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Foraging through multiple target categories reveals the flexibility of visual working memory☆

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ABSTRACT

A key assumption in the literature on visual attention is that templates, actively maintained in visual working memory (VWM), guide visual attention. An important question therefore involves the nature and capacity of VWM. According to load theories, more than one search template can be active at the same time and capacity is determined by the total load rather than a precise number of templates. By an alternative account only one search template can be active within visual working memory at any given time, while other templates are in an accessory state – but do not affect visual selection. We addressed this question by varying the number of targets and distractors in a visual foraging task for 40 targets among 40 distractors in two ways: 1) *Fixed-distractor-number*, involving two distractor types while target categories varied from one to four. 2) *Fixed-color-number* (7), so that if the target types were two, distractors types were five, while if target number increased to three, distractor types were four (etc.). The two accounts make differing predictions. Under the single-template account, we should expect large switch costs as target types increase to two, but switch-costs should not increase much as target types increase beyond two. Load accounts predict an approximately linear increase in switch costs with increased target type number. The results were that switch costs increased roughly linearly in both conditions, in line with load accounts. The results are discussed in light of recent proposals that working memory reflects lingering neural activity at various sites that operate on the stimuli in each case and findings showing neurally silent working memory representations.

1. Introduction

As you search for mustard and ketchup in an unfamiliar super-market, what is the optimal strategy? You do not know which brands this super-market sells, and you cannot think of a defining feature in the shape of mustard or ketchup bottles that distinguishes them from most other condiments except that mustard tends to be yellow and ketchup red. You scan the shelves searching for red and yellow, occasionally pausing as your eyes land on a red or a yellow bottle. But what is actually happening as we search the shelves for the two colors? Do we look for both colors simultaneously, or are we possibly searching for one color at a time, rapidly switching between searching for yellow and red as our eyes scan the shelves? This question touches on many important questions within the scientific literature on vision and attention. How do we search complex scenes? What roles do working memory and attention play in the search process? Do we form search images, or templates to search effectively, and how do they guide our search? Can we maintain more than one search image (or template) at the same time? Can we, in other words, search for ketchup and mustard simultaneously?

To address such questions, several models of attention have been developed. Some of the most influential are two stage models involving a pre-attentive parallel stage followed by an active attentive stage involving serial processing such as Feature-Integration Theory (Treisman & Gelade, 1980) and the Guided Search model (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). These models are mostly based on findings from single target search tasks and do not as easily account for results from search tasks involving multiple targets, such as visual foraging tasks (Kristjánsson, Jóhannesson, & Thornton, 2014; Wolfe, 2013). Note that the latest version of the guided search model will take data and results from foraging and other multi-target search tasks into account (Wolfe, Cain, Ehinger, & Drew, 2015).

Early models of visual foraging compared human foraging with optimal foraging, that assumes that as the target yield within a particular search environment, decreases below average, foragers will switch to a new foraging patch (Charnov, 1976; Pyke, Pulliam, &

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Charnov, 1977). But optimal foraging models also apply to foraging patterns, that is, foragers should choose the closest possible target to minimize the total distance travelled while foraging (Pyke et al., 1977). While this account is logically enticing, several studies have shown that humans are not optimal foragers (e.g. Hutchinson, Wilke, & Todd, 2008; Pierce & Ollason, 1987) and that there are biases and flexibilities in foraging behavior, not accounted for by optimal foraging models (Cain, Vul, Clark, & Mitroff, 2011).

1.1. Templates guide foraging

Most researchers agree that during search and foraging observers use *search images* or *templates* whose content reflects the task goals in each case (Bond & Kamil, 2002; Dukas & Kamil, 2001; Jackson & Li, 2004; Nakayama, Maljkovic, & Kristjánsson, 2004). Such templates are assumed to be held in capacity limited working memory (Awh & Jonides, 2001; Bundesen, 1990; Carlisle, Arita, Pardo, & Woodman, 2011; Desimone & Duncan, 1995; Grubert & Eimer, 2013; Vickery, King, & Jiang, 2005; Woodman, Carlisle, & Reinhart, 2013), and these capacity limits may be one reason why participants do not always forage optimally.

There are, however, long standing disagreements over how these templates guide attention. A fundamental question involves the number of templates that can simultaneously guide attention. According to a recent proposal, there can only be one template active in working memory at any given time (van Moorselaar, Theeuwes, & Olivers, 2014; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Ort, Fahrenfort, & Olivers, 2017; see also Oberauer, 2002). Similarly, Huang and Pashler (2007) proposed that observers only have access to one feature value at a given moment. This idea has also been proposed in the literature on animal foraging. For example, birds are bad at dividing their attention, and have trouble searching for two categories of prey simultaneously (Dawkins, 1971; Dukas, 2002). Recent evidence, that mostly involves demonstrations of a cost to switching between templates, is seemingly consistent with this proposal. In Houtkamp and Roelfsema (2009) observers performed an RSVP task where they searched for either one or two targets within a stream of rapidly presented items. They had great difficulty with performance when there were two potential targets within the stream, while when there was only one, performance improved greatly, suggesting that participants could only use a single template for guidance at a given time, and that any additional templates increased the chances of missing targets. In Dombrowe, Donk, and Olivers (2011) observers made saccades from the left to the right between target items of one color or two different colors. Performance was impaired when targets were of two different colors and Dombrowe et al. (2011) concluded that changing or switching between attentional templates takes around 250-300 ms. In van Moorselaar et al. (2014) observers performed visual search while they maintained a variable number of items in visual working memory. van Moorselaar et al. (2014) found only interference from the visual working memory load when a single color was maintained in working memory, not when more colors were maintained.

