The Underlying Mechanism of Attentional Templates in Facilitating Visual Search

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Abstract

The visual search ability of organisms is of vital survival significance for adapting to complex external environments. Attentional templates can enhance relevant information and suppress irrelevant information during search tasks, thereby rapidly locating targets. A summary of recent research findings reveals the following key discoveries: during the establishment of attentional templates, it remains unclear whether they are based on semantic information or visual feature information; attentional templates can be stored not only in working memory but also in long-term memory; the neural mechanisms of different types of attentional templates exhibit differences. Future research should focus on how internal information is transmitted during the establishment of attentional templates, investigate the neural mechanisms of attentional templates across different populations, and resolve theoretical controversies regarding the suppression mechanism of rejection templates.

Full Text

The Internal Mechanisms of Attentional Templates in Facilitating Visual Search

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Abstract

The visual search ability of organisms is of crucial survival significance for adapting to complex external environments. Attentional templates can enhance relevant information and suppress irrelevant information during search tasks, thereby rapidly locating targets. Recent research findings can be summarized as follows: It remains unclear whether the establishment of attentional templates relies on semantic information or visual feature information; attentional templates can be stored not only in working memory but also in long-term memory; and different types of attentional templates exhibit distinct neural mechanisms. Future research should focus on how internal information is transmitted during the establishment of attentional templates, examine the neural mechanisms of attentional templates in different populations, and resolve theoretical disputes regarding the suppression mechanisms of rejection templates.

Keywords: attentional templates, rejection template, neural mechanism, memory

In daily life, we frequently need to search for specific targets within complex and rich visual environments. In laboratory research, visual search generally refers to the process of locating a particular target or determining whether it appears against a certain background. Visual search tasks primarily involve the following processes: first, extracting an abstract description of the target and forming a mental image of it to serve as an attentional template (or search template) maintained in short-term memory; subsequently, during the search process, attention is continuously shifted to match incoming visual information against the template in short-term memory until the best-matching target is found, thus completing the search (Vickery, King, & Jiang, 2005). Investigating the internal mechanisms of templates in visual search tasks is essential for understanding human visual search processes.

The concept of templates can be traced back to Duncan and Humphreys' (1989) Attentional Engagement Theory, which posits that visual search comprises three stages: first, a parallel processing perceptual description stage that constructs multi-spatial-scale structural representations of information within the visual field; second, a selection process that matches incoming information with internal templates required for current behavior; and finally, the selected information enters visual short-term memory (Duncan & Humphrey, 1989; Duncan & Humphreys, 1992). In visual search tasks, template information stored in short-term memory is used to determine the priority of sensory information processing and to judge whether current information matches the target (Geng & Witkowski, 2019). Previous studies did not strictly distinguish between the concepts of attentional template and search template (Geng & Witkowski, 2019; Malcolm & Henderson, 2009; Reeder, van Zoest, et al., 2015; Witkowski & Geng, 2019). As research on attentional templates (or search templates, hereafter referred to as attentional templates) has expanded, researchers have categorized them into target templates and rejection templates. Based on the type of information stored, attentional templates can be divided into two types: one stores target-related information for attentional selection of the target, generally called a target template (Hout & Goldinger, 2015; Vickery et al., 2005; Won et al., 2020); the other stores distractor-related information for suppressing distractors, called a rejection template (Arita et al., 2012; Cunningham & Egeth, 2016; Geng, 2014; Moher & Egeth, 2012; Sawaki & Luck, 2011; Vatterott & Vecera, 2012; Won & Geng, 2018).

