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Neural Dynamics of Categorical Representations Used for Visual Search

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NEURAL DYNAMICS OF CATEGORICAL REPRESENTATIONS USED FOR VISUAL SEARCH

by

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ABSTRACT

Decades of visual attention research have predominantly used pictorial search paradigms that cue participants with the exact perceptual details of the target. However, in everyday life, people often search for categories rather than specific items (i.e., any pen rather than a specific pen). To study visual attention in a more realistic context, researchers can use categorical search paradigms that cue participants with text indicating the target category. In these instances, one must rely on long-term memory to retrieve categorical features of the target. Both experiments in this study were a reanalysis of experiments previously designed and collected by Schmidt and colleagues at Stony Brook University. In Experiment One, participants completed a pictorial or categorical search. Eye movements were used to assess search performance and electrophysiological data were assessed in response to the target cue and RI before search to evaluate the encoding and maintenance of the target. Although participants in the categorical condition were slower and exhibited weaker guidance, as measured by initial saccade direction (to the target, strong; to a distractor, weak), no differences in power or synchronous activity were observed when compared across target cue types. However, when the data were separated by guidance (strong or weak), categorical cues produced significantly more frontal-posterior theta synchrony before good guidance trials compared to bad guidance trials. In Experiment Two, participants were given categorical and specific text cues (i.e., the text always corresponded to a single target item). Specific text cues were expected to behave similarly to pictorial cues because participants knew the exact target features. Whereas specific text cues resulted in superior search performance across several measures, minimal neural differences were observed. The results from Experiment One implicate frontal-posterior theta synchrony as a potential neural marker of categorical information used to direct attention during visual.

To my husband, to my son. Everything I do, I do for you two.

APTTMH.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CCFs:	Category-Consistent Features
CDA:	Contralateral Delay Activity
EEG:	Electroencephalogram/Electroencephalography
ERP:	Event-related potential
ISD:	Initial saccade direction
ISPC:	Intersite phase clustering
LTM:	Long-term memory
MS:	Milliseconds
PLI:	Phase-lag Index
RT:	Response time
RI:	Retention interval
SEM:	Standard error of the mean
VWM:	Visual working memory

CHAPTER ONE: INTRODUCTION

Attention is a key component of all cognitive processes, yet it is also one of the most difficult to define. In the simplest terms, attention is the mechanism used to selectively filter out unnecessary information and focus on a specific aspect of the environment. Sometimes attention is automatic: a brightly lit billboard on the side of a desolate highway seems to capture attention effortlessly. Sometimes attention is deliberate: methodically searching for your car keys before leaving the house. When it is automatic, an item's physical properties and/or saliency can capture attention. However, in the case of deliberate or selective attention, the target information used to search for a target and how it is represented in the brain have a large impact on search performance (Vickery et al., 2005; Bravo & Faird, 2009; Malcolm & Henderson, 2009; Hout & Goldinger, 2015).

To study selective visual attention, visual search paradigms are frequently used. In a typical search paradigm, participants are instructed to find a target, or targets, among several distractors. These paradigms can vary in many ways and engage various cognitive processes. Often visual search experiments show participants an image of a simple stimulus composed of a single, or very few features (an oriented line or a colored shape) just prior to the search display (i.e., a cue). Traditional models of search postulate that the perceptual information provided in the cue is encoded in an attentional template and maintained in visual working memory (VWM) to guide search (e.g., Bundesen, 1990; Bundesen et al., 2005). Several electrophysiological studies highlight the presence of contralateral delay activity (CDA), a slow wave parietal-occipital event-related potential (ERP) that indexes the amount of information in VWM (for review, see Luria et al., 2016). In a typical CDA search paradigm, the cue screen is bilateral with the target item(s) on one side and a perceptually equivalent but task-irrelevant item(s) on the other. The participant is instructed to covertly attend one side of the cue screen, indicating the target(s) for the upcoming search. Because of the contralateral organization of the visual system, the task-relevant cue is processed in the contralateral hemisphere of the brain (i.e., if the cue appears on the left, it is processed on the right side), and the task-irrelevant cue is processed in the ipsilateral hemisphere of the brain relative to the cued direction. The difference in activity between the contralateral and ipsilateral sides in the parietal-occipital areas is interpreted as the amount of information encoded and maintained in VWM. CDA amplitude increases with increasing memory load and reaches an asymptote at an individual's VWM capacity limit (Vogel & Machizawa, 2004; Woodman & Arita, 2011). Reasonably, one would assume more target information would lead to better search performance and, consequently, would expect a positive relationship between CDA and search performance. However, several studies have demonstrated a negative relationship between CDA amplitude and search performance; when target cue-related CDA decreases, search performance improves suggesting that the information directing attention is not strictly represented in VWM or may not be measurable with CDA. (Carlisle et al., 2011; Gunseli et al., 2014a; Gunseli et al., 2014b; Schmidt et al., 2014).

A limitation of using CDA as a marker of VWM utilization is the reliance on providing perceptually relevant information in the cue display. However, visual search in the real world often occurs without the benefit of a pictorial cue. To address this, researchers utilize categorical search paradigms in which participants are cued with text naming the target category for the upcoming search using real-world stimuli. These paradigms are more analogous to everyday searches in three critical ways. First, we typically search for more complex items instead of simple, single-feature items. Second, we are not given, nor need a pictorial representation of our search target. Lastly, we typically search for categories of complex items (e.g., any pen versus a specific pen). Unlike pictorial cues, categorical cues do not contain perceptually relevant information. Accordingly, the meaning of the text must be interpreted to retrieve features from long-term memory (LTM) that pertain to the target category. Although pictorial cues result in stronger search performance, categorical cues also result in relatively strong search performance and can rapidly direct spatial attention to the target, suggesting robust target representations (Yang & Zelinsky, 2009; Schmidt & Zelinsky, 2009; Ercolino et al., 2020; Phelps et al., 2022). While the behavioral characteristics of categorical search are well-researched, the neurophysiological indicators of categorical target representations used for visual search are virtually nonexistent. Because categorical cues do not provide task-relevant, perceptual information, traditional indicators of VWM, such as CDA, are not interpretable as it would be unclear if CDA were reflecting the maintenance of the text or the category indicated by the text. Consequently, alternatives must be investigated. Other neurophysiological studies suggest a more general mental representation may not reside in any specific brain region (as with VWM and CDA) but rather may be characterized by synchronous activity between brain regions (Stokes, 2015; Postle, 2016). Accordingly, this dissertation will attempt to establish if measures of synchrony between brain regions can provide better insight into categorical target representations that are used specifically for search.

CHAPTER TWO: LITERATURE REVIEW

At the broadest level, visual attention is deployed via bottom-up and top-down processes. Bottom-up attention depends on the contrast of stimulus properties such as color, motion, shape, and size (Found & Müller, 1996; Wolfe, 1998; Wolfe & Horowitz, 2017). In the previous example of a brightly lit billboard on a desolate highway, salience drives attention (i.e., local differences; Duncan & Humphreys, 1989; Itti & Koch, 2000). Saliency increases when the target and surrounding stimuli have different perceptual properties. In this case, the target seems to "pop-out," and attention is directed to it. The surrounding stimuli themselves also influence a target's saliency. The surrounding stimuli can either be homogeneous, leading to stronger attentional capture to the target, or heterogeneous, leading to weaker attentional capture to the target. In a search, attention can be directed toward a salient stimulus whether it is the target or not. When these salient properties correspond to the target (i.e., you are looking for a billboard for the next gas station), localization of the target is facilitated. When they do not, attentional control must be exerted to direct attention away from the salient, non-target object (Chen & Zelinsky, 2006).

Whereas bottom-up attention is stimulus-driven, top-down attention is goal-driven. When top-down mechanisms drive attention, explicit knowledge of the target is required. Top-down attention can be spatial-based and/or feature-based. Spatial-based attention can be facilitated when the likely location of the target is known (Posner, 1980; Neider & Zelinsky, 2006; Zelinsky & Schmidt, 2009). This is especially prevalent in real-world search as the target's semantic properties can indicate its probable location. For example, when looking for a jeep, one would tend to start searching on the ground. Conversely, when searching for a blimp, one would tend to start searching in the sky (Neider & Zelinsky, 2006). This suggests that semantic information and context can effectively limit the search space leading to a more efficient search.

Unlike spatial-based attention, feature-based attention relies on the perceptual features of the target and search display. It is hypothesized that target features are encoded and maintained within an attentional template located in VWM (Bundesen, 1990; Bundesen et al., 2005). With this information, feature-based attentional mechanisms can selectively enhance responses in the visual cortex corresponding to those specific features (Heinze et al., 1994; Desimone & Duncan, 1995; DiRusso et al., 2003; McAdams & Reid, 2004; Kelly et al., 2008). Biasing or up-weighting the relevant target features also helps filter out irrelevant features, thereby increasing the signal-to-noise ratio and making the target easier to find (Kastner & Ungerleider, 2000).

In almost all cases, bottom-up and top-down processes interact to affect our ability to localize targets (Desimone & Duncan, 1995). Classic theories of search, such as Feature Integration Theory (Treisman & Gelade, 1980), propose that search occurs in two stages: the preattentive stage and the selective attention stage. In the preattentive stage, all basic features (i.e., color, shape, size, etc.) within the visual field are rapidly processed in a parallel fashion. In the selective attention stage, an individual combines these features into perceptible objects. When the target features do not overlap with the distractor features, search can occur in parallel, within the preattentive stage. When target and distractor features overlap, the searcher proceeds to the second phase, where selective attention will serially process each object until the target is found.

Whereas Feature Integration Theory placed heavier weight on bottom-up processing, the Guided Search model (Wolfe et al., 1989; Wolfe, 1994) attempted to emphasize top-down control. In the Guided Search model, search is still divided into the preattentive and selective attention stages. However, the key difference in this model is that the features in the attentional template are more heavily weighted, and thus attention is guided, preferentially, to items with those matching features. Inherent to both models is the reliance on the perceptual information of both the target and the distractors. When searching for simple stimuli with limited features, perceptual information is all that is given and required to complete the task. These older models fail to account for additional sources of information, such as what can be derived from categorical or complex real-world objects. However, newer models are beginning to consider these things (see Wolfe, 2021).

Quantifying Search Performance

Much of the work examining search behavior has quantified the efficiency of search using search slopes which are calculated by dividing the change in response time (RT) to detect the target by the change in search set size. In theory, as the number of items in the search display increases, so should RTs as this would require additional time to process the additional items (i.e., serial search, Triesman & Gelade, 1980). However, in searches with strong guidance to the target, RTs do not change drastically as the number of distractors increases (i.e., there is a shallow rather than steep search slope). Although widely used, search slopes are a gross measure that does not consider the multiple cognitive processes occurring between search onset and the subsequent response.

Research has shown a strong association between eye movements and attention (Deubel & Schneider, 1996; Greene & Rayner, 2001; Henderson et al., 1989), leading to the widespread use of eye-tracking in visual search research. Eye-tracking allows researchers to parse RTs into separable search stages: preparation, navigation, and target verification (Castelhano et al., 2008; Malcolm & Henderson, 2009; Goldstein & Beck, 2018). In the preparation stage, the first saccade is programmed using information from the attentional template. This stage can be evaluated by looking at the amount of time between search onset and the first saccade or initial saccade latency. For example, when the preparation stage is successful, initial saccade latencies are longer, resulting in a more accurate first saccade (i.e., toward the target; Chen & Zelinsky, 2006).

