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Mechanisms of Representation Construction in Categorical Search: the Role of Attention and Working Memory

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Abstract

Introduction. The task of visual search involves locating target stimuli among distractors. This task is one of the most popular in attention research. Both the methodology and theoretical understanding of attention mechanisms in this task have undergone significant changes with the development of cognitive psychology. Modern studies focus more on the ecological validity of the stimulus material used and the participant's response methods, while contemporary theoretical models attempt to consider different variations of target stimulus presentation. **Theoretical Justification.** We examine categorical search, a type of visual search in which target stimuli are specified by category name. We propose a theoretical model for constructing a representation of the target stimulus in categorical search. This type of search is viewed as a two-stage process: the first stage involves selecting a set of objects in the visual field through attentional guidance, and the second stage involves checking these objects for compliance with the attentional template. The verification process entails verbally naming stimuli based on motor program activation. Within this representation of categorical search mechanisms, we also consider empirical data obtained from various task modifications. Special attention is given to the methodology of hybrid search, where participants need to locate several pre-memorized target stimuli. **Discussion.** It is suggested that hybrid search is guided by one of the representations (likely the first memorized one), followed by sequential comparison of objects to the attentional template representation of the target stimulus. Each of the non-matching objects is sequentially compared with the other representations.

Keywords

categorization, visual attention, visual search, categorical search, hybrid search, representation, working memory

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Introduction

Visual search is the process of finding a target object among distracting stimuli (distractors) (Wolfe, 2010). This strict definition encompasses a multitude of tasks that we perform every day, often without even realizing it: searching for keys on a table, finding the right type of tomatoes in a supermarket, locating a friend in a crowd... Furthermore, there are professions that require constant visual search task-solving, such as radiology and baggage screening.

Visual search is also one of the most popular research methods in the field of perception and attention in cognitive psychology. The interest in this methodology is driven not only by the practical significance of studying the mechanisms of visual search task-solving (see, e.g., Biggs, Kramer, & Mitroff, 2018) but also by the fact that this method provides a convenient way to investigate both object-based (as instructions typically involve object-based selection) and spatial attention (as the search process involves scanning specific spatial locations).

This article will examine the fundamental findings of visual search research, theoretical perspectives on the mechanisms of this process, and propose a model for forming representations during visual search.

Despite visual search tasks appearing to be one of the most "real-life" manifestations of cognitive psychology, experiments typically use highly "unrealistic" stimulus materials: vertically and horizontally oriented lines (Wolfe, Palmer, & Horowitz, 2010), triangles (Wolfe, 1998), letters T and L (Fleck, Samei, & Mitroff, 2010). Moreover, participants' responses usually do not resemble what we do in everyday life: the classic visual search methodology involves pressing one key if the target is present and another key if it is absent. However, for everyday tasks, we often need to clearly point to an object or even grasp it with our hands. This discrepancy between laboratory studies of phenomena and their everyday manifestations is not unique to the psychology of attention but is characteristic of other areas of cognitive psychology as well. It is primarily driven by the desire to study cognitive processes in maximum isolation from extraneous variables. Nevertheless, in recent years, there has been a growing interest among cognitive psychologists in ecologically valid tasks. This increased interest is associated with developments in cognitive psychology approaches, such as embodied, extended, and distributed cognition (see, e.g., Clark, 2008; Rogers & Ellis, 1994; Varela, Thompson, & Rosch, 1991), as well as practical demands.

Theoretical Justification

The emergence of new theoretical approaches is inseparably linked to the development of new research methodologies. Key modifications to the classic visual search task include: the search for multiple target stimuli (the "hybrid search" method) (Wolfe, 2012), the presence of two or more target stimuli on the screen (the " Subsequent search misses" methods (Adamo, Cox, Kravitz, & Mitroff, 2019; Adamo, Cain, & Mitroff, 2013) and "Incidental findings" (Wolfe, Soce, & Schill, 2017)), as well as various ways for the participant to respond – from clicking on the target stimulus with a mouse (Cain, Adamo, & Mitroff, 2013) to literally "capturing" the found stimulus (Gilchrist, North, & Hood, 2001). Some of these mentioned methods will be discussed in more detail later. For now, let's turn to another variation of the classic visual search task - categorical search.