Research on attentional templates primarily focuses on their establishment process, the information they contain, their relationship with memory, and the neural mechanisms of different template types. Feature-Integration Theory proposes that visual search involves two stages: in the first stage, different features of stimuli (such as color, orientation) are processed in parallel, which is an automatic processing stage; in the second stage, different features of the same object are integrated to enable correct object representation, a stage that requires focused attention (Treisman & Gelade, 1980; Treisman & Sato, 1990). The Biased Competition Model suggests that during visual search, targets and distractors compete to capture attention, and that beyond bottom-up attentional biases, top-down attentional control is required (Desimone & Duncan, 1995). Both theories view visual search as an interactive process between top-down knowledge and bottom-up information, where selecting a target among distractors requires matching visual input with a top-down attentional template. Attentional templates are typically established based on relevant information about targets or distractors, usually presented to participants as cues, who then form templates and search for targets accordingly. For example, Vickery et al. (2005) used a cueing paradigm to investigate template establishment. Across five experiments, they employed different cue types to examine the role of different information types in establishing target templates. Results showed that search was faster when picture cues exactly matched the target (precise cues) compared to neutral cues (no information) or semantic cues; fine-grained cues also produced faster search than small or rotated cues. Compared to semantic or neutral cues, small or rotated cues facilitated faster search. The researchers concluded that visual information is more beneficial than semantic information for establishing attentional templates and improving visual search efficiency.

Attentional templates are not stored exclusively in working memory. For instance, Woodman et al. (2007) found that when search targets varied between trials, search performance was significantly affected by a memory task, indicating that attentional templates were stored in visual working memory; however, when search targets remained constant across trials, search performance was unaffected by the memory task, suggesting that under these conditions, search targets might be stored in long-term memory. In research on the neural mechanisms of attentional templates, studies on primates have found that template activation involves neurons in the prefrontal cortex, which play a role in selecting and maintaining targets (Chelazzi et al., 1998; Evans et al., 2011) and project to the inferotemporal cortex that represents objects (Hout & Goldinger, 2015; Peelen et al., 2009). Wei et al. (2009) found that during visual search, the bilateral frontal eye field, intraparietal sulcus, precentral gyrus, and supplementary eye field represent targets to detect their presence and guide responses, while the right superior frontal gyrus and bilateral temporoparietal junction may filter and reject distracting information.

In recent years, researchers have conducted more in-depth investigations into the internal mechanisms of attentional templates. This article will elaborate on existing research findings regarding the information relied upon during template establishment, the relationship between templates and memory, and the mechanisms by which templates facilitate search, as well as future research directions.

2.1.1 The View That Visual Information Is Used to Establish Attentional Templates

Some researchers have found that visual information is relied upon when establishing attentional templates during visual search tasks. In studies of target templates, Reeder and Peelen (2013) used a dot-probe paradigm to investigate the contents of target templates in category-level natural scene search tasks. The experiment consisted of 75% visual search trials and 25% dot-probe trials. In visual search trials, participants judged whether the target appeared on the left or right side of the screen based on cue information. In dot-probe trials, different probe stimuli were presented on both sides of the screen before the dot appeared, with participants instructed to ignore these stimuli. After the probes disappeared, a dot appeared, and participants judged whether it appeared on the left or right side. Since 75% of trials were visual search tasks, participants would form target templates based on the cues when they appeared. The experiment hypothesized that if the attentional template contained a particular probe stimulus, the side presenting that probe would capture attention, resulting in faster reaction times when the subsequent dot appeared on the same side compared to the opposite side (a congruency effect). Results showed significant congruency effects for partial contour features, indicating that attentional templates contain partial features for judging object categories. Wurth and Reeder (2019) used the same paradigm with natural scene images and found that object category-level attentional templates consist of whole object contours and partial features for judging categories, but that partial features alone are insufficient to constitute an adequate target template. Zhang and Li (2020) used a dot-probe paradigm and found that in rapid visual search, target template information in short-term memory is primarily low-frequency information, and that low-frequency information near threshold can implicitly facilitate target recognition, thereby improving visual search efficiency. These results demonstrate that attentional templates contain visual information about object features relevant for search.