The navigation stage is the amount of time between the start of the first saccade and the first fixation on the target. This stage's success depends on the success of the preparation stage and the ability to rapidly reject any fixated distractions. This stage can be assessed by examining several measures including the proportion of trials in which the first search saccade was directed to the target (Schmidt & Zelinsky, 2009; 2011), the average number of distractors fixated before the target (Schmidt & Zelinsky, 2009), and/or the amount of time from the end of the preparation stage to target fixation (scanning time; Castelhano et al., 2008; Malcolm & Henderson, 2009). However, this time-based measure is almost certainly influenced by distractor rejection time.

The target verification stage is when comparisons between the attentional template and the target are made; this is the time between the first fixation on the target and the identification of the target without any additional fixations on distractors. This could also be separated into the amount of time participants fixated on the target or time fixated on distractors (Ercolino et al., 2020). By separating RTs, researchers can assess how experimental manipulations independently affect search guidance, distractor rejection, and target verification.

Attentional Templates in Visual Working Memory

Because of the largely automatic nature of bottom-up attentional mechanisms, the ability to control top-down attentional mechanisms is of greater relevance to the study of selective visual attention. One method of examining the utility of the attentional template is a cued search. In a pictorially cued search, a picture of an upcoming search target is shown before the search display, providing the participant with the target's exact perceptual features. Many models of search are predicated on one’s ability to encode and maintain the perceptual features of the target in VWM (Bundesen, 1990; Desimone & Duncan, 1995; Bundesen et al., 2005)—for example, a more accurate (with respect to the target) attentional template results in stronger search performance. Using simple stimuli, search was faster and more accurate with a cue that matched the target exactly as opposed to a cue that slightly deviated from the target and even more so than a cue that moderately deviated from the target. (Vickery et al., 2005; Wolfe et al., 2004). This was also demonstrated with real-world objects; overall RTs, guidance (as measured by scan-path ratios), and verification were negatively affected by increased cue imprecision (Hout & Goldinger, 2015, experiments 1a-d).

There is substantial neurophysiological evidence for the encoding and maintenance of the attentional template in VWM. Early neurophysiological evidence of this account derived from single neuron recordings in nonhuman primate studies showed there is sustained neural firing in the inferior temporal cortex after the target cue and until the onset of the search display (i.e., the retention interval, RI; Chelazzi et al., 1993; Chelazzi et al., 1998). This was interpreted as active encoding and maintaining the attentional template. A similar effect can be observed in humans by measuring CDA. Specifically, CDA amplitude increases as the number of items held in VWM increases but becomes asymptotic when an individual observer has reached their VWM capacity limit (Vogel & Machizawa, 2004).

CDA also gives us great insight into the efficient and selective nature of VWM storage and utilization. Schmidt and colleagues (2014) found that CDA can be fluid and change over time. Trials in which the first search saccade went to the target (strong search guidance) resulted in a rapid decrease in CDA shortly before search onset. In contrast, trials in which the first search saccade went to a distractor (weak search guidance) resulted in CDA sustained until search onset. This may suggest that offloading target-related details outside of VWM may improve search. CDA amplitude can also be affected by an individual's ability to filter out irrelevant information; distracting stimuli were selectively stored in VWM by low-capacity individuals but not by high-capacity individuals (Vogel et al., 2005). Lastly, CDA is also sensitive to task demands; when expecting a difficult search, CDA amplitude was larger than when expecting an easy search (Schmidt & Zelinsky, 2017), suggesting that it changes with the expected context. Together, these findings demonstrate the flexibility of establishing and maintaining attentional templates in VWM.

Spectral Characteristics of the Attentional Template

More recent evidence suggests that persistent neural firing during RIs (e.g., CDA) is not the only type of activity indicative of the encoding and/or maintenance of working memory information (Stokes, 2015; Postle, 2016; van Driel et al., 2017; Nikolaev & Leeuwen, 2019). Instead, this type of information may be represented by synchronized, population-level electrical activity between local and long-range brain regions (Stokes, 2015; Postle, 2016). To examine this type of activity, the EEG signal must be decomposed via time-frequency analysis to extract frequency (the number of cycles per second, in Hertz, Hz), power (the magnitude of the signal), and instantaneous phase (the position of the signal at a single point in time) for all time points and all electrodes. Time-domain analyses, like ERPs, assess two-dimensional (time by amplitude) data, whereas time-frequency analyses allow for a three-dimensional (time by frequency by power) inspection of the data. In time-frequency analysis, frequencies are often examined in frequency bands: delta (0-4 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (30-above Hz).

An important frequency band related to attention and search is alpha. Alpha oscillations serve two critical roles in the brain; an increase in alpha power, or alpha enhancement, reflects inhibition of neuron populations, while a decrease in alpha power, or alpha suppression, reflects a release from inhibition (Klimesch, 2012). In posterior visual areas, alpha enhancement increases inhibition, suppressing neurons that process task-irrelevant features. Conversely, alpha suppression decreases inhibition, thereby enhancing the excitability of neurons that process task-relevant features. The clearest example of this relationship between alpha enhancement and suppression can be observed in paradigms used to assess CDA; alpha suppression is present in the contralateral (relative to the cue, task-relevant) hemisphere and alpha enhancement is present in the ipsilateral (or the to-be-ignored) hemisphere consistent with the enhancement of attended information and suppression of task-irrelevant information (Medendorp et al., 2007; van Dijk et al., 2010; Reinhart & Woodman, 2014; de Vries et al., 2017; van Driel et al., 2017). Although CDA and lateralized alpha suppression may seem to reflect the same VWM mechanisms, there is evidence that they are dissociable as alpha power is sustained beyond the RI, suggesting alpha power modulations are necessary for top-down control over perception during visual search (Fukuda et al., 2015; Fukuda et al., 2016).

Although not explicitly related to visual search, Theta (3 to 7 Hz) has been implicated in several working memory and episodic memory-related processes. For example, theta power increases with memory load (Gevins et al., 1997; Gevins et al., 1998; Gevins & Smith, 2000) and is thought to be indicative of encoding and maintenance of working memory information (Klimesch, 1999). In fact, theta enhancement is critical to encoding WM representations and predicts later episodic memory performance (Klimesch et al., 1996; Klimesch et al., 1997c). Importantly, theta power in the parietal areas seems to be more related to the early processing and encoding of episodic memory. In contrast, theta in the frontal regions seems to be related to maintaining that information for top-down control processes (Klimesch et al., 2008). Although these studies did not use a visual search task, one might argue that a cue can be considered an episodic memory as it is a memory for an event, or in this case, an image. Thus, theta may play a role in encoding and retrieving the visual information provided in a cue.

In addition to examining power, phase in specific frequency bands can be used to determine if brain regions exhibit synchronized activity (Lachaux et al., 1999; Cohen, 2015). Specifically, alpha and theta synchrony have been implicated in several studies involving attention and memory. Alpha phase synchrony between frontal and posterior seems to reflect mechanisms that allow frontal regions to exert top-down control over visual areas via inhibition or excitation (see reviews, Engel et al., 2001; Siegel et al., 2012; Klimesch, 2012). Furthermore, frontal-posterior alpha synchrony increases with memory load (Palva et al., 2010; Crespo-Garcia et al., 2013) and task difficulty (van Driel et al., 2017).

Theta phase synchrony has been associated with various working memory processes. Some studies have implicated frontal-posterior theta with encoding during general working memory tasks (Sauseng et al., 2004), whereas others have implicated it during retrieval (Sauseng et al., 2005; Summerfield & Mangels, 2005). Frontal-posterior theta synchrony was also observed during a RI before participants were asked to draw a previously previewed item from memory (Sarnthein et al., 1998). Sauseng and colleagues (2004) found larger frontal-posterior theta synchrony when participants had to retrieve two previously encoded images and mentally compare them relative to recalling a single encoded image. This suggests that theta reflects either executive control functions or an increased memory load. Theta synchrony was also larger when maintaining verbal and spatial information in WM relative to either separately, suggesting a binding mechanism for WM representations (frontal-temporal, Wu et al., 2007). This was also observed when words were bound with font color (frontal-posterior, Summerfield & Mangels, 2005).

Although some studies implicate alpha in attentional processes (Palva & Palva, 2010; de Vries et al., 2017; van Driel et al., 2017) and theta in memory-related processes (Sarnthein et al., 1998, Sauseng et al., 2004; Summerfield & Mangels, 2005) it is important to note that the literature is mixed; other studies link theta to attention-like mechanisms (Sauseng et al., 2005) and alpha to memory (Sauseng et al., 2005; Palva et al., 2010; Crespo-Garcia et al., 2013; Kwon et al., 2015). This is not surprising because of the close relationship between attention and memory that is difficult to disentangle. Moreover, the attentional template requires attention and memory mechanisms (see Olivers et al., 2011). Regardless, it is clear that alpha and theta synchrony are certainly related to both mechanisms.

The most convincing evidence linking alpha to attention in the context of search was found in van Driel et al. (2017). This study found alpha synchrony between frontal and parietal sites was stronger when preparing for search relative to simple recognition. Because search requires attention-directing mechanisms and a simple recognition task only requires memory, this would suggest frontal-posterior alpha synchrony plays a role in the ability to direct attention during search when competing visual information is present in a search display. Unfortunately, none of the studies concerning theta synchrony were directly related to search, making it unclear if theta would more likely be related to attention or memory in the context of search.

Lastly, synchrony in the beta (18-24 Hz) and gamma-band (30-40 Hz) between frontal and poster areas during the VWM RI was also related to VWM load (Palva et al., 2010). Specifically, local synchrony (between neighboring scalp locations) in the visual areas was dominated by beta and gamma frequency range activity. This is consistent with other findings implicating gamma in the perceptual binding of features (Keil et al., 2001; Engel & Singer, 2001).

Attentional Templates Derived from Long-Term Memory

In pictorial search, participants, to some degree, encode and maintain the perceptual information provided in the cue in preparation for the upcoming search. Conversely, in categorical search, in which the participant is cued with a word that indicates the category of the target item (e.g., the word “mug” instead of a picture of a specific mug), the information used and how it is represented in the brain is largely unknown. In this case, the cue lacks relevant perceptual information. Without this information, the assumption is that one must rely on LTM to create an attentional template of the target to aid search (Schmidt & Zelinsky, 2009). Despite the lack of perceptual information, categorical cues can still rapidly guide attention to a target (Wolfe et al., 2004; Yang & Zelinsky, 2009; Schmidt & Zelinsky, 2009; Maxfield & Zelinsky, 2012; Maxfield et al., 2014, Ercolino et al., 2020).

The information provided in a categorical cue can vary greatly. Like pictorial cues, more precise descriptions result in better search performance (i.e., brown boots versus footwear; Schmidt & Zelinsky 2009). Categories can also be defined on a superordinate, basic, or subordinate level which can inherently provide more or less information (Rosch et al., 1976). A subordinate categorical cue (i.e., police car), which provides more categorical information, yields the best advantage for guiding attention to the target, but a basic cue (i.e., car), which provides less categorical information, yields the best advantage when verifying the target (Maxfield & Zelinsky 2012).

Moreover, categorical typicality also matters (Maxfield et al., 2012; Robbins & Hout, 2015). As the target typicality of basic level cues increased, guidance improved, and verification time decreased (Maxfield et al., 2012). Robbins and Hout (2015) examined how the specificity of a categorical cue interacts with typicality when distractors are from the same or different basic-level categories. They found that search guidance and verification time improved as typicality increased, even in the presence of distractors from the same basic-level category. The interpretation of these results suggests categorical attentional templates are constructed with features typical of a given category.