Categorical Search

Categorical search represents a variant of visual search in which the target stimulus is defined by the name of a category (e.g., "search for apples") (see, e.g., Maxfield, Stalder, & Zelinsky, 2014). This type of task is ecologically valid (Schmidt & Zelinsky, 2009). Research on categorization is of particular interest because categorization itself enables efficient storage and manipulation of information through the grouping of objects (Rosch & Mervis, 1975).

Classical theories of categorization (Mervis & Rosch, 1981) suggest that categorization can occur at the subordinate, basic, and superordinate levels. The subordinate level includes the narrowest group of objects (e.g., "dachshunds"), the basic level encompasses a broader category ("dogs"), and the superordinate level is the most general ("animals"). Objects specified at the basic level category enjoy an advantage in various tasks, including visual search. The increase in speed and accuracy in tasks where the target stimulus is defined at the basic level, compared to superordinate and subordinate levels, is known as the "basic-level category superiority effect" (Murphy & Smith, 1982). Categorization theories typically explain the advantage of the basic level in terms of a balance between the specificity of the object and its distinctiveness at the intermediate basic level (Murphy & Brownell, 1985). Features of objects at the subordinate level may be highly specific, but these features often overlap with those of other object categories, thus lacking distinctiveness. Conversely, characteristics of superordinate category objects are highly distinctive, but properties of category objects usually lack specificity.

The basic theoretical models of visual search

The most well-known theory in cognitive psychology that describes the mechanisms of visual search and the functioning of attention in general is the classical Feature Integration Theory (FIT) by E. Treisman (Treisman & Gelade, 1980).

FIT postulates that prior to the engagement of attention, various basic features of objects (color, orientation, shape, etc.) freely "float," while the visual system constructs independent maps of individual features. Features associated with the same location in the visual field are then integrated on the master location map, allowing the perception of a coherent object only when attention is directed to that specific location on the map. Subsequently, FIT was further elaborated to include the concept of top-down attentional control through the "object file," which comprises various attributes of an object (see, e.g., Kahneman, Treisman, & Gibbs, 1992; Wolfe & Bennett, 1997). The object file can be modified through experience, with new features added, and it can also incorporate categorical information, such as an object's belonging to a certain class and ways of interacting with it. Categorical information enables the formation of expectations about what might happen with a given object. FIT is primarily employed to explain simple processes of parallel and serial search, as well as asymmetries in visual search (see, e.g., Wolfe, 2001). More complex variants of visual search have been explained through the Guided Search model proposed by J. M. Wolfe (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994; Wolfe & Gancarz, 1997; Wolfe, 2007).

The latest version of the Guided Search model, " Guided Search 6.0" (Wolfe, 2021), considers attention in a manner similar to the Feature Integration Theory (FIT), as a mechanism that selects elements in the visual field in such a way that their features can be associated into recognizable objects. To optimize the processing of objects, attention is "directed" towards them, and there are five sources of such attentional guidance: bottom-up and top-down guidance from features, past experience, reward (motivation), and scene characteristics (Wolfe & Horowitz, 2017). These sources of attentional guidance converge into a spatial "priority map" – a kind of dynamic landscape of attention that evolves during the course of a search. Selective attention is directed to the most active location on the priority map approximately 20 times per second, with the distribution of attention on the map being uneven – for example, prioritizing objects located near the fixation point. Objects in the visual field need to be compared to the template of the target stimulus to identify them as target stimuli or reject them as distractors. The template of the target stimulus is stored in the memory system.