Reeder, van Zoest, and Peelen (2015) used the dot-probe paradigm to explore whether target templates in natural scene search are based on visual features from the search scene or semantic information in the mind. Results indicated that the critical factor in natural scene search is the activation of target templates by visual features. Moreover, Chen et al. (2018) found that target templates can be used to search for occluded images through amodal completion, a mechanism by which the visual system automatically completes missing parts of occluded objects. The experiment used simple or compound shapes as targets, with these two presentation forms randomly appearing in the search task. Results showed that in global search tasks (with complete images), searching for compound shapes was faster and more accurate than in local tasks (with partial images) or mosaic tasks (with partially occluded images). This suggests that during global search, attentional templates are formed when searching for global shapes, which then automatically complete missing parts when searching for occluded compound shapes. The finding that target templates established during global shape search can automatically complete occluded shapes also demonstrates that attentional templates can be established through visual feature information of targets.

Target templates contain not only target feature information but also distractor feature information. In studies of rejection templates, Geng et al. (2017) manipulated the probability of distractors similar to the target appearing in visual search tasks. In the high-similarity group, distractors with colors similar to the target appeared frequently, while in the low-similarity group, such distractors appeared infrequently. Results showed that compared to the low-similarity group, the high-similarity group responded faster, reached asymptotic performance earlier, and showed an inflection point closer to the target color. This indicates that rejection templates also contain visual information about distractors and that this information can be flexibly adjusted based on distractor characteristics; the more frequently distractors similar to the target appear, the more precisely the rejection template represents them and the stronger its suppression capability.

2.1.2 The View That Semantic Information Is Used to Establish Attentional Templates

Semantic information is not irrelevant when establishing attentional templates, as real-world templates do not always provide information that precisely matches the visual attributes of specific targets; search target information is often provided by semantic information. For example, when someone asks you to find their bag in a closet, you may not know the specific visual information about that bag beforehand—whether it is red or green, large or small—yet you can still locate it accurately. Researchers have also provided evidence that semantic information influences template establishment. Nako et al. (2015) used event-related potentials to investigate how different cue types affect the efficiency of target template establishment. In each trial, a new search target was presented, with each target appearing only once throughout the experiment. The N2pc (N2 posterior contralateral) component was used as a spatial attention index for target selection (Luck & Hillyard, 1994). After the search target was presented, three consecutive search displays appeared, and participants had to find the target and report its location in each display. The experiment compared N2pc components elicited by targets on their first, second, and third presentations. When target templates were defined by words, N2pc amplitude was reduced during the first search compared to the second and third searches. In a control experiment where word cues were replaced with accurate target images (picture-defined cues), no significant differences were found in N2pc components between the first and subsequent presentations.

These results suggest that when cues are pictures, precise target templates are formed before the first search; when cues are words, precise target templates are not well-established before the first search but develop as the target appears in subsequent searches. This indicates that word cues may be less efficient than picture cues for establishing precise target templates.

Baier and Ansorge (2019) investigated whether color-based attentional capture in visual search depends on linguistic or semantic information and similarly found that target templates based on color visual information produced higher search efficiency than those based on semantic information, suggesting that semantic information may be less effective than visual information for establishing target templates (Baier & Ansorge, 2019). Sun et al. (2015) examined whether concept-related words (e.g., "ocean" associated with blue) could activate corresponding color target templates and found that target templates can be generated through semantic information without visual features, with no significant performance differences between concept-generated and visual feature-generated templates. Although research on semantic information for establishing rejection templates is less extensive than for target templates (Daffron & Davis, 2015), some researchers have found that rejection templates can also rely on semantic information (Balani et al., 2010; Daffron & Davis, 2015, 2016). In summary, current research shows that attentional templates involve activation of both semantic information and object visual information (Hwang et al., 2011; Lupyan, 2008; Meyer et al., 2007; Moores et al., 2003; Nako et al., 2015; Sun et al., 2015; Telling et al., 2010). We cannot separately examine the effects of semantic or visual features on attentional templates because these features cannot be well separated in research (Hwang et al., 2011). During template establishment, semantic features may dominate early on, while visual features may show superior effects later in the search process (De Groot et al., 2017; Hwang et al., 2011; Nako et al., 2015). Whether the template establishment process uses visual information, semantic information, or both to find targets remains to be investigated in future research.