To quantify features inherent to specific categories, Yu and colleagues (2016) used computer vision techniques to capture category-consistent features (CCFs; features consistent throughout a category) from 4,800 images across many categories at the superordinate, basic, and superordinate levels. Once the model was trained to extract CCFs, it predicted where eye movements would be directed in a search display based on eye movement behavior from real participants during a categorical search. The CCFs predicted a subordinate-level advantage when guiding attention to the target and a basic-level advantage when verifying the target. As the categorical hierarchy decreased (superordinate to subordinate), the number of CCFs increased. Accordingly, a subordinate categorical cue provides more features to construct a more robust attentional template to assist guidance. Conversely, when verifying the target, the abundance of CCFs with a subordinate cue makes the stimuli less distinguishable from other stimuli from the same basic level category, which will necessarily contain some feature overlap with the target category. It is important to note that this basic-level advantage exists when subordinate cues designate a target among distractors from the same basic-level category. In the absence of these target similar distractors, the increased number of CCFs would likely aid verification as well.

To test the utility of CCFs in constructing categorical attentional templates, Hout and co-authors (2017) hypothesized that more visually consistent categories would yield a more precise template, resulting in stronger search performance. In a series of experiments, they compared search performance between “societally important” vehicles (i.e., ambulances, police cars, etc.), which, by design, are more visually consistent (more CCFs), and civilian vehicles, which are considerably less visually consistent (fewer CCFs). Categorical search guidance was stronger for “societally important” vehicles relative to civilian vehicles, and pictorial search verification was slower for “societally important” vehicles in the presence of distractors from the same category relative to civilian vehicles. These studies further suggest categorical attentional templates are likely constructed with features most consistent with a given category.

Although categorical attentional templates have been studied behaviorally and with oculomotor measures, neurophysiological studies examining the retrieval and maintenance of categorical information are lacking. Unlike pictorial cues, categorical text cues do not offer any perceptual information that would be useful to maintain. Although CDA can be observed in response to the encoding and maintaining visually presented words before a search display of words (Rajsic et al., 2019), categorical search is very different. A categorical cue is only a prompt telling the observer what information to retrieve from LTM. Observing CDA in response to a word cue should, in theory, only reflect the encoding and maintenance of the perceptual features of the word itself. Other electrophysiological correlates of LTM have been mainly limited to memory encoding (see the difference-due-to-memory effect; Paller, 1990) or semantic processing (see N400; Weisbrod et al., 1999) unrelated to visual search. Functional magnetic resonance imaging (fMRI) studies demonstrate that visually processing categories of images or words occur in discrete clusters in the temporal cortex (Thompson-Schill et al., 1999; Leube et al., 2001). However, extracting categorical information from these areas for later attentional biasing certainly results in a different pattern of activity and likely recruits additional brain regions.

Repeating the identical pictorial target cue over several trials is one method to investigate the relationship between LTM and VWM utilization. In theory, by repeating the target several times, the target can be transferred to LTM (Carlisle et al., 2011; Gunseli et al., 2014a; Gunseli et al., 2014b; Goldstein & Beck, 2018). Goldstein and Beck (2018) used eye-tracking to directly compare how VWM and LTM templates affected the three stages of visual search: preparation, navigation, and verification. They found faster overall RTs with repeating targets; however, the difference was primarily driven by the preparation and navigation stages, suggesting that LTM representations result in faster template establishment and distractor rejection. Additionally, identical target repetition results in a decreased reliance on VWM as indicated by a reduction in CDA and a corresponding reduction in RTs (Carlisle et al., 2011; Gunseli et al., 2014a; Gunseli et al., 2014b). The interpretation provided in these studies suggests that over repetition, the perceptual information provided in the cue is no longer represented in VWM and is transferred to LTM. These studies also point to an early ERP component called the p170 as evidence of LTM utilization. However, the cited study conducted by Voss and colleagues (2010) highlighted the p170 in contextual and perceptual priming, not necessarily LTM representations or the maintenance of those representations. Therefore, the absence of CDA as evidence of LTM utilization seems to be implied rather than directly demonstrated. Whereas repeating targets clearly reduce the attentional template's reliance on VWM (as indicated by a decrease in CDA), it is unclear how informative this would be when examining a representation derived solely from memory, as is the case for categorical attentional templates (i.e., there is no reason why LTM retrieval would be lateralized in a way suitable for CDA). A neural marker that can directly index the activation and maintenance of a categorical attentional template derived from LTM is missing from the literature.

Spectral Characteristics of Categorical Templates

No work has specifically examined the spectral characteristics of categorical attentional templates. However, some work has examined the spectral characteristics of LTM traces such as semantic memory. Semantic memory is characterized as an individual’s general knowledge store containing concept-based memories. Accordingly, categorical information falls under the umbrella of semantic memory. Although categorical information can be considered a type of semantic memory, categorical attentional templates differ in several ways. Most importantly, semantic memory traces require access to the general knowledge store but do not require the attention-directing mechanisms necessary to guide search. Conversely, a categorical attentional template must include feature selection from the general knowledge store and be used by attentional mechanisms to exert top-down control over early visual areas that process the search display.

Although semantic memory and categorical attentional templates differ, perhaps certain findings observed in the semantic memory tasks can also be observed in categorical searches. Importantly, alpha suppression and theta power have been observed during semantic memory judgments. When words are semantically related (paw-dog), larger alpha suppression was observed in the left hemisphere's frontal and temporal areas compared to words semantically unrelated (pen-dog; Klimesch et al., 1997b). Larger alpha suppression also predicted better semantic memory performance (Klimesch et al., 1997a). Similarly, theta power increases in the frontocentral and frontoparietal areas in the left hemisphere when making semantic judgments between two words (congruent versus incongruent; Salisbury & Taylor, 2012) and also when reading words that have greater semantic meaning versus syntactic or function words (e.g., “dog” versus the word “but”; Bastiaansen et al., 2005). These findings implicate the left hemisphere and alpha/theta as important for semantic memory retrieval and/or processing.

Alpha synchronization is also important for encoding and memorizing auditorily presented words. In Schack et al. (2003), participants were presented with abstract (i.e., truth) and concrete nouns (i.e., chair). Results indicated that temporoparietal to frontal synchrony was more pronounced for abstract than concrete nouns. That suggests more communication between these areas when semantic complexity increases. Although this study used auditory stimuli, visual stimuli may result in a similar pattern of activity. For example, a text cue or real-world stimuli requires integrating the visual percepts and the corresponding semantic properties.

CHAPTER THREE: HYPOTHESIZED MODELS

Given the sparse neurophysiological research on categorical cues, this dissertation proposes a novel model depicting the neural dynamics of categorical attentional templates used for visual search. The first step in doing so was to propose a model for pictorial cues as there is a greater abundance of neurophysiological research on this topic. From those more established findings and findings from related literature, a model of categorical cues was put forth. Figure 1a outlines a hypothetical model for real-world pictorial cues and Figure 1b outlines a hypothetical model for categorical cues. Several analysis techniques were applied to previously collected data from Stony Brook University by Schmidt and colleagues to garner evidence for the models: manual and eye movement metrics, local power, phase synchrony, and brain-behavior analyses.

Pictorial Cue Model

When a participant is presented with a pictorial cue, visual information in the cue is first processed in the visual cortex and the perceptual information is extracted. From there, information is communicated to two places: directly to frontal areas for top-down attentional biasing (for reviews, see Soto et al., 2008; Woodman et al., 2013; Stokes, 2015) and temporal areas for object-recognition and CCF extraction (for reviews, see Miyashita, 1993; Gross, 1994). The information gained from object recognition and CCF extraction is then communicated to frontal areas to further contribute to top-down attentional biasing of early visual areas.

Categorical Cue Model

When presented with a categorical text cue, the visual information processing stream is necessarily different. Because the text cue does not provide any useful perceptual information, perceptual details are not utilized beyond word recognition. Instead, perceptual information is communicated to Wernicke's area in the parietal/temporal lobe, which has been implicated in written language comprehension (Bogen & Bogen, 1976). Once the meaning of the word is understood, CCFs should be extracted from the temporal cortex. CCFs are then communicated to the frontal areas which will later be used for top-down attentional biasing of early visual areas (i.e., later communication from frontal to posterior brain regions).

Model Comparisons

The models differ in two critical ways. First is the bi-directional flow of information between frontal and posterior areas in the pictorial cue model but not in the categorical cue model. Because the perceptual information in the pictorial cue is useful for the upcoming task, it can be directly communicated to frontal areas for top-down biasing. This is often thought to occur rapidly and is generally restricted to coarse low spatial frequency information (Fenske et al., 2006; Ercolino et al., 2020). Conversely, the perceptual information in a categorical text cue is not useful and must be interpreted first. This bi-directional communication with pictorial information should produce more robust synchronization between frontal and posterior areas relative to categorical cues. Second, categorical text cues will likely result in stronger reliance on temporal regions because the text must be interpreted, the word meaning extracted, and the corresponding categorical information must be retrieved. Real-world object pictorial cues result in object recognition and CCF extraction that may be used for top-down biasing but almost certainly to a lesser extent than categorical text cues. This is expected to result in stronger synchrony between temporal and posterior regions as well as temporal and frontal regions with categorical text cues relative to pictorial cues. To summarize, pictorial cues are expected to take two routes to frontal areas, one directly from posterior brain regions and another from temporal areas; this should result in stronger frontal-posterior synchrony. In contrast, categorical cues must feed primarily through temporal- regions. However, in both cases, frontal regions are expected to synchronize with posterior brain regions signifying top-down biasing of visual areas.

Model Caveats and Hypotheses

Caveats

There are three caveats to address in these models:

1. Because of the spatial imprecision of the EEG, strong claims regarding specific anatomical brain regions cannot be included in the model. Instead, electrodes will be divided into four general regions: frontal, left temporal, right temporal, and posterior.
2. Although the model suggests strict lateralization, it is likely that this will not be the case. For example, previous research suggests language processing seems largely specific to the left hemisphere (Bogen & Bogen, 1976) but this is not universal and can vary from person to person (Corballis, 2014; Riès et al., 2016). Furthermore, evidence suggests this information is transferred and represented inter-hemispherically (Palva et al., 2010; Binder, 2015).

3. All analyses conducted on the neural data were focused on the cue and RI to specifically assess the processing, encoding, and maintenance of the cue.

Hypotheses by Analysis

Five analysis methods were applied to the data: manual responses, eye movements, local power, synchrony, and brain-behavior. The hypotheses for the first two analyses (manual and eye movements) were based on previous findings whereas the last three (local power, synchrony, and brain-behavior) were based on previous findings and the hypothesized models. A summary of the hypotheses can be found in Table 1.

Manual Response and Eye Movements

Consistent with prior research, search performance is expected to be better following pictorial cues than categorical cues resulting in higher accuracy, faster RTs, stronger guidance, and faster verification times (Schmidt & Zelinsky, 2009; Ercolino et al., 2020; Phelps et al., 2022).

Power

The local power analysis focused on three brain regions within three frequency bands of interest: frontal theta, posterior lateral alpha, and posterior gamma. Frontal theta power was expected to be larger for pictorial cues relative to categorical cues because theta enhancement is indicative of encoding new episodic memory traces (Klimesch, 1999; 2012), and a pictorial cue should result in a stronger episodic memory trace. In alignment with previous literature (Medendorp et al., 2007; van Dijk et al., 2010; Reinhart & Woodman, 2014; de Vries et al., 2017; van Driel et al., 2017), alpha suppression is expected to be larger in the posterior electrodes contralateral to the cue relative to the posterior electrodes ipsilateral to the cue for both cue types. This lateralized posterior alpha suppression was expected to be larger with categorical cues relative to pictorial cues as alpha suppression has been shown to increase with semantic processing demands (Klimesch et al., 1997b; Klimesch et al., 1997a). Because gamma-band activity is indicative of feature binding (Keil et al., 2001; Engel & Singer, 2001), gamma in the posterior region was expected to be larger with pictorial cues early in the RI. If participants bind perceptual features extracted from the semantic information provided by the categorical cue, gamma would be larger later in the RI.

