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Category-based attentional guidance can operate in parallel for multiple target objects

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ABSTRACT

The question whether the control of attention during visual search is always feature-based or can also be based on the category of objects remains unresolved. Here, we employed the N2pc component as an on-line marker for target selection processes to compare the efficiency of feature-based and category-based attentional guidance. Two successive displays containing pairs of real-world objects (line drawings of kitchen or clothing items) were separated by a 10 ms SOA. In Experiment 1, target objects were defined by their category. In Experiment 2, one specific visual object served as target (exemplar-based search). On different trials, targets appeared either in one or in both displays, and participants had to report the number of targets (one or two). Target N2pc components were larger and emerged earlier during exemplar-based search than during category-based search, demonstrating the superior efficiency of feature-based attentional guidance. On trials where target objects appeared in both displays, both targets elicited N2pc components that overlapped in time, suggesting that attention was allocated in parallel to these target objects. Critically, this was the case not only in the exemplar-based task, but also when targets were defined by their category. These results demonstrate that attention can be guided by object categories, and that this type of category-based attentional control can operate concurrently for multiple target objects.

1. Introduction

In visual search, observers have to find target objects that are defined by particular features and appear among other task-irrelevant distractor objects. The allocation of attention to candidate target objects during the search process is guided by mental representations of known target-defining features (attentional templates; e.g., Duncan & Humphreys, 1992; Olivers, Peters, Houtkamp, & Roelfsema, 2011). These target templates can be activated during the preparation for a particular search episode, and are assumed to bias attentional selection processes towards objects with template-matching features (Wolfe, 1994, 2007; Desimone & Duncan, 1995). There are many different types of search tasks where targets are defined by different sets of features. It is obvious that not all target attributes are equally capable in guiding attention (e.g., Wolfe & Horowitz, 2004). Simple visual features such as stimulus colour, shape, or orientation are effective guiding attributes. In contrast, it is often assumed that higher-level attributes such as an object's category are unable to contribute to the guidance of attention during visual search. In line with this hypothesis, several studies have demonstrated that search for category-defined targets is much less efficient than search for targets that are defined by specific visual features (e.g., Malcolm & Henderson, 2009; Yang & Zelinsky, 2009). However, there is also behavioural evidence that object categories can affect the allocation of attention during search. For example, nontarget objects that are semantically related to a current target attract attention during visual search even when these objects share no visual features with the target (e.g., Belke, Humphreys, Watson, Meyer, & Telling, 2008; Moores, Laiti, & Chelazzi, 2003; Telling, Kumar, Meyer, & Humphreys, 2010).

The question whether and to what degree object categories are involved in the guidance of attention during visual search is unlikely to be resolved on the basis of behavioural measures alone. Template-based control processes result in attentional biases of visual processing in favour of objects with template-matching features. Because such attentional biases can emerge early and develop gradually over time (see Eimer, 2014, 2015, for reviews), their presence may be revealed by event-related brain potential (ERP) markers of attentional selectivity, which can track these biases on a millisecond-by-millisecond basis. The N2pc component has been employed in many studies of visual attention and visual search as an electrophysiological marker for attentional

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object selection. The N2pc is an enhanced negativity elicited at posterior electrodes contralateral to the visual hemifield of a candidate target object that is presented among other nontarget objects in visual search displays. It is generated in extrastriate areas of the ventral visual processing stream (Hopf et al., 2000), and is assumed to reflect the allocation of spatial attention to objects with target-matching properties (e.g., Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999, 2003). Although the N2pc often emerges at about 200 ms after search display onset, its onset latency is variable and is determined by how effectively a target object can be discriminated from distractors in the same display. In visual search tasks where target objects are defined by simple visual features such as a particular colour or shape, these targets trigger N2pc components (e.g., Eimer, Kiss, & Nicholas, 2011; Luck & Hillyard, 1994) that are reliably present from about 180 ms post-stimulus. Such results demonstrate that when feature-specific attentional templates for target colours or shapes are activated, template-matching objects trigger rapid spatially selective biases of visual processing. To determine whether object categories play a role in the control of attention, it is important to investigate whether similar N2pc components will also be elicited in response to target objects in search tasks where these targets are defined not by basic visual features, but by the object category to which they belong. If categories cannot guide attention, no N2pc should be found for category-defined targets.

This question was addressed in a recent study from our lab (Nako, Wu, Smith, & Eimer, 2014) where search displays contained line drawings of kitchen and clothing objects. In different blocks, participants either searched for a particular target object (e.g., frying pan; exemplar-based search) or for any of 11 possible objects from the same category (kitchen objects or items of clothing; category-based search). In the exemplar-based search task, target objects triggered large N2pc components that emerged early (at 190 ms post-stimulus), confirming that attention was allocated effectively to target objects when this process was guided by a search template for specific visual target features. Critically, reliable target N2pc components were also found in the category-based search task. However, these N2pcs were smaller in amplitude than those found during exemplar-based search, and were delayed by about 50 ms. These findings suggest that in contrast to previous claims (e.g., Wolfe & Horowitz, 2004), attentional allocation processes can be guided by object categories, and that this type of guidance can result in modulations of relatively early stages of visual processing. On the other hand, they also demonstrate that category-guided attentional selection processes are considerably slower and less efficient relative to the selection of targets that are defined by a set of known visual features.