2.2.1 The View That Attentional Templates Are Stored in Working Memory

Attentional templates are generally considered to be stored in visual working memory to guide attention during visual search (Olivers et al., 2011; Zhang Bao et al., 2013; Che Xiaowei et al., 2020). The view that templates are maintained in working memory dates back at least to behavioral and neurophysiological research from the 1990s (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). Duncan and Humphreys (1989) proposed that during visual search, visual information matching internal templates enters short-term memory, thereby achieving attentional control. Visual search is thought to be guided by visual working memory representations formed by task-relevant features, i.e., attentional templates (van Loon et al., 2017). The most widely accepted theory regarding the relationship between attentional templates and memory posits that templates are directly stored in working memory and are therefore equivalent to working memory representations (Soto et al., 2008). This view is supported by cognitive neuroscience research; Woodman and Arita (2011) used the contralateral delay activity (CDA) to investigate whether working memory is involved in maintaining attentional templates. The CDA component is considered a reliable index of visual working memory load (Vogel et al., 2005; Vogel & Machizawa, 2004), and results showed that cue-elicited CDA persisted until search execution, confirming that templates are indeed maintained in working memory (Woodman & Arita, 2011).

Some researchers argue that although multiple items can be stored in working memory, only one template can be activated at a time, with other items stored as accessory memory representations (Burra & Kerzel, 2013; Carlisle & Woodman, 2011; Hollingworth & Hwang, 2013; Olivers et al., 2011; Ort et al., 2017; Soto et al., 2012; van Moorselaar et al., 2014, 2015). For example, in research on target templates, Houtkamp and Roelfsema (2009) used signal detection theory to fit data to different template models to estimate the number of templates that could be stored in working memory. Using a rapid serial visual presentation paradigm, they presented two shapes (shape experiment), two colors (color experiment), or one shape and one color (combination experiment) before search, with participants judging whether the presented sequence contained the previously shown shape or color. Behavioral results showed that searching for two items yielded worse performance than searching for one item, and model fitting revealed that the estimated number of templates ranged from 0.9 to 1.1 whether searching for one or two items, suggesting that only one template is stored in working memory.

In research on rejection templates, van Moorselaar (2014) found that when memory load consisted of only one color, the presence of a distractor matching that color slowed reaction times; when memory load included two or more colors, there was no significant difference in interference between distractors matching or not matching the memory colors, indicating that only one rejection template is stored in working memory. Other researchers hold the opposite view, arguing that multiple attentional templates can be simultaneously stored in working memory (Ansorge & Horstmann, 2007; Beck et al., 2012; Beck & Hollingworth, 2017; Hollingworth & Beck, 2016; Irons et al., 2012; Kerzel & Witzel, 2019; Worschech & Ansorge, 2012; Zhou et al., 2020). For example, in research on target templates, Beck et al. (2012) investigated whether two target templates are maintained simultaneously or switched between in working memory. Participants searched for two colored items sequentially in half the trials (sequential search condition) and simultaneously in the other half (simultaneous search condition). Results showed no significant difference in search speed between simultaneous and sequential search conditions; sequential search showed significant switch costs (longer fixation times when switching between colors compared to fixating on the same color), while simultaneous search showed smaller switch costs, with no difference in average fixation times between conditions. This suggests that under different task instructions, two target templates can be either sequentially activated or simultaneously activated in working memory.

Grubert and Eimer (2015) used the N2pc component as an index of attentional selection and found that delays in searching for two color-defined targets were not due to template switching costs but rather resulted from competition between the two target templates. Kerzel and Witzel (2019) measured the number of attentional templates for color targets and found that cue effects in color search were unaffected by the number of colors held in memory, indicating that more than one target template can be stored in working memory. In research on rejection templates, Hollingworth and Beck (2016) found that more than one rejection template can be stored in working memory. Participants memorized one or two color patches, which always appeared as distractor colors in the subsequent search task. Results showed no significant difference in search reaction times whether the search display contained one or two colors matching the memorized colors, suggesting that at least two rejection templates can be maintained in memory.