Synchrony

For the synchrony analysis, there were three interregional connections of interest, frontal-posterior, frontal-temporal, and posterior-temporal, within two frequency bands of interest, alpha and theta. Alpha and theta were chosen as they are related closely to attention (Palva & Palva, 2010; de Vries et al., 2017; van Driel et al., 2017) and memory (Sarnthein et al., 1998, Sauseng et al., 2004; Summerfield & Mangels, 2005), respectively. As the model hypothesizes, there will first be posterior to frontal communication as visual features are extracted from visual areas and relayed to frontal areas for top-down attentional biases. Second, frontal-posterior communication as top-down control exerts attentional biasing of the extracted visual features. This would result in stronger frontal-posterior synchrony with pictorial cues relative to categorical cues. Frontal-temporal synchrony was expected to be larger with categorical cues as there is a larger dependence on CCFs extracted from the temporal regions to provide frontal areas with information to exert top-down attentional biasing of early visual areas for search. Lastly, posterior-temporal synchrony was expected to be larger with categorical cues because categorical cues require language processing in addition to CCF extraction.

Brain-Behavior

For the brain-behavior analysis, the goal was to determine if there is a positive relationship between frontal-posterior synchrony and a metric of search guidance. As was mentioned previously, research has demonstrated that frontal-posterior alpha synchrony is related to attention (Palva & Palva, 2010; de Vries et al., 2017; van Driel et al., 2017) and frontal-posterior theta is related to memory (Sarnthein et al., 1998, Sauseng et al., 2004; Summerfield & Mangels, 2005). The exact perceptual information in a pictorial cue provides more information to exert top-down control over visual areas and arguably creates a stronger memory trace. Accordingly, the relationship between alpha and theta frontal-posterior synchrony and guidance is expected to be stronger for pictorial cues relative to categorical cues. Furthermore, stronger guidance should indicate a strong attentional template; thus, the relationship between alpha and theta frontal-posterior synchrony and guidance should be stronger in good than bad guidance trials. These findings would provide strong evidence that frontal-posterior alpha and theta synchrony is a neurophysiological marker of the attentional template.

Table 1. Hypotheses for Experiment One

Analysis	Pictorial Cue	Categorical Cue
Manual		
Accuracy	More	Less
RT	Faster	Slower
Eye Metrics		
Guidance	Stronger	Weaker
Verification Time	Faster	Slower
Power		
Frontal Theta	More	Less
Posterior Lateral Alpha	Less	More
Posterior Gamma	More early, less later	Less early, more later
Synchrony		
Frontal-Posterior	Stronger	Weaker
Frontal-Temporal	Weaker	Stronger
Posterior-Temporal	Weaker	Stronger
Brain-Behavior		
Frontal-Posterior/Guidance	Stronger	Weaker

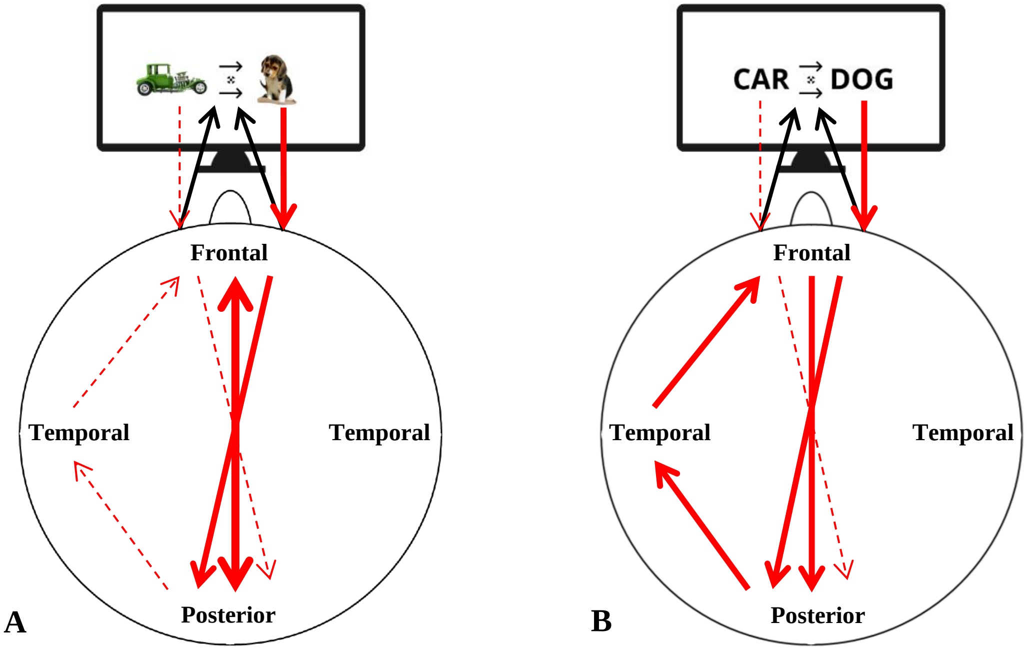


Figure 1. *Hypothetical Models. Dashed lines represent information transfer/processing occurring but to a lesser extent relative to the solid lines. A) Hypothetical model of information transfer/processing with pictorial cues. During the cue screen, participants are centrally fixated. Using peripheral vision and covert attention, participants will process the stimulus on the right side of the screen in the contralateral hemisphere. Perceptual information is extracted and transferred to frontal areas for top-down attentional biasing and to temporal areas for object recognition and CCF extraction. Any additional categorical information is transferred to frontal areas to contribute further to attentional biasing of posterior brain regions. B) Hypothetical model of information transfer/processing with categorical cues. The cue screen is processed the same as the previous model; however, perceptual information from the cue is not transferred directly to frontal areas but instead is transferred to temporal areas for language processing and CCF extraction. The categorical information is then transferred to frontal areas for top-down attentional biasing of early visual areas.*

CHAPTER FOUR: EXPERIMENT ONE

Experiment One was a reanalysis of an experiment designed and collected by Schmidt and colleagues at Stony Brook University. The portion of this experiment's pictorial cue condition was used in Schmidt et al. (2014, experiment 2) and Miuccio et al. (2022). The categorical text cue data has not been presented before but was also collected at Stony Brook University by Schmidt and colleagues.

Methods

Participants

Sixty-nine participants were recruited from Stony Brook University and were randomly assigned to one of two conditions: 31 in the pictorial cue condition and 38 in the categorical cue condition. 62% were female and the average age was 20.5 years old. Participants had normal or corrected-to-normal vision and were native English-speakers by self-report. Participants received course credit for completing the experiment. The Stony Brook University IRB approved the experimental protocol and participants gave informed consent prior to participation.

Design and Procedure

Participants were assigned to one of two conditions in which they were given a pictorial or categorical cue before a search task. In the pictorial cue condition, participants were cued with the exact pictorial representation of the target in the upcoming search. In the categorical cue condition, participants were cued with a categorical text cue indicating the target category in the upcoming search. The timing of the task, stimuli, and all experimental parameters were identical except for the cue screens.

Before the experiment began, participants completed a 13-point calibration and validation routine; the average error was less than .49°, and the maximum error was less than .99°. Participants were recalibrated after breaks and throughout the experiment as needed. Participants then completed eight practice trials to familiarize themselves with the task. At the beginning of each trial, participants were instructed to fixate the central fixation dot and press the "X" button on the game controller to start the trial. Any drift in the eye position since the last calibration was recorded. The central fixation dot was then replaced with a central "X" and an arrow above and below it (200 milliseconds, ms), pointing to the left or the right of the screen to indicate the side of the upcoming target cue. The arrows were then removed, and the "X" remained in the center of the screen for 400 ms. The cue screen was then displayed for 400 ms. The cue screen contained a centrally presented "X" and one real-world object or text cue to the right and one to the left of central fixation, each appearing 3.5° from the center of the screen. Participants were instructed to remain centrally fixated and attend to the item appearing on the cued side. The cue screen was followed by an RI of 1000 ms in which only a centrally presented "X" was displayed. If a blink or an eye movement greater than 0.75° occurred or the eye position deviated by more than 1.25° from central fixation during these time intervals, the trial was recycled (if it occurred before the cue) or terminated (if it occurred during the cue or RI). Finally, the search display presented four real-world objects arranged in a square 14.5° from central fixation. Participants were instructed to fixate on the stimulus and press the "X" button on the gamepad to identify the target. The eye tracker recorded the eye position at the time of response to verify if the participant was looking at the target (correct response) or a distractor (incorrect response). All stimuli were presented on a white background and each search display contained one target and three distractors. Target locations were balanced over screen locations. There were 400 test trials and all were 100% target present. See Figure 2 for the trial sequence.

Stimuli

Stimuli used for this experiment were obtained from the Hemera Photo Object database and other web sources. The cue and search items were each resized to an area of 1.35° (the aspect ratio was free to vary). The font size for the text cues was 35 in the Verdana font. Basic-level category labels were used for the categorical cue condition. Targets and distractors were repeated once throughout the experiment. Except for this single repetition, each target was from a unique basic-level category. Distractors were picked at random with the constraint that they did not come from the same category as the targets.

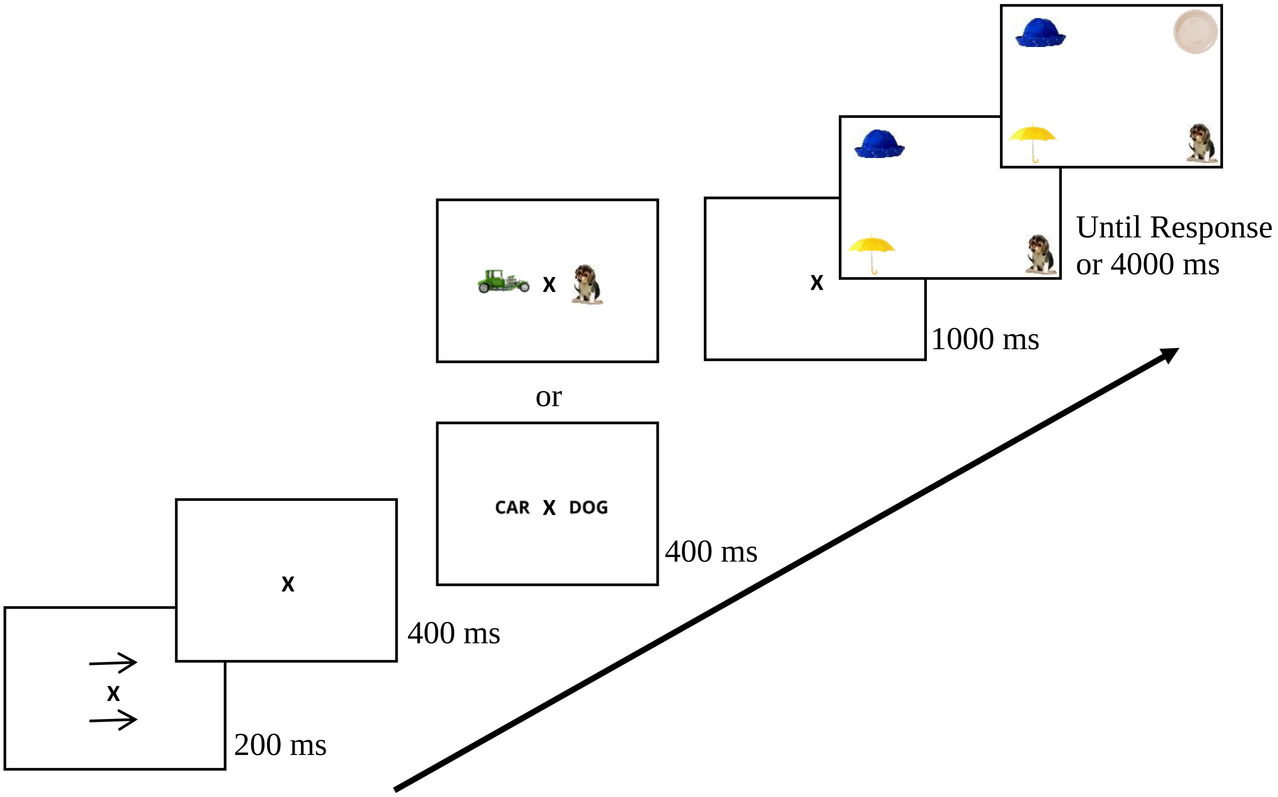


Figure 2. Trial sequence for Experiment 1. Participants were instructed to maintain central fixation until the appearance of the search display. First, participants were cued to the left or the right of the screen, indicating the side would contain the target cue. The cue was followed by a 1000 ms RI before the search display was presented. The search display was presented until a response was made but for no longer than 4000 ms. Note, stimuli in this figure are not drawn to scale.