The goal of the current study was to provide further insights into the similarities and differences of category-based versus exemplar-based attentional control processes during visual search for real-world target objects. Do these two types of attentional guidance processes differ only quantitatively (with category-based guidance operating more slowly than feature-based guidance, e.g., Nako et al., 2014), or are there more fundamental qualitative differences between them? More specifically, we investigated the ability to allocate attention rapidly and in parallel to two different target objects in exemplar-based and category-based search tasks. The distinction between parallel and serial mechanisms is central to theories of visual search, such as Feature Integration Theory (e.g., Treisman & Gelade, 1980) and Guided Search (Wolfe, 1994, 2007), and this dichotomy is usually based on behavioural measures. Serial search is inferred when reaction times (RTs) increase with the number of objects in a search display, while search is described as parallel when target RTs are not affected by display set size. However, the question whether attentional target selection processes operate in a serial or parallel fashion can also be addressed with electrophysiological markers such as the N2pc component.

Evidence for parallel attentional selection processes in tasks where target objects were defined by physical features (a specific colour or shape) comes from a series of recent studies from our lab that used a rapid sequential visual presentation procedure. Two displays that each contained a target and a nontarget object on opposite sides were presented in rapid succession, with stimulus onset asynchronies (SOAs) varied between 10 and 100 ms. To measure N2pc components separately for targets in the first and second display, one of these displays contained a stimulus pair on the horizontal midline and the other a pair on the vertical midline, with display order varied randomly across trials. Because the N2pc is a lateralised component that is only elicited by lateralised target objects but not by targets on the vertical midline, it will only reflect the attentional selection of horizontal but not of vertical targets (see Eimer et al., 2011; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, Theeuwes, 2006; Woodman & Luck, 1999, 2003, for previous N2pc studies that employed this logic). When target objects were defined by their colour (Eimer & Grubert, 2014; Grubert & Eimer, 2015), N2pc components of equivalent size were elicited by horizontal targets in the first and second display. Importantly, when the SOA between the displays was very short (10 ms), these two N2pc components overlapped in time, and their onset latency difference matched the objective onset asynchrony between the two displays. These results demonstrate that multiple colour-guided attentional target selection processes can be triggered concurrently, with each selection process following its own independent time course. Further studies obtained analogous findings when both target-colour objects appeared simultaneously in a single display (Grubert & Eimer, 2016), when targets were defined by their shape (Jenkins, Grubert, & Eimer, 2016, Exp.1), and also when they were defined by a colour/shape conjunction (Jenkins, Grubert, & Eimer, 2017).

These results demonstrate that feature-based attentional guidance can operate rapidly, flexibly, and in parallel for different feature-defined target objects at different locations in the visual field. The goal of the present study was to find out whether such parallel attentional selection processes are only triggered when targets are defined by basic visual features such as their colour or shape, or whether they are also elicited during search for category-defined targets. If category-based attentional guidance is slower and less efficient than feature-based guidance (e.g., Nako et al., 2014), it may be impossible to allocate attention simultaneously to multiple category-defined target objects that appear in rapid succession. We first tested this hypothesis in a task that employed the same rapid sequential presentation procedure as the studies reported above, except that target objects where now defined by their alphanumerical category (letters or digits; Jenkins et al., 2016, Exp.2). In this task, lateral target objects in the first and second display again triggered temporally overlapping N2pcs, with onset delays that closely matched the objective SOA between the two displays. However, the overall size of these N2pc components was smaller than the N2pcs elicited by shape-defined targets in the same study (Jenkins et al., 2016, Exp.1). Although these findings provide initial evidence for rapid parallel target selection processes with category-defined target objects, the guidance of attention by alphanumerical category might be a special case that is not representative of other types of category-based search. Classifying items as letters or digits is a well-practiced skill, and it has been suggested that alphanumerical category is already extracted during the early parallel processing of visual input (e.g., Duncan, 1980). In line with this hypothesis, numerous studies have shown that letter/digit search is very efficient (Duncan, 1980; Egeth, Jonides, & Wall, 1972), even when the physical similarity between and within these two categories is matched (Dixon & Shedden, 1987).

In the present study, we investigated the guidance of multiple-target selection by object categories in a search task where target categories were more typical of the types of categories used in everyday search tasks. Participants saw line drawings of real-world target objects from two categories (kitchen objects and items of clothing). The set of objects was identical to the set used by Nako et al., 2014, except that these images were now shown in the context of a rapid sequential presentation procedure (see Fig. 1). On each trial, two stimulus pairs (one on the horizontal and the other on the vertical midline) appeared in rapid