Based on such findings, Olivers et al. (2011) proposed a model of visual working memory where only a single template is active at any given time and capable of influencing ongoing visual tasks (such as visual search or visual foraging). According to their proposal, more templates can be kept in visual working memory, but only one template is *active* and can interact with perception at any given time, and non-active templates are kept in an accessory working memory state and do not affect current visual performance (see also Huang & Pashler, 2007).

Other results seemingly contradict this, however. Predators who divide attention among an increasing number of different prey types decrease their ability to detect any given type (Dukas & Ellner, 1993). This decrease in performance is gradual, but does not involve a collapse in performance as load increases from one to two templates with little, or no difference between two or three templates, as a single-template model predicts, since according to such models, observers must simply switch to one of the items in the accessory state, that are all in a similar state (van Moorselaar et al., 2014). Carlisle et al. (2011) then found ERP evidence for more than one simultaneous attentional template in visual working memory, as did Grubert and Eimer (2015). Strong counter-evidence against the idea of a single active template was provided by Beck, Hollingworth, and Luck (2012), who reported that observers can maintain more than one active visual working memory template. Their observers searched for a target among distractors, attempting to limit attention to objects of two colors, finding that observers switched gaze back and forth between the two colors with no switch costs, in contrast to single-template proposals.

Perhaps the strongest evidence that observers can simultaneously maintain at least two active search templates comes from recent studies on human foraging (e.g. Jóhannesson, Kristjánsson, & Thornton, 2017; Jóhannesson, Thornton, Smith, Chetverikov, & Kristjánsson, 2016; Kristjánsson et al., 2014; Kristjánsson, Thornton, & Kristjánsson, 2016). In Kristjánsson et al. (2014), participants foraged, by tapping on the screen of an iPad, for 40 targets of two types (e.g. red and green disks) among 40 distractors of two different types (e.g. blue and yellow disks). More than 95% of observers switched freely between the two target types during foraging trials, without large costs. Another interesting finding was that when intertarget times (times between successive taps, ITTs) were compared between when the previous target was from the same category, or from a different category, the difference in ITTs ("switch-cost") was only around 50 ms (Kristjánsson et al., 2016). In a recent unpublished study (Ólafsdóttir, Gestsdóttir, & Kristjánsson, 2017), such switch costs were almost non-existent, and are as low as 15 to 20 ms in other studies (Jóhannesson et al., 2016; Ólafsdóttir, Kristjánsson, Gestsdóttir, Jóhannesson, & Kristjánsson, 2016; see Grubert & Eimer, 2015 for related findings). Also, in a study where observers foraged with eye gaze rather than fingers, the switch costs between target-types were essentially zero (Jóhannesson et al., 2016). These results show that people can switch between target categories with seemingly little switch costs, an order of magnitude lower than the 250–300 ms suggested by Dombrowe et al. (2011) and therefore involve a challenge for single-template accounts, since they must then include a mechanism for rapid switching between templates.

Another intriguing question is why participants performing these foraging tasks seemingly do not seem to care whether the next target they choose during foraging is from one target category or the other. The runs during foraging for two colored targets among two distractors are typically close to random (Kristjánsson et al., 2014). If switch costs between templates are around 250–300 ms this would be an extremely inefficient strategy. These findings therefore seem highly discrepant with the idea of a single active template, which takes time to be replaced. They appear to be more consistent with load theories of visual working memory that assume that working memory has limited capacity, but do not place any constraints upon the nature of the WM representations, but simply impose a capacity limit (Alvarez & Cavanagh, 2004; Bays & Husain, 2008). In fact, as load increased in Kristjánsson et al. (2014) and observers had to forage for 2 more complex "conjunction" targets (e.g. red square and green disk targets among green square and red disk targets) they changed their strategy, tending not to switch between targets (Jóhannesson et al., 2017; Kristjánsson et al., 2014). Observers seemed, in other words to maintain two simultaneous templates that involved simple features, but were unable, or unwilling, to maintain two more demanding conjunction templates.

1.2. Current goals

Our aim was to directly address the question whether more than one template can be simultaneously actively maintained in visual working memory. We therefore varied the number of targets and distractors in a visual foraging task for 40 targets among 40 distractors. We varied the number of target and distractor types in two ways: 1) Fixed distractor