Controversy remains regarding the number of templates stored in working memory. Some researchers argue that searching for two items yields worse performance than searching for one, indicating that only one attentional template is stored in working memory (Burra & Kerzel, 2013; Hollingworth & Hwang, 2013; Olivers et al., 2011; Ort et al., 2017; Soto et al., 2012; van Moorselaar et al., 2015). However, the inferior performance in searching for two items simultaneously can be attributed to many factors and does not directly indicate that only one template is stored. For example, when two templates are simultaneously stored in working memory, limited working memory resources must be divided, reducing the resources available for each template compared to when only one template is stored, thereby decreasing search efficiency. Additionally, template representations in working memory may involve either simultaneous activation or switching between templates; when two templates are simultaneously activated, information in the online state may interfere with each other, leading to poorer performance in dual-item search (Zhang et al., 2021). When templates switch between each other, switching requires time and may impair memory representations, also reducing efficiency in dual-item search compared to single-item search (Zhang et al., 2021). Furthermore, different experimental paradigms may contribute to different results (Frătescu et al., 2019); in different paradigms, different items have different priorities in working memory. When items have equal priority in an experiment, they may receive equal resources and allow for the establishment of two templates (Grubert & Eimer, 2020), whereas when one item is deprioritized due to task demands, it receives fewer resources in working memory and cannot establish multiple attentional templates (Kerzel & Witzel, 2019).

2.2.2 The View That Attentional Templates May Be Stored in Long-Term Memory

Other theories suggest that although storing attentional templates in working memory may be necessary, it is insufficient to equate working memory representations with templates (Dube & Al-Aidroos, 2019; Hollingworth & Hwang, 2013; Kerzel & Cong, 2021). Some researchers argue that attentional templates have properties independent of working memory representations, indicating that they can be dissociated from working memory (Carlisle & Woodman, 2011; Kerzel, 2019). However, Kong et al. (2020) demonstrated that attentional templates and working memory are not equivalent but also not completely independent, suggesting a shared mechanism may be responsible for both. Although many studies have found that attentional templates can be stored in working memory (Berggren & Eimer, 2018a; Carlisle & Nitka, 2019; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Sawaki & Luck, 2011; Shirama et al., 2017), some researchers argue that attentional templates can also be stored in long-term memory (Carlisle et al., 2011; Cowan, 1995; Woodman et al., 2013). When targets remain constant throughout an experiment, search performance is unaffected by memory tasks, suggesting that attentional templates may be stored in long-term memory (Woodman et al., 2001), whereas when targets vary between trials, attentional templates are stored in visual working memory (Woodman et al., 2007).

However, some researchers argue that attentional templates cannot be simply considered as stored in either working memory or long-term memory. Carlisle et al. (2011) found that attentional templates are initially maintained in visual working memory but gradually transfer to long-term memory over time. Using a cueing paradigm with randomly appearing search targets (single or dual-target cues), they found that CDA amplitude in dual-target cue conditions was double that in single-target cue conditions, indicating that search target representations were maintained in visual working memory. They also used a fixed-target search paradigm and found that the CDA component gradually decreased as the experiment progressed, suggesting that as attentional templates are acquired, templates stored in visual working memory transfer to long-term memory. Other studies support this finding (Grubert et al., 2016; Gunseli et al., 2014; Reinhart et al., 2015; Reinhart & Woodman, 2014a). For example, Grubert et al. (2016) cued participants with one, two, or three possible target colors at the beginning of each trial. In constant-color trials, target-relevant colors remained unchanged; in variable-color trials, target colors changed between trials. Results showed that CDA amplitude was larger in variable-color trials than in constant-color trials and increased with color memory load, suggesting that when targets vary between trials, different target templates may be switched between, and templates are stored in working memory; when targets remain constant, attentional templates stored in working memory at least partially transfer to long-term memory.