Apparatus

The experiment was presented on a 22-inch LCD ViewSonic monitor (Model VX2268) at a screen resolution of 1680 x 1050 pixels and a refresh rate of 120 Hz. Eye movements were sampled at 1000 Hz using a desktop-mounted EyeLink 1000 in head-stabilized mode utilizing default saccade detection thresholds. Participants were seated with their chin on a chinrest, yielding an approximate eye-to-screen distance of 81 centimeters. The experiment was programmed and displayed with Experiment Builder version 1.10.165. Participants made manual responses with a Microsoft Sidewinder 1.0 gamepad controller.

Manual and Eye Metrics

Search performance was assessed using four criteria: search accuracy, RT, search guidance, and target verification time. Search guidance was defined as the proportion of trials in which the first search saccade greater than 2° was directed to the target. Target verification time is defined as the amount of time between the first fixation on the target and the manual response identifying the target (Castelhano et al., 2008; Goldstein & Beck, 2018). RT, guidance, and target verification were assessed on correct trials only.

EEG Data Recording

EEG data were recorded using 64 active Ag/AgCl electrodes in a BioSemi Active Two system utilizing a standard 10-20 configuration. Data were digitized at a 24-bit resolution and sampled at 512 Hz with a low pass fifth-order sinc filter with a -3- dB cutoff at 104 Hz. Two additional electrodes were placed on the left and right mastoids and were re-referenced offline. Four additional electrodes were placed around the eyes to monitor blinks and eye movements; two were placed one cm from the outer canthus of the left and right eye, and two were placed one cm above and below the right eye.

Data Preprocessing

Raw EEG data were preprocessed with Brain Vision Analyzer (BVA; Version 2.1.2.327). As is typical in EEG analysis procedures, artifact identification thresholds were adapted on a subject-by-subject basis (Luck, 2014). However, these general steps and criteria were followed.

The data were first down-sampled from 512 Hz to 256 Hz then filtered using a low cutoff of .5 Hz and a notch filter at 60 Hz. The data were initially segmented into full trials; 600 ms before cue onset to 5500 ms after cue onset. Artifact rejection criteria were as follows: voltage step exceeded 50 µv per ms, a voltage difference of 80 µvs within 150 ms, any amplitude less than -200 µv or more than 200 µv, and/or any activity less than .05 µv for 100 ms within a single trial. This procedure was applied to a smaller time interval, -600 ms to 1400 ms, relative to cue onset. Any trial with an artifact on any channel was discarded. If over 30% of trials were discarded, the participant's data were excluded from the experiment. In the pictorial condition, five participants were excluded and on average, 17% (minimum: 9%, maximum:27%) of trials were discarded. In the categorical condition, five participants were excluded and on average, 15% (minimum: 5%, maximum: 25%) of trials were discarded. This left 26 and 33 participants in the pictorial and categorical conditions, respectively. The data were also rearranged so that the left electrodes would always correspond to the ipsilateral side, and the right electrodes would always correspond to the contralateral side, relative to the cue, for ease of the analysis and visualization.

Time-Frequency Analysis

Procedures and parameters for the steps below were largely adapted from Cohen (2014) and van Driel and co-authors (2017).

Laplacian Transform

After the above preprocessing steps, BVA was also used to apply the Laplacian transformation (also known as the current source density, CSD), which serves as a spatial high-pass filter. This sharpens the scalp topography and transforms the EEG signal into a reference-free system by taking the distance-weighted derivative of nearby channels. Removing this activity reduces volume conduction (detecting a signal originating from a distance electrode and the signal from the recording electrode). The parameters for estimating the Laplacian were a 10^{th}-order Legendre polynomial and λ at 10^{-5}.

Morlet Wave Convolution

The data were then exported from BVA and imported into Matlab for the remaining steps. The segmented EEG time series were convolved with Morlet wavelets with frequencies from 1 to 50 Hz in 40 logarithmically spaced steps. Complex morlet wavelets were created by multiplying a complex sine wave ($e^{2i\pi ft}$, *i* is the imaginary operator, *f* is the frequency, and *t* is time) and a Gaussian ($e^{-t^2/2s^2}$, s is the full width at half maximum of the Gaussian, $s = \delta/2\pi f$). The full width at half maximum was set depending on δ, which is the number of cycles in the wavelet. The number of cycles in the wavelet is an important parameter in obtaining frequency and/or temporal precision. As the number of cycles in the wavelet increases, the Gaussian in the time domain widens and therefore decreases temporal precision. Conversely, increasing the number of cycles narrows the Gaussian in the frequency domain and thus increases frequency precision. The number of cycles in the wavelet varied between 3 and 12, logarithmically spaced, to maximize temporal and frequency precision. The Fast Fourier Transform was then applied to the EEG signal and the morlet wavelets and multiplied in the frequency domain. The product of that calculation was processed through an inverse Fast Fourier Transform. The power at each frequency and time point was the squared magnitude of the convolved complex signal (in Experiment Two, first separated by cue type) and averaged over trials. Power was baseline normalized using the following equation: dB Power = 10 X $\log_{10}$ (Power/Baseline Power). The baseline window was 500 to 300 ms before cue onset.

Synchrony

Every EEG signal has three characteristics: frequency, the speed of the signal, power, the strength of the signal, and phase, the position of the signal. The time-frequency analysis explored the frequency and the power characteristics of the data whereas the synchrony analysis explored the phase characteristics of the data. In phase-based synchrony analysis, the idea is to compare the position of the signal of two electrodes. This is referred to as the phase-angle difference. Several methods exist to quantify and interpret phase-angle differences, but intersite phase clustering (ISPC; Cohen, 2014) and the phase-lag index (PLI; Cohen, 2014) were used for this dissertation. It is important to note that ISPC is more sensitive to detecting synchrony but more susceptible to Type 1 errors while PLI is less sensitive to detecting synchrony but more susceptible to Type 2 errors (Cohen, 2015). Accordingly, Cohen (2015) suggests following up an ISPC analysis with a PLI analysis to cross-validate the results, thus, both will be presented below.

The ISPC between the two electrodes was calculated using the following formula:

$$ISPC = \left| n^{-1} \sum_{t=1}^{n} e^{i(\emptyset^{j}-\emptyset^{k})t}) \right|$$

Here, *n* is the trial, *i* is the imaginary operator, $\emptyset^{j}$ and $\emptyset^{k}$ are the phase of electrodes *j* and *k*, and *t* is time. The phase angle difference, $(\emptyset^{j}$- $\emptyset^{k})$, between two electrodes at each time point (*t*) is calculated and averaged over trials for all time points for each frequency. In simpler terms, this measures the average positional difference between two electrodes. If this difference remains consistent over many time points (i.e., strong intersite clustering of phase angle differences), it can be inferred that the signals are oscillating in synchrony with one another.

The PLI between two electrodes was calculated with the following formula:

$$PLI = \left| n^{-1} \sum_{t=1}^{n} sgn\left(Im\left[e^{i(\emptyset^{j} - \emptyset^{k})t} \right] \right) \right|$$

Here, *n* is the trial, *sgn* is the sign (positive or negative), *Im* is the function that extracts only the imaginary part of the complex number, *i* is the imaginary operator, $\emptyset^{j}$ and $\emptyset^{k}$ is the phase of electrode *j* and *k*, and *t* is time. In this formula, the phase angle difference, ($\emptyset^{j}$- $\emptyset^{k}$), at each time point (*t*), is converted into a complex vector and projected onto a complex plane. Next, the imaginary part and the sign of the complex vector are extracted for all time points and then averaged, and the absolute value is taken. This average is computed over trials for all time points for each frequency. For this measure, the main concern is whether the phase angle differences between electrodes fall above or below the real axis. Phase angle differences that fall on the real axis would be 0 or π, indicating no positional difference. These phase angle differences are ignored as they may indicate spurious synchrony caused by volume conduction artifacts. See Figure 3 for an example.