J. Wolfe, in his model, considers not only classical visual search but also various modifications of this methodology, paying particular attention to the process of hybrid search. In experiments involving hybrid search, participants conduct searches on a screen containing a set of pre-memorized objects, with variations typically involving the number of memorized objects and the number of objects present on the screen (Drew, Boettcher, & Wolfe, 2017). The task of hybrid search resembles a trip to a supermarket, where a list of groceries is memorized beforehand, and then the items are searched for on the shelves. J. Wolfe posits that in this scenario, two types of representations are formed: a "guiding template" and a "target template." The guiding template is a representation from working memory that "selects" objects in the visual field that fit the desired category. For example, if one needs to search for specific animals, and the visual field contains both animals and numbers, the guiding template will select only the animals, guided primarily by perceptual features, particularly shape. Subsequently, the target template determines whether a given animal in the visual field corresponds to those memorized as target stimuli. The target template is a more precise representation compared to the guiding template and operates within an activated long-term memory, which serves as a specialized intermediate system between working memory and long-term memory (Cowan, 2019).

J. M. Wolfe's notions about different types of representations in hybrid search resonate with G. Zelinsky's earlier proposition distinguishing between the processes of guidance and verification in classical visual search. In experiments conducted by Maxfield & Zelinsky, participants were tasked with locating objects that could be specified by a basic, superordinate, or subordinate category, with eye movements being recorded (Maxfield & Zelinsky, 2012). The process of stimulus discovery was divided into two subprocesses: guidance (the time from the start of the trial to fixation on the target stimulus) and verification (the time from fixation on the target stimulus to the response moment). The guidance time proved to be the shortest for subordinate-level categories and the most significant for superordinate-level categories. The authors attribute this result to the degree of specificity (a measure of perceptual differences) among categories. Conversely, verification time was the shortest for basic-level categories, explained by the clarity of categories associated with the distinctive features of the target object.

The Guided search model describes the fundamental factors influencing attentional guidance in visual search and aligns with a substantial body of experimental data. However, the process of forming a "guiding template" – a representation of the target stimulus – is not extensively detailed within this model. Furthermore, insufficient attention is given to the mechanisms involved in creating a "guiding template" for verbally specified stimuli, despite the fact that in real life, we often encounter such situations. For instance, when we need to find a cup but lack a clear mental image of its color, size, or spatial orientation. In such cases, the representation of the target stimulus is not predefined but rather formed within the information processing system based on several factors. In this article, we propose a model for constructing a representation of the target stimulus in categorical search.

Discussion

Before proceeding with the description of the model, let's define the key concepts that will be used in our discussion. Traditionally, **working memory** (WM) is understood as a memory system whose function is the short-term storage and manipulation of a limited volume of information (Baddeley, Anderson, & Eysenck, 2011; Cowan, 2010). This term has sparked considerable debate among researchers, particularly in the context of distinguishing between the functions of short-term and working memory (Cowan, 2008; Baddeley, 2011). In the framework of our model, we will adhere to the classic definition of working memory but will specify its function as the manipulation of **representations** (visual and verbal images) of stimuli. Additionally, there is a specialized system called the **activated long-term memory (ALTM)**, which acts as a link between working memory and long-term memory proper. Activated long-term memory represents the portion of long-term memory that is relevant to the task currently being performed (Cowan, 1995). We posit that when solving a visual search task, WM engages in the comparison of representations of stimuli in the visual field with guiding representations of target stimuli stored in ALTM. The selection of representations relevant to the task at hand and their transfer from ALTM to WM (for immediate task solving) is facilitated by **attention**.