A recent study challenged this finding, showing that even when searching for one of two targets with fixed identity, attentional templates can continue to be stored in working memory (Berggren & Eimer, 2018b). Woodman et al. (2013) used the P170 component as a direct index of information accumulation in long-term memory. By reanalyzing data from Carlisle et al. (2011), they observed that as CDA disappeared, P170 amplitude increased. In subsequent studies, they also found that P170 amplitude gradually increased as targets were repeated across trials, indicating that target templates can transfer to long-term memory (Reinhart & Woodman, 2014b). The storage of attentional templates in these two memory systems may be conditionally constrained: depending on presentation format, templates may be stored differently—when targets are constant, templates stored in working memory transfer to long-term memory; when targets vary, different templates may be switched between, preventing sustained learning of a single template and requiring maintenance in working memory. However, the view that attentional templates can be stored in long-term memory is primarily based on research on target templates; more experimental evidence is needed to determine whether rejection templates can transfer from working memory to long-term memory during visual search.

Attentional templates in different categories may have different storage mechanisms. Existing research has focused primarily on precise object categories, whereas category-level templates are relatively imprecise and can include different objects within the same category. Whether category-level templates continuously adjust their content to become more precise during search or maintain their original content, and whether their storage is similarly affected by target variability, remain to be investigated.

2.3.1 Mechanisms of Target Templates

During visual search, it is necessary not only to enhance attention to targets but also to suppress distractors to achieve faster search. Therefore, successful target search involves two attentional mechanisms: enhancing target-relevant information and suppressing distractor information (Won & Geng, 2018). Most research has focused on the former, finding that target features can be prioritized through enhanced sensory processing, though this may also cause distractors sharing target features to be incorrectly selected (Desimone & Duncan, 1995; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe & Horowitz, 2004). Studies of the latter have revealed a suppression mechanism for distractors that can improve search efficiency (Cunningham & Egeth, 2016; Gaspar & McDonald, 2014; Gaspelin et al., 2015, 2017; Noonan et al., 2016; Sawaki & Luck, 2011). Thus, both target templates and rejection templates can facilitate visual search, though they may operate through different mechanisms (Zhang et al., 2020). Suppression mechanisms can independently inhibit specific stimuli or locations in the environment and are controlled by different neurons (Chelazzi et al., 2019), a view supported by cognitive neuroscience research. Studies have found that the right posterior temporal cortex (pTC) represents information about object categories to be detected and facilitates target search (Reeder, Perini, et al., 2015). The anterior superior parietal lobule is involved in representing task-relevant features by target templates (Peelen & Kastner, 2011). Cortical alpha-band activity may be related to inhibiting task-irrelevant neurons or increasing the excitability of task-relevant neurons (Van Diepen et al., 2019). Reeder et al. (2017) used functional magnetic resonance imaging to investigate brain regions involved in rejection templates and found that target templates and rejection templates activate different brain regions. In a search task requiring participants to report whether target letter T faced left or right, cue types were presented before search: "+" , "-" , and "o" represented positive cues (target appeared in a colored circle matching the cue color), negative cues (distractor appeared in a colored circle matching the cue color), and neutral cues (cue color did not appear in the search display). Results showed that target template selection was associated with activation in the bilateral occipital pole and lateral occipital cortex, while posterior parietal cortex bordering the precuneus played a role in filtering task-irrelevant information in rejection templates. Furthermore, Reeder et al. (2018) found that target templates had clear representations in primary visual cortex, whereas distractor templates did not, supporting the view that target and rejection templates have different neural mechanisms.

2.3.2 Mechanisms of Rejection Templates

Arita et al. (2012) proposed an inhibitory attentional template called a "rejection template," which is established based on distractor cues, can suppress distractor features, and facilitates search more than neutral cues.