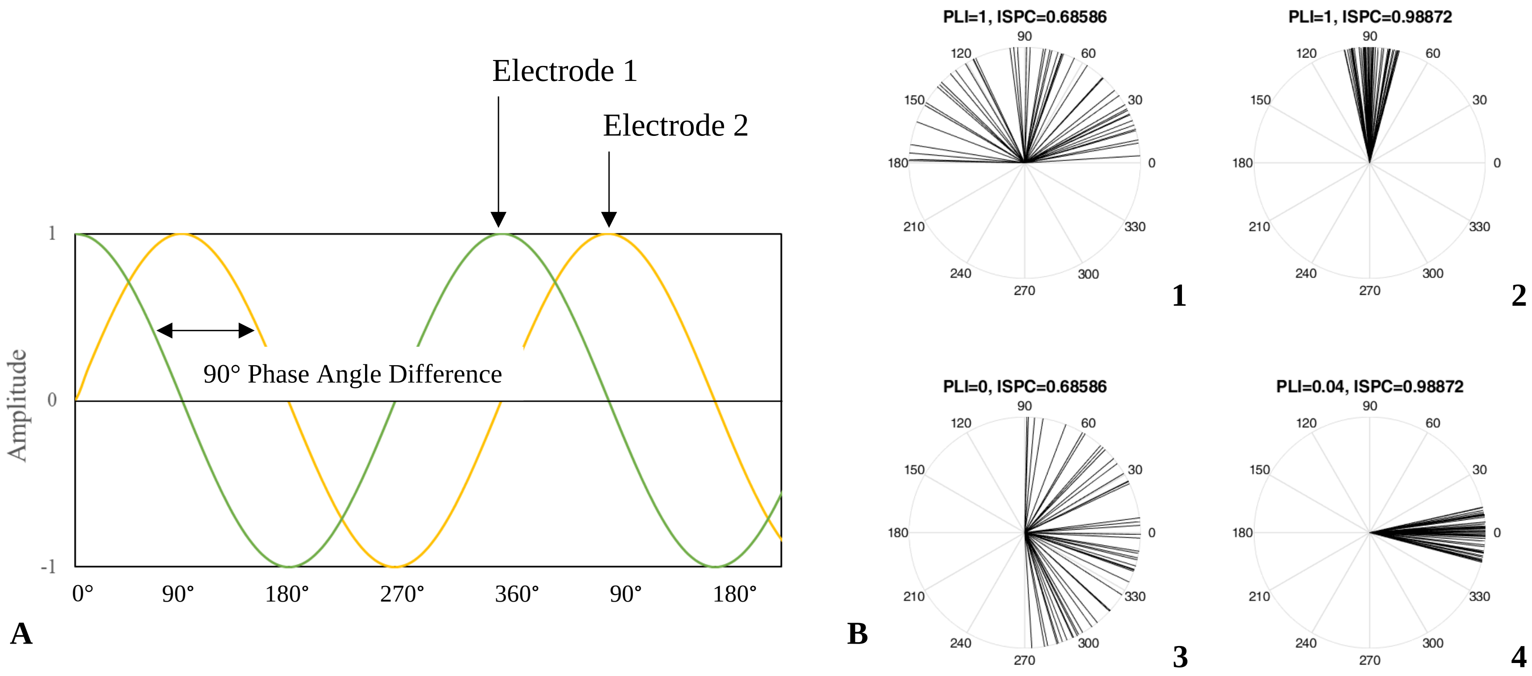


Figure 3. Phase Synchrony Example. A) Simulated sine waves from Electrode 1 and 2 with phase angle on the x-axis and amplitude on the y-axis. At every time point, the signal has an instantaneous phase angle value. Because these are two simulated, stationary signals, the phase angle difference between these two electrodes at all time points is 90°. In real data, the phase angle difference between two electrodes likely differs over time. B) Four polar plots, each with distributions of phase angle differences. B1/B3 and B2/B4 have identical distributions of phase angle differences. In B1 all of the phase angle differences are above the real axis (the perfect horizontal dashed line within the circle) resulting in a PLI of 1. In B3, however, the identical distribution has a PLI of 0. This is because exactly half of the phase angle differences fall above the real axis and the other half below. Conversely, the ISPC in B1 and B3 are the same because the clustering is the same, irrespective of the location of the phase angle differences on the polar plots. B2 and B4 depict the same concept with a tighter distribution of phase angle differences. In B2, all the phase angle differences are above the real axis resulting in a PLI of 1 and the tight clustering results in an ISPC of close to 1. In B4, approximately half of the phase angle differences are above and below the real axis, resulting in a PLI close to 0 whereas the identical distribution (to B2) results in the same ISPC (as B2). Figure 3B1-4 is from adapted Cohen (2015).

Brain-to-Behavior Relationship: Guidance and Frontal-Posterior Synchrony

To determine if frontal-posterior synchrony affects later search performance, the average ISPC and PLI of good guidance trials (trials in which the first search saccade was directed towards the target) and bad guidance trials (trials in which the first search saccade was directed towards a distractor) for each cue type was compared in a two (good guidance, bad guidance) by two (pictorial cue, categorical cue) mixed factor ANOVA.

Statistics

Manual (accuracy and RT) and eye movements (guidance and verification) metrics were assessed using independent samples t-tests comparing cue type (pictorial versus categorical). However, the time-frequency and synchrony analyses utilized non-parametric permutation testing. The first step in permutation testing is to combine participants into one group. Next, the participants are randomly assigned to a condition (in this case, one of two), and a test statistic is computed (in this case, a t-statistic). This will be repeated for 5,000 permutations, resulting in a null hypothesis, a Gaussian-like distribution of possible test statistics. This is an empirically derived chance-level that considers the variance in the given dataset to determine an unbiased estimate of the likelihood of a significant difference between conditions. After the participants are regrouped into the original conditions, the test statistic is computed and compared to the empirically derived null value to determine significance, specifically, a z-statistic: $Z = \frac{obs_t - exp_t}{std_{exp_t}}$, where obs_t is the observed test statistic (empirically derived null), exp_t is the expected test statistic, or the center of the distribution, and std_{exp_t} is the standard deviation of the distribution.

Lastly, the z-statistic is converted to a p-value (pixel-level, $p = .05$). This process is repeated for all time-frequency points. To correct for multiple comparisons, a cluster-based correction was applied. To do this, the permutation procedure is repeated, but this time, the goal is to count the number of pixels in the largest cluster of contiguous significant pixels in the time-frequency map for each of the 5,000 iterations. After that, a distribution of cluster sizes is created, and a threshold at the 95th percentile (i.e., the cluster-level p-value, $p = .05$) is established; any cluster larger than this threshold is considered significant. For significant clusters, the cluster-level p-value (i.e., the percentile) will be reported along with the highest Z-statistic and corresponding effect size, the median Z-statistic and median effect size, and the average Z-statistic and average effect size. The median and average Z-statistics and effect sizes were calculated over an approximated box that encapsulated the significant cluster, as suggested by Meyers et al. (2021). For tests that did not reveal any significant clusters, the cluster-level p-value (i.e., the percentile) of the largest cluster of significant pixels will be reported. For tests that did not reveal any significant pixels, the largest Z-statistic and corresponding p-value will be reported. All reported statistics correspond to the difference maps in the power and synchrony analyses.

Results

Accuracy and Response Time

Inconsistent with the hypotheses, independent samples t-tests showed no difference in accuracy, $t\ (57) = .04$, $p = .97$, $d = .10$, although high accuracy found in both conditions likely resulted in a ceiling effect. Consistent with the hypotheses, participants responded faster in the pictorial cue relative to the categorical cue condition, *t* (57) = -7.85, *p* < .001, *d* = -2.06. The means and standard deviations can be found in Table 2.

Eye Metrics

Consistent with the hypotheses, both eye metrics showed stronger performance in the pictorial cue condition compared to the categorical cue condition (guidance/ISD, *t* (57) = 13.39, *p* < .001, *d* = 3.51, verification time, *t* (57) = -4.92, *p* < .001, *d* = -1.29). The means and standard deviations can be found in Table 2.

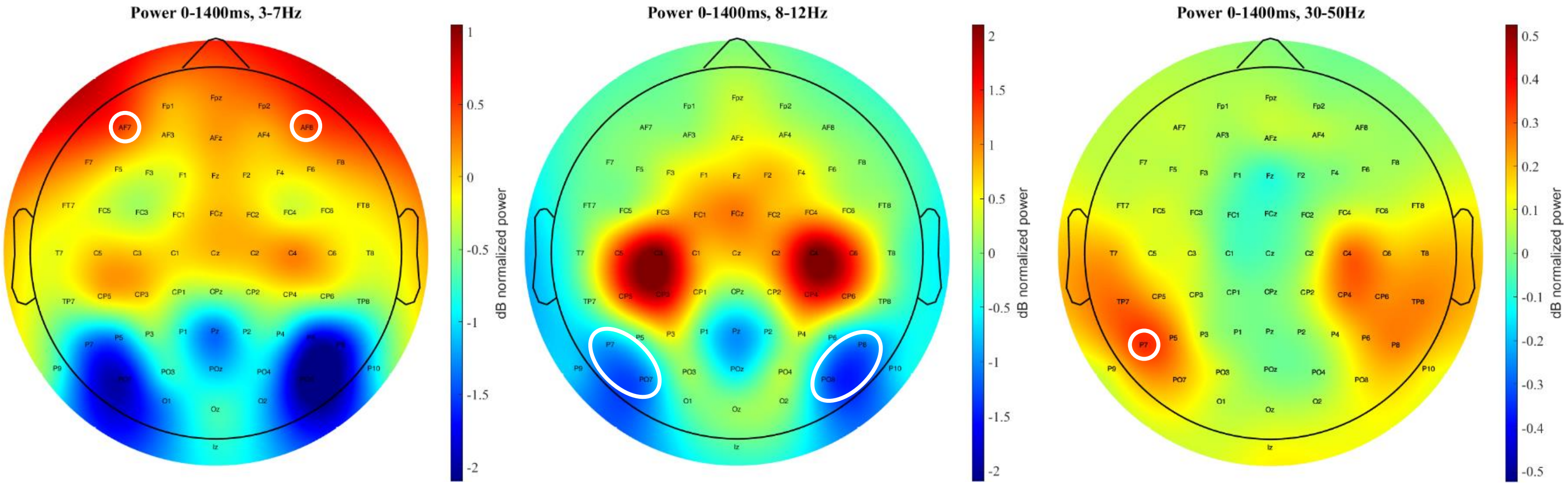
Table 2. Means and Standard Deviations for Experiment 1.

Metric	Pictorial Cues	Categorical Cues
Accuracy (%)	99 (1)	99 (2)
RT (ms)	889 (201)	1261 (163)
Initial Saccade Direction (%)	71 (9)	42 (7)
Verification Time (ms)	458 (172)	652 (130)

Note. Standard deviations are in parentheses.

Power Analysis

Local power differences were compared between cue types at various electrode sites. To choose the electrode(s), a topographical map was created displaying the average power across the cue and RI (0 to 1400 ms) within the respective frequency ranges (theta: 3 to 7 Hz; alpha: 8 to 12 Hz; gamma: 30 to 50 Hz) at each electrode collapsed across cue type. The peak of power within each respective area (theta-frontal, alpha-lateral/posterior, gamma-posterior) was selected for each analysis. Collapsing over conditions produces an unbiased selection of electrodes at the peak of each respective effect to compare across conditions. See Figure 4.



Theta Alpha Gamma

Figure 4. Total Power Maps for Experiment 1. Each map shows the total dB normalized power, averaged over all participants (both conditions), and time (cue and RI) and frequency (theta, alpha, and gamma) specified above each topographical map. White circles on each map indicate the presumed peak of power at the given frequency band during the specified time interval.

Theta

The peak of power was observed at AF7 and AF8. Frontal theta power was expected to be larger for pictorial cues than categorical cues. However, there was no significant difference in frontal theta power between pictorial cues and categorical cues (largest nonsignificant pixel, cue: $Z = -1.39$, $p = .08$, RI: $Z = -1.33$, $p = .09$). See Figure 5.

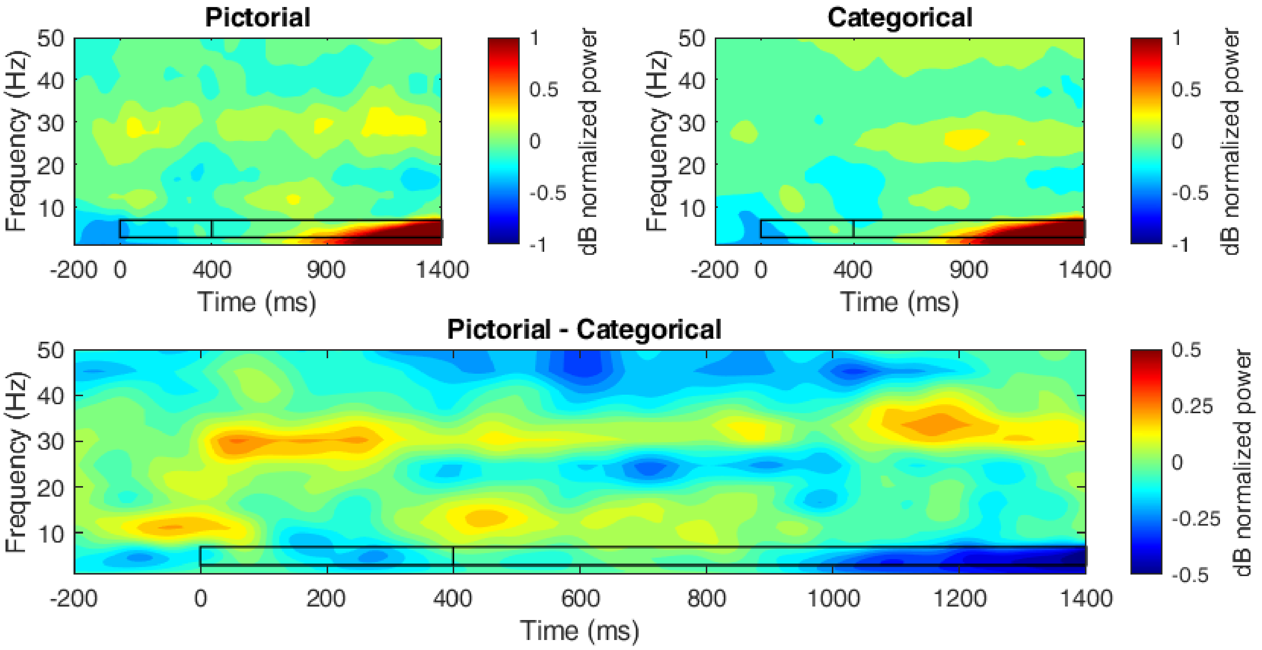


Figure 5. Theta Power for Experiment 1. Average power dB normalized power at AF7 and AF8 in the pictorial cue condition (top left), in the categorical cue condition (top right), and the average difference between the pictorial and categorical cue conditions (bottom). The boxes drawn on each plot indicate the cue and RI in the theta frequency band, respectively.