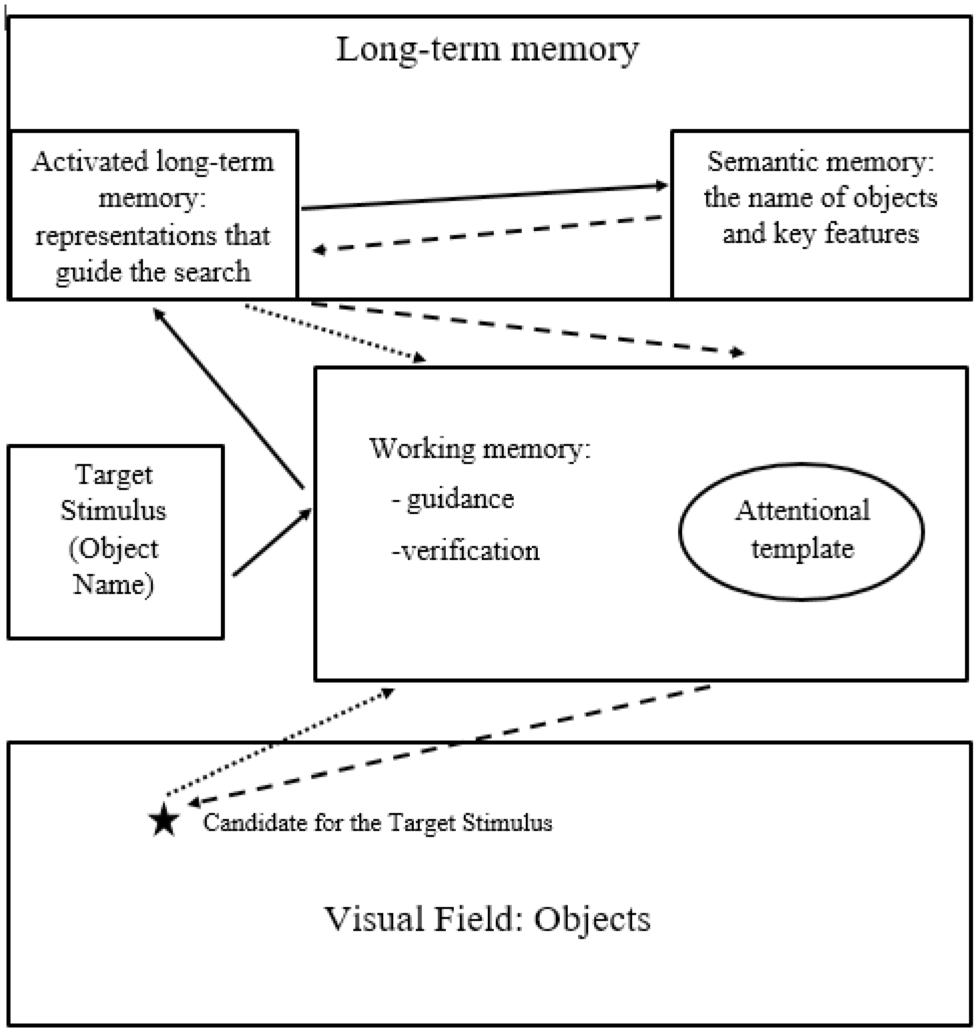
The process of categorical search occurs as follows. A verbally specified goal enters the activated long-term memory system. The activated long-term memory triggers the retrieval of the name of the target object in semantic memory, which, in turn, activates key features for that object (characteristic shape, color, typical spatial position). Subsequently, the combination of these features is loaded into working memory, which carries out the process of guidance - directing attention - to these features in the visual field using an attentional template. The term "attention template" was previously proposed to denote representations in working memory that guide the visual search process (see, e.g., Carlisle, Arita, Pardo, & Woodman, 2011; Desimone and Duncan, 1995; Bundesen, Haberkost, & Kyllingsbaek, 2005), and is essentially analogous to the term "guiding template" proposed by J. Wolfe. In our view, the term "attention template" is more suitable than "guiding template" as it emphasizes the role of attention in transferring representations from ALTM to WM.

The number of features guiding the guidance process depends on how clear the representation of the target stimulus is. The clarity of the representation will primarily depend on two factors: the level of the category at which the target stimulus is specified (basic, superordinate, or subordinate), as well as the breadth of the category (the number of objects within that category). Additionally, the specificity of the representation may be influenced by past experience: if the search goal is a specific object that has previously appeared in the visual field, its representation will be the most detailed.

Visual search is a two-stage process. Initially, attention is directed towards objects in the visual field that match a set of target features, and each of these objects starts to act as a "candidate for the target stimulus." The second stage of the visual search process involves verifying each of these "candidates" - verification. The verification process occurs in the working memory system and involves verbally naming the stimulus and comparing it to the verbal representation in ALTM. In this process, verification likely primarily relies on the function of the object and is associated with the activation of motor programs. If the "candidate for the target stimulus" passes verification, the search concludes with a response. If the "candidate" does not meet the criteria, attention is directed to the next "candidate." The graphical representation of the proposed model is shown in Table 1.