Research on the neural mechanisms of rejection templates has used event-related potentials to show that when visual search displays contain salient but task-irrelevant distractors, more positive components are elicited in posterior brain regions contralateral to these distractors. This component, called Pd (distractor positivity), is thought to reflect active distractor suppression (Burra & Kerzel, 2014; Kiss et al., 2012; Sawaki et al., 2012; Sawaki & Luck, 2010). In Berggren and Eimer' s (2018a) study, where only one side of the search display contained task-relevant stimuli, Pd components were elicited contralateral to distractors, indicating active suppression of contralateral distractors. If distractor suppression is controlled by rejection templates, the presence of Pd components should indicate that rejection templates have been activated. Activation of the dorsolateral prefrontal cortex may be related to distractor suppression (Geng, 2014; Suzuki & Gottlieb, 2012). Suppression can occur before attentional shifting to prevent salient stimuli from capturing attention, and this suppressive ability strengthens as participants gradually learn distractor features (Gaspelin & Luck, 2019).

Previous research on high-anxiety individuals has found that attentional suppression effects decrease with increasing anxiety levels. For example, Gaspar and McDonald (2018) used N2pc and Pd components to investigate whether high anxiety traits are associated with preventing attentional capture and suppressing distractors. They found that distractors elicited significant N2pc components in high-anxiety groups, but Pd components were observed in both high- and low-anxiety groups, indicating that low-anxiety individuals can actively suppress distractors, while high-anxiety individuals only begin suppression after being captured by distractors. Moreover, Salahub and Emrich (2021) found that higher anxiety levels increase the likelihood of being captured by distractors matching rejection templates, while lower-anxiety individuals can avoid such capture. Rejection templates may affect search efficiency differently across populations; for example, in older adults, reduced cognitive control capacity limits the ability to suppress irrelevant distractors, and the mechanisms by which attentional templates facilitate search may differ. Therefore, results from studies of typical populations may not be universally applicable, and future research on attentional templates should consider differences between populations.

In research on inhibitory mechanisms, many researchers have proposed that distractor suppression may be location-based (Dark et al., 1996; Theeuwes et al., 1998; Watson & Humphreys, 1997). Recent probability learning studies have found that when specific distractors appear in a location much more frequently than in other locations, selection efficiency for that location decreases (Ferrante et al., 2017; Wang & Theeuwes, 2018a, 2018b). Location-based suppression of distractors has also received electrophysiological support. For example, Schönhammer et al. (2020) used a spatial cueing paradigm and found that responses were faster when cue location matched target location than when they differed, and an inhibitory Pd component was generated contralateral to the cue location, indicating location-based suppression of distractors. Beck and colleagues (2015, 2018) found that rejection template suppression of distractors is unlikely to be feature-based and may involve converting feature information to spatial information when the search display appears, suggesting that rejection template suppression is location-based (Beck et al., 2018; Beck & Hollingworth, 2015). However, Carlisle and Nitka (2019) used a cueing paradigm to test Beck et al.’ s (2015) location-based rejection template and found no evidence that participants used location-based strategies. Recent studies have also found that rejection templates suppress distractor features rather than locations (Tanda & Kawahara, 2020). Even when distractor features are salient, they can be effectively suppressed after learning and training (De Tommaso & Turatto, 2019; Gaspelin & Luck, 2018; Turatto et al., 2018). Some researchers have investigated how template search strategies (feature search mode vs. singleton search mode) affect suppression of salient distractors (De Tommaso & Turatto, 2019; Graves & Egeth, 2015). They found that in feature search conditions, participants could effectively suppress salient distractors with learning; in singleton search conditions, suppression learning failed, possibly because both targets and salient distractors were feature singletons (De Tommaso & Turatto, 2019) or because target and distractor features were not fixed and switched between each other (Graves & Egeth, 2015).