Alpha

The peak of lateralized posterior alpha suppression was observed at P7/8 and PO7/8. Alpha suppression was expected to be larger in the electrodes contralateral to the cue relative to the ipsilateral electrodes with both cue types and the lateralized effect was expected to be larger with categorical cues relative to pictorial cues. Partially consistent with the first hypothesis, there was a significant difference between contralateral and ipsilateral posterior alpha suppression in which there was more alpha suppression in the contralateral electrodes during the pictorial cues (*p* = .04, median *Z* = -2.16 median *d* = -.68, average *Z* = -2.12, average *d* = -.67, largest *Z* = -2.97, largest *d* = -.89). This was not observed during the RI (largest nonsignificant cluster, *p* = .27) after pictorial cues, nor was this observed during or after categorical cues (cue: largest nonsignificant cluster, *p* = .38; RI: largest nonsignificant pixel, *Z* = -1.56, *p* = .12). Furthermore, there was no difference in the posterior lateralized effect between pictorial and categorical cues in the cue (largest nonsignificant cluster, *p* = .12) or RI (largest nonsignificant cluster, *p* = .44). See Figure 6.

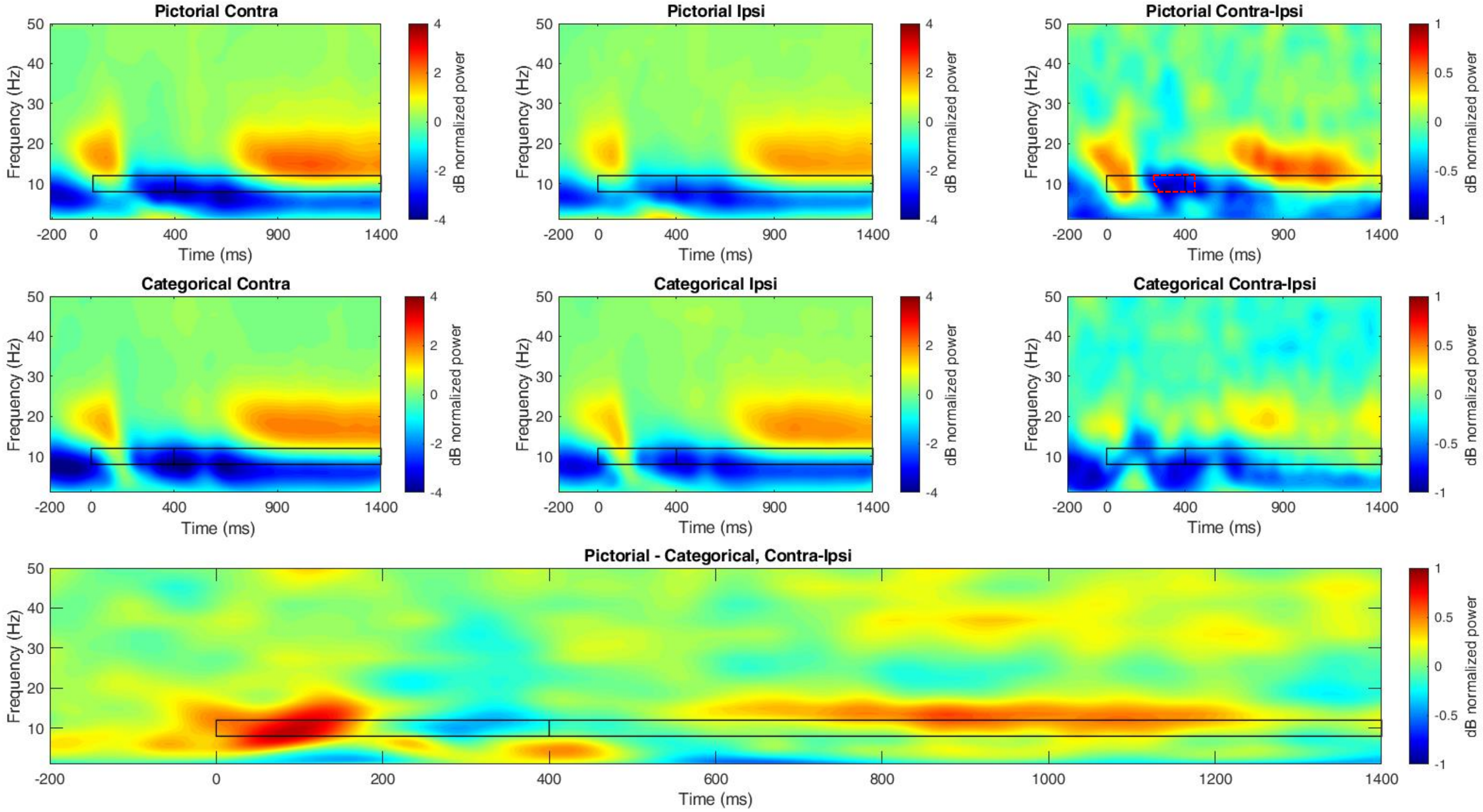


Figure 6. Alpha Power for Experiment 1. Plots in the top row are average dB normalized power in the pictorial cue condition, and plots in the middle row are power in the categorical cue condition. The data were rearranged so the left electrodes were ipsilateral, and the right electrodes were contralateral, relative to the cue. Contra plots are averaged from the P8 and PO8 electrodes, and Ipsi plots are from the P7 and PO7 electrodes. Contra-Ipsi plots are a subtraction of the average of Contra plots and Ipsi plots. The bottom row is a subtraction of the Pictorial and Categorical Contra-Ipsi plots. The boxes drawn on each plot indicate the cue and RI in the alpha frequency band, respectively. The dotted red line in the Pictorial Contra-Ipsi plot signifies the significant cluster.

Gamma

The peak activity for gamma was at P7. Posterior gamma was expected to be larger with pictorial cues early in the RI but larger with categorical cues later in the RI. However, there were no significant differences between the two cues in any time interval (largest nonsignificant pixel, cue: $Z = -1.26$, $p = .21$, early RI: $Z = -1.15$, $p = .25$, late RI: $Z = -1.17$, $p = .24$). See Figure 7.

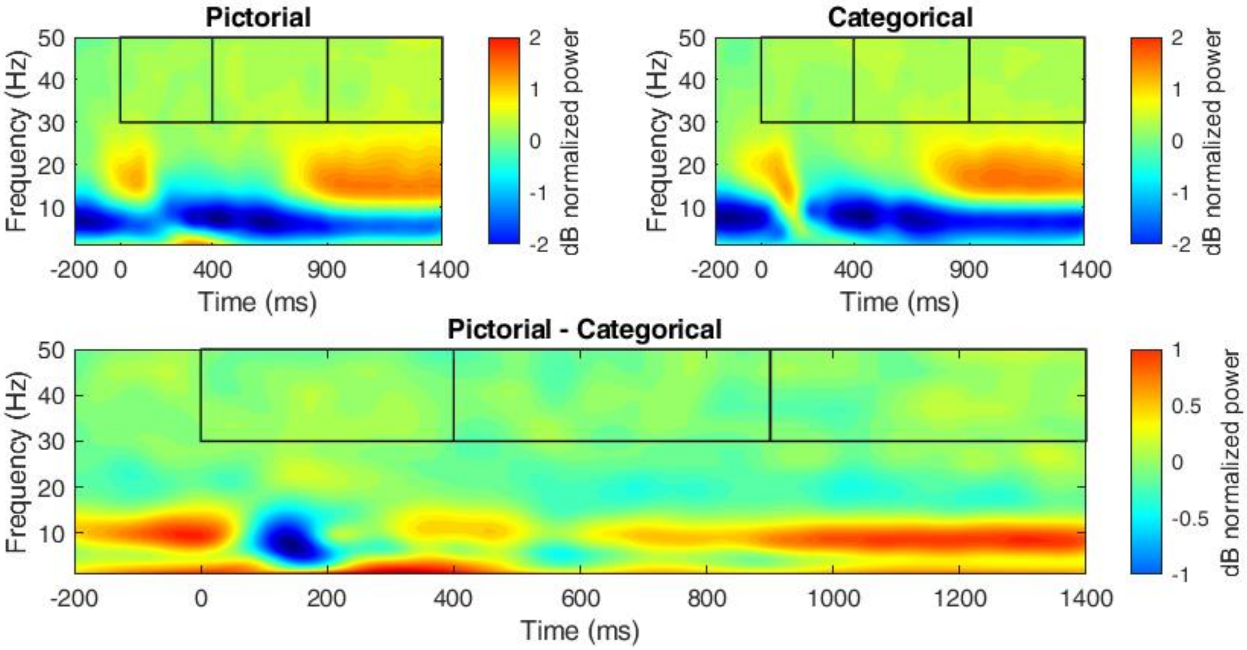


Figure 7. Gamma Power for Experiment 1. The top row depicts dB normalized power at P7 for the pictorial (left) and categorical (right) cue conditions. The bottom plot is a subtraction of the pictorial and categorical plots. The three boxes drawn on each plot indicate the cue, early RI, and later RI in the gamma frequency band, respectively.

Synchrony Analysis

Based on the hypothesized models, an ISPC synchrony matrix was calculated for a subset of preselected electrodes from each of the four main areas (frontal, posterior, ipsi/left, and contra/right temporal; see Table 3). This resulted in a 14x14 matrix with each cell containing an ISPC value for each electrode pair. This analysis was conducted over the theta-alpha range, 3 to 12 Hz, over the cue and RI (0 to 1400 ms), collapsed across cue types. From this, the pair of electrodes with the highest ISPC value was chosen within the three hypothesized connections: Frontal-Posterior, Frontal-Temporal, and Posterior-Temporal. See Figure 8 for a head map of the preselect electrodes and the resulting maximum connections.

