competition with presaccadic objects per se. To this end, the peripheral saccade target appeared either alone, or was flanked by two, or four irrelevant non-target objects (digits). The non-targets were extinguished as soon as participants made the saccade. Now, if there was no attentional competition across the saccade, as proposed by the visual separation hypothesis, then the number of presaccadic non-targets should have no effect on performance in recognizing the postsaccadic letter. In contrast, if there was attentional competition, for instance, due to lingering presaccadic representations (Irwin, 1992; Irwin et al., 1988), then postsaccadic object recognition should deteriorate as more presaccadic non-targets are presented. To preview the results of Experiment 1, the number of presaccadic non-targets had no effect on the postsaccadic object recognition, compatible with the visual separation hypothesis.

In Experiment 2, we then went on to test the task-driven competition hypothesis. Here, we investigated whether processing of a postsaccadic object suffers from attentional competition with presaccadic objects in a dual-task, where presaccadic objects were task-relevant for a second short-term memory task. The paradigm was identical to the one of Experiment 1, except that the non-targets were now task-relevant because they had to be matched against a probe at trial end in the second task. The results of Experiment 2 support the task-driven competition hypothesis: the more presaccadic non-targets had been shown, the lower was performance in recognizing the postsaccadic letter. Cross-experiment analyses corroborated that this effect was indeed larger than the null effect of Experiment 1.

Experiment 3 investigated characteristics of the mechanisms underlying the task-driven attentional competition across the saccade more closely. By cutting the resources used to process an object, attentional competition is assumed to reduce the speed with which the object is processed (Bundesen, 1990). Object recognition suffers because processing of the object is not finished on time, before it is masked by another object or before the required capacity in VWM is filled-up (Bundesen, 1990). The attentional competition effect observed in Experiment 2 may thus be due to a slowing down of visual processing after the saccade. In contrast, however, the effect may also be due to a delayed onset of visual processing after the saccade, or a combination of both. To decide between these hypotheses, Experiment 3 comprised more presentation durations than Experiment 2. This allowed us to assess object recognition performance as a function of presentation duration and fit it with a mathematical model based on Bundesen's (1990) Theory of Visual Attention (TVA). This offered a critical advantage over experiments using only a single presentation duration or using reaction time as a measure of object recognition performance. Specifically, by applying this methodology, we could disentangle the visual processing speed after the saccade and a temporal threshold of perception, which marks the time necessary to start visual processing (Bundesen, 1990).

## 2. Method

### 2.1. Participants

Nine participants performed Experiment 1. An additional participant was excluded from analysis due to letter reports at chance level. Participants were between 22 and 30 years old (*MD* = 25 years), three were male, six were female, eight were right-, one was left-handed.

Eight different participants performed Experiment 2. An additional participant aborted the experiment. Participants were between 20 and 31 years old (*MD* = 23.5 years), three were male, five were female, seven were right-, one was left-handed.

Again, fifteen different participants performed Experiment 3. They were between 21 and 34 years old (*MD* = 25 years), three were male, twelve were female, and all were right-handed.

Participants of all experiments reported normal or corrected-to-normal visual acuity and normal color vision. They gave written informed consent before participation. The experiments followed the ethical guidelines of the German Psychological Association (DGPs) and were approved by Bielefeld University's ethics committee.

### 2.2. Apparatus and stimuli

Participants performed the experiments in a semi-lit room. A head- and a chin-rest ensured that they viewed the computer screen (G90fB, ViewSonic, Brea, CA, USA) from a distance of 71 cm. The screen had a resolution of 1024 × 768 pixels at physical dimensions of 36 × 27 cm, a refresh rate of 100 Hz, and was controlled by a GeForce GTX 970 graphics card (driver version 344.48, NVIDIA, Santa Clara, CA, USA). The screen was warmed up for at least 20 min before the experiment, which was the warm-up time required for stable luminance (following

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