Current research paradigms tend to confound features and spatial locations, making it difficult to exclude location effects when suppressing distractor features (Tanda & Kawahara, 2019). Moreover, the priority of location-based versus feature-based suppression may differ across paradigms. For example, when location information is cued before search, location-based suppression may dominate (Schönhammer et al., 2020); when feature information is cued, feature-based suppression may dominate (Arita et al., 2012; De Tommaso & Turatto, 2019). Future research should employ more refined paradigms that separate features and spatial locations while matching the difficulty of feature and location information, and use eye-tracking to further investigate factors influencing the priority of rejection templates in suppression based on these two types of information.

3 Future Research Directions

Research on the internal mechanisms of visual attentional templates involves several controversies: First, current experimental studies cannot adequately separate visual and semantic information when establishing attentional templates in visual search tasks, leaving debate about whether template establishment relies on visual information, semantic information, or both. Second, in research on suppression mechanisms, factors influencing the priority of location-based versus feature-based suppression of distractors require further investigation. Third, attentional templates cannot be simply considered as stored in working memory but may also be stored in long-term memory, yet current research has not distinguished the conditions for storing templates in these two memory systems. In addition to these issues, other problems in attentional template research remain to be addressed:

First, we know little about how template information is transmitted and used during visual search. Most laboratory tasks have not focused on the template establishment process, especially in tasks with fixed targets where participants have already formed corresponding attentional templates after practice, leading some studies to neglect this process (Alfandari et al., 2019). The process by which attentional templates facilitate search is complex. Hout and Goldinger (2015) and Rajsic and Woodman (2019) propose that attentional templates have dual functions in guiding search and making decisions, directing attention to potentially relevant items and comparing visual input with templates for target confirmation or rejection. Some researchers suggest that during visual search using templates, there are actually two related representations or "templates": a "guiding template" containing relatively coarse features for directing attention to candidate targets, and the previously mentioned "target template" containing precise object features for target confirmation (Anderson, 2014; Cunningham & Wolfe, 2014; Kerzel, 2019; van Loon et al., 2017; Wolfe, 2012, 2020a, 2020b). Yu et al. (2022) investigated how template information is used during guidance and decision stages of visual search and found that different information is used for single target templates in these two processes. However, few studies have examined the time course of guidance and decision processes during visual search cycles or whether the same information is used in these processes when searching for multiple targets, issues that require more experimental evidence.

Second, research on atypical populations has found that individuals with Autism Spectrum Disorder (ASD) show clear visual search advantages compared to typically developing (TD) individuals (Hessels et al., 2014; Marciano et al., 2021; Shirama et al., 2017). Under equivalent task difficulty, ASD individuals show higher search accuracy and fewer fixations on targets and peripheral distractors than TD individuals (Peng Xiaoling & Huang Dan, 2018). ASD and TD individuals also activate different brain regions during visual search: ASD individuals primarily activate frontal, occipital, and parietal regions, while TD individuals show activation concentrated in the left putamen (Keehn et al., 2012). Given these potential differences, future research on attentional templates should be extended to atypical populations.

Third, despite significant progress in understanding rejection template suppression mechanisms, controversy remains about how this suppression occurs. Some researchers propose that rejection templates facilitate search through active suppression of known distractors, known as the active attentional suppression hypothesis (Arita et al., 2012; Zhang et al., 2020). Zhang et al. (2020) used a dot-probe paradigm to investigate early attentional effects of rejection templates, presenting negative cues (indicating distractor colors) before search so participants knew the cued features belonged to distractors. Results showed that 100 ms after search onset, targets captured more attention than distractors, supporting active attentional suppression. Other researchers propose that attention is first captured by distractors, with suppression occurring only after capture, known as the search and destroy hypothesis (Moher & Egeth, 2012). This view is supported by eye-tracking studies where participants were cued with distractor information (features or locations) before search and instructed to saccade directly to targets; results showed that despite instructions, participants initially made more saccades to distractors, gradually showing suppression with fewer direct saccades to distractors as the experiment progressed (Beck et al., 2018; Chang et al., 2019; Kugler et al., 2015; Moher & Egeth, 2012). Although both hypotheses have experimental support, the debate remains unresolved.

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