Table 1

Model of the representation building process in visual search. Solid lines represent the process of primary representation formation based on the target stimulus name, dashed lines represent the guidance process, and dotted lines represent the verification process



In this context, a particular interest arises when there can be more than one target stimulus in the visual field. We conducted a series of experimental studies on the phenomenon of "Subsequent Search Misses" (SSM) - a decrease in the success rate of detecting the second target stimulus after successfully finding the first target stimulus in the visual search paradigm (Adamo, Gereke, Shomstein, & Schmidt, 2021). In such studies, participants' task is to find all present target stimuli on the screen, which can be either one or two. Typically, the main finding is that the success rate of detecting the second target stimulus after finding the first one is lower compared to the success rate of detecting a single target stimulus. In a series of experiments, participants were required to search for target stimuli that could be perceptually similar (same color), categorically similar (belonging to the same category, e.g., pear and pineapple - both fruits), or could be similar both perceptually and categorically, or not similar either perceptually or categorically. It was found that the probability of finding the second target stimulus increased both with perceptual and categorical similarity, but categorical membership proved to be a stronger factor (Rubtsova & Gorbunova, 2021). It's worth noting that overall, the success rate of finding categorically defined stimuli (e.g., "find something sweet") was lower compared to the search for specific objects (e.g., "find a candy") (see, for example, (Rubtsova & Gorbunova, 2022). This result can be associated with either better guidance for specific objects or the fact that they exhibit greater perceptual differences between target stimuli and distractors. We believe that the perceptual similarity of objects influences the process of finding the second target stimulus at the guidance stage, while categorical similarity becomes significant at the verification stage.

Additionally, it is worth considering the situation when there is only one target stimulus in the visual field, but the search process is guided by multiple representations simultaneously. In one of our experiments, participants performed a hybrid search task – searching for a series of previously memorized objects on the screen (Angelgardt, Makarov, Gorbunova, 2021). These objects could belong either to basic-level categories ("apple") or superordinate-level categories ("fruits"). Participants were given 1 to 4 objects to memorize, and there could be 4, 8, 12, or 16 objects on the screen. The primary comparative measure was reaction time when searching for stimuli from basic or superordinate categories, with the expectation that, due to the category advantage effect, it would be shorter in the first condition. However, upon analyzing the data, no significant differences were found when comparing the search for objects from basic or superordinate categories. One possible reason for this could be the "overlap" in the fixed reaction time of the guidance process – directing attention to the stimulus and the verification process – identifying the stimulus as the target. To separate these processes, we conducted the following experiment.

The design of the new experiment was practically identical, with the exception that eye movements were additionally recorded (Sapronov, Makarov, Gorbunova, in press). Consequently, besides analyzing behavioral data, a comparison of eye-tracking metrics was conducted under conditions of searching for a target stimulus defined by basic or superordinate categories. Two metrics were used for analysis: guidance time and verification time. Guidance time was calculated as the time from the beginning of the trial to fixation on the target stimulus, while verification time was the time from fixation on the target stimulus to the moment of pressing the response key. Guidance time was found to be shorter in the condition of searching for a stimulus defined by a basic category, which aligns with the results of experiments in classical visual search (Maxfield & Zelinsky, 2012). This result is likely associated with the creation of a more precise guidance when searching for an object defined by a basic-level category. Objects within the same basic category (as opposed to objects in the same superordinate category) possess more specific features and a greater number of distinguishing characteristics from other categories. For example, the category "apples" would provide a clearer guidance for locating a stimulus compared to the category "fruits." Thanks to a clearer guidance in the search for basic categories, a smaller number of objects become "relevant" in the visual field, resulting in a faster actual process of locating the target stimulus.

A separate question is how the process of guidance is implemented in hybrid search since there are multiple representations of the target stimulus in this case. We assume that initially the search is directed towards one of the representations (most likely the first one remembered). Subsequently, a series of consecutive fixations on objects corresponding to this template occurs, and if each of the objects does not match the template, it is sequentially compared with the other representations.