Table 3. Subset of Electrodes for All-to-All Synchrony Matrix

Frontal	Posterior	Ipsi/Left Temporal	Contra/Right Temporal
Fpz	Iz	FT7	FT8
Afz	Oz	C5	C6
Fz	Poz	T7	T8
		TP7	TP8

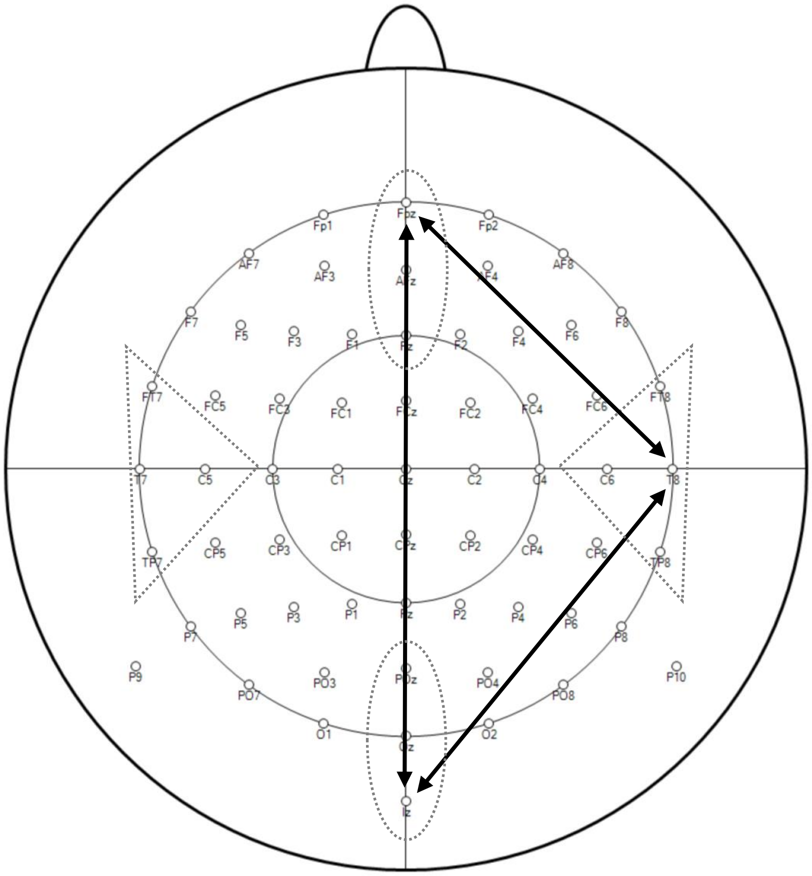


Figure 8. Head map of Peak Synchronous Activity for Experiment One. This figure depicts the strongest frontal-posterior (Fpz-Iz), frontal-temporal (Fpz-T8), and posterior-temporal (Iz-T8) connections out of a pre-selected subset of electrodes, circled in gray.

Frontal-Posterior

Synchrony was the strongest between electrodes Fpz and Iz. Frontal-posterior synchrony was expected to be larger with pictorial cues than with categorical cues. Unfortunately, no such pattern was observed with ISPC (largest nonsignificant cluster, cue: p = .40, RI: p = .20) or PLI (largest nonsignificant cluster, cue: p = .62, RI: p = .70). See Figure 9.

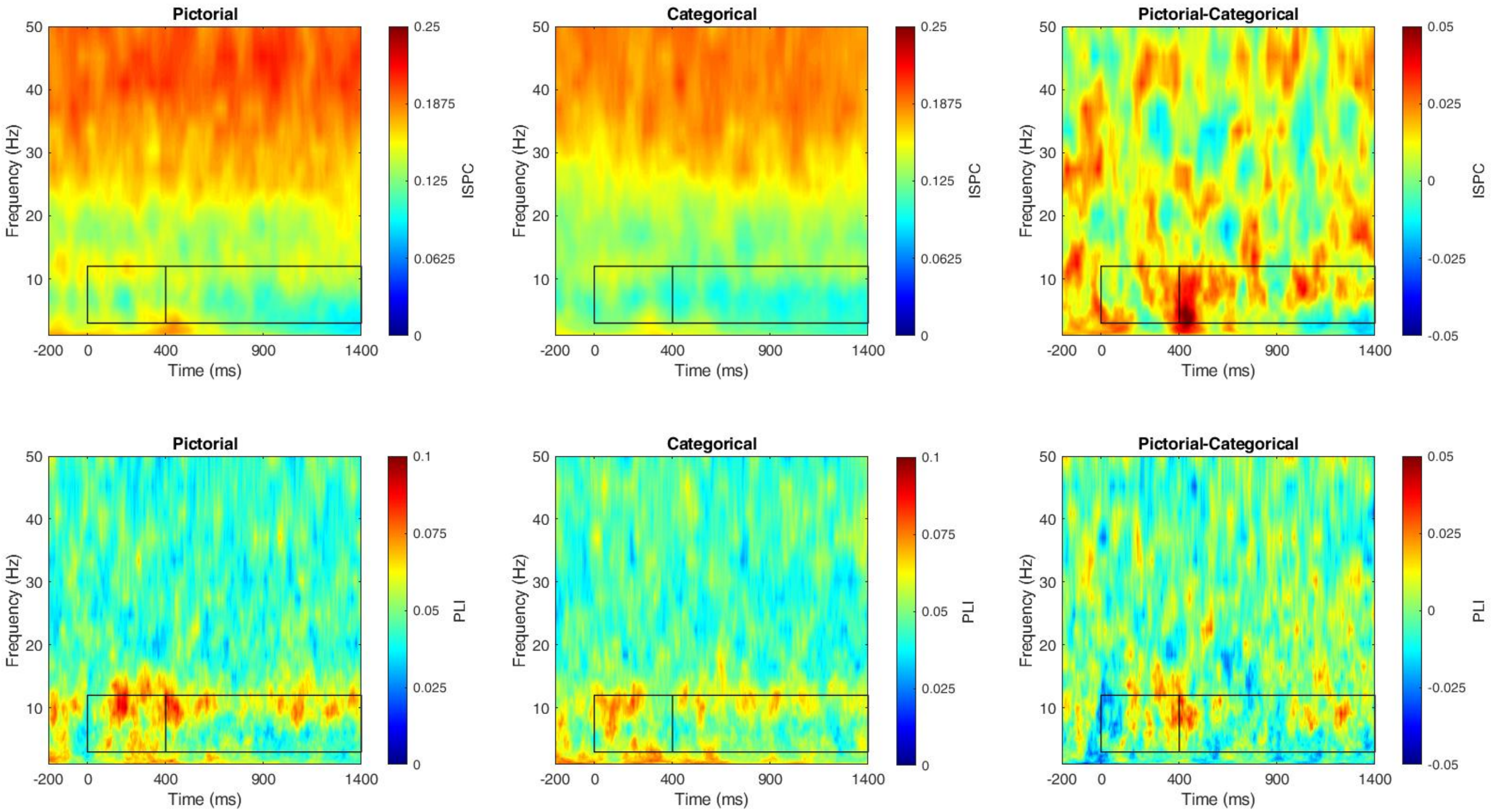


Figure 9. Frontal-Posterior Synchrony for Experiment 1. The top row depicts the ISPC between Fpz and Iz electrodes in the pictorial cue (left), the categorical cue (center), and the difference between the two(right). The bottom row depicts the PLI. The two boxes drawn on each plot indicate the cue and RI in the theta-alpha frequency band, respectively.

Frontal- Temporal

Synchrony was the strongest between electrodes Fpz and T8. Frontal-temporal synchrony was expected to be larger with categorical cues. However, ISPC (largest nonsignificant cluster, cue: $p = .42$, RI: $p = .33$) nor PLI (largest nonsignificant cluster, cue: $p = .89$, RI: $p = .87$) indicated any significant differences between pictorial and categorical cues. See Figure 10.

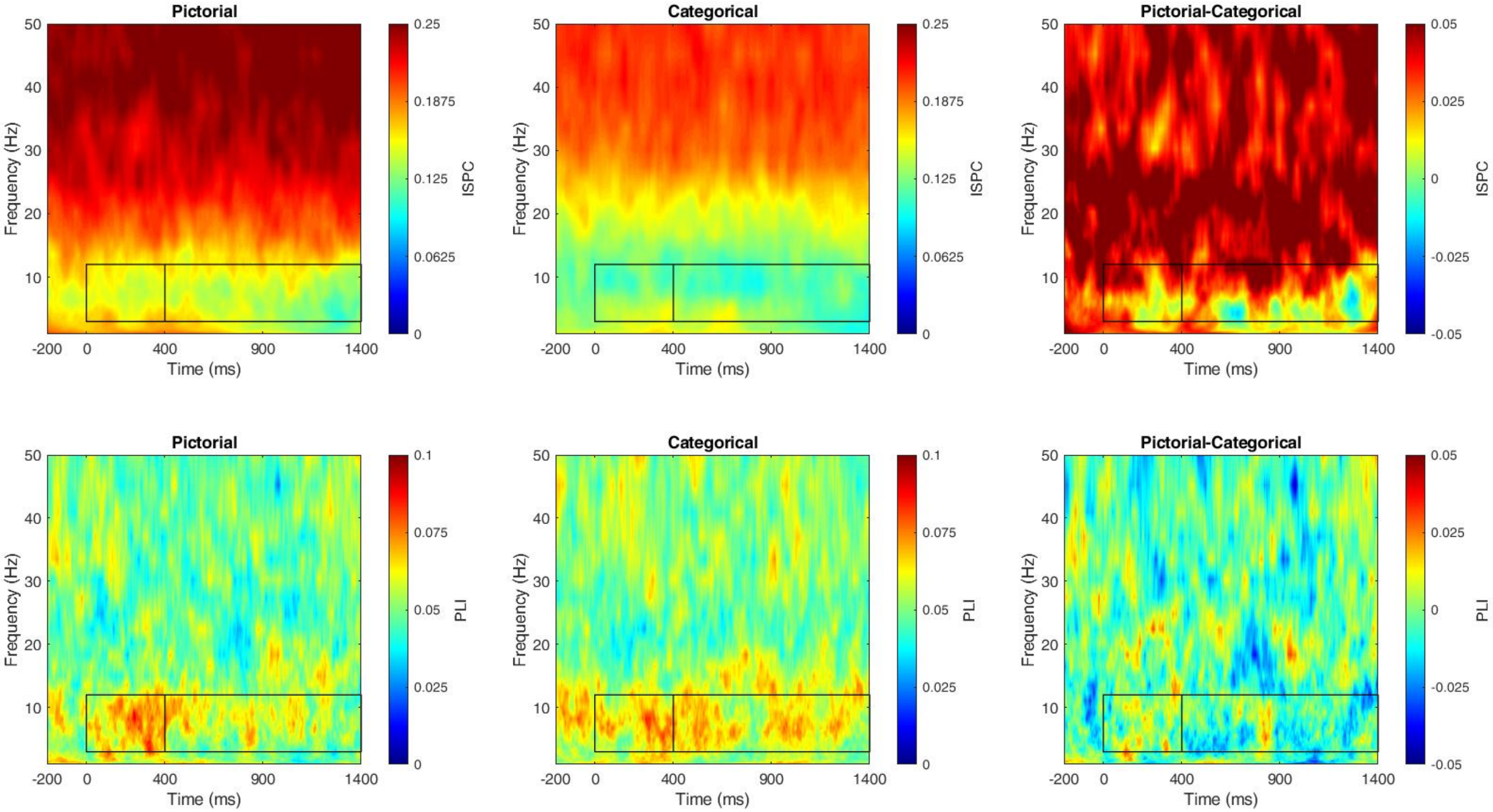


Figure 10. Frontal-Temporal Synchrony for Experiment 1. The top row depicts the ISPC between Fpz and T8 electrodes in the pictorial cue (left), the categorical cue (center), and the difference between the two(right). The bottom row depicts the PLI. The two boxes drawn on each plot indicate the cue and RI in the theta-alpha frequency band, respectively.

Posterior- Temporal

Synchrony was the strongest between electrodes Iz and T8. Posterior-temporal synchrony was expected to be larger with categorical cues. However, no differences were observed in ISPC (cue: largest nonsignificant cluster, $p = .66$, RI: largest nonsignificant pixel, $Z = 1.64$, $p = .10$) or PLI (largest nonsignificant cluster, cue: $p = .86$, RI: $p = .34$). See Figure 11.