At the same time, the verification time in the hybrid search paradigm remains the same for objects of both the basic and superordinate categories, while in the study of classical visual search (Maxfield & Zelinsky, 2012), there was an advantage in verification for basic-level categories. During the verification stage, the perceptual system needs to make a decision about whether the fixated stimulus is the target (whether the object belongs to the list of pre-memorized categories). It would be logical to assume that in the process of hybrid search, this process occurs sequentially in several stages. According to our data, verification time in hybrid search depends on the number of categories to be memorized, meaning that the fixated stimulus is likely to be matched with each of the pre-memorized categories in order, while in classical visual search, by definition, only one such comparison occurs.

Of particular interest is also the role of functional knowledge in the formation of object representations and their categorization. By functional knowledge, we mean the understanding of the function that a particular object can perform. This term is closely related to the concept of affordance – the potential way of interacting with an object (Osiurak, Rossetti, & Badets, 2017). This issue becomes especially important since verification, according to our model and in line with Zelinsky's views, is based precisely on the function of the object and is associated with the activation of motor programs. A significant amount of research indicates that functional knowledge about an object affects its processing. For example, there is the widely known "compatibility effect" – the congruence of an object's position and the human's action: when the object is positioned in accordance with the actions performed by the person, its processing speed increases (see e.g., Borghi, Bonfiglioli, Ricciardelli, Rubichi, & Nicoletti, 2007). However, this effect is not always replicated, leading to doubts about the universality of this phenomenon. For instance, in our recent study, participants performed a "pinching" or "grasping" hand movement, while simultaneously conducting object search in the miss-and-continue paradigm (Anufrieva, Gorbunova, 2022). The hand movements could be either congruent or incongruent to the target stimulus. No congruence effect was found: participants solved the task equally effectively regardless of whether the hand movement was "suitable" for the target stimulus. It's worth noting that the results might be related to the fact that the movement was performed by the non-dominant hand, as well as the possibility of concurrently launching irrelevant programs. However, such findings at least cast doubt on the stability of the congruence effect.

The task of categorization level assignment in the search task does not happen automatically but can be flexibly adapted depending on the context and the task at hand. For instance, in one of the studies employing the classical visual search paradigm, an intra-group design was used, where participants were tasked with searching for basic and superordinate categories, with objects corresponding to these categories being identical (Angelgardt, Anufrieva, Sapronov, & Gorbunova, 2024). Event-related potentials were recorded, and the CDA and N2PC components were analyzed, traditionally associated with guidance and the formation of attention templates in working memory. During the analysis, these components were observed, but differences in their amplitude were not found, and behavioral data were nearly identical when searching for basic and superordinate categories. The obtained results are likely related to the characteristics of the intra-group design used in this study: participants initially underwent a series of searches for superordinate categories and then basic ones (or vice versa), possibly implicitly learning to search for specific objects. Consequently, the task of searching for an object of a certain category was reduced to finding this stimulus based on perceptual features.

Conclusion

As cognitive psychology continues to evolve, increasing attention is being given to the ecological validity of research and the role of motor programs in cognitive processes.

Visual search studies are no exception: instead of simple geometric stimuli, experiments increasingly use real-world objects, and responses are made using methods more closely aligned with the real world, rather than keyboard presses.

The modification of visual search methodologies reflects the development of theoretical understandings of attention in this context. One of the most contemporary models of visual search is J. M. Wolfe's guided search model. The latest version of this model aligns well with a wealth of empirical data, but it does not provide a detailed account of the process of constructing representations in categorical search tasks, where the goal is to find an object by its name; precisely the types of tasks encountered frequently in real life.

We believe that in visual search, the leading role is played by the working memory system, which compares representations from the activated long-term memory system with representations of stimuli in the visual field. We consider categorical visual search as a two-stage process: first, attention directs the selection of a set of objects, and then these objects are checked for correspondence to the attention template. The verification process involves verbal naming of stimuli and is based on the activation of motor programs.

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Conflict of Interest information

The author has no conflicts of interest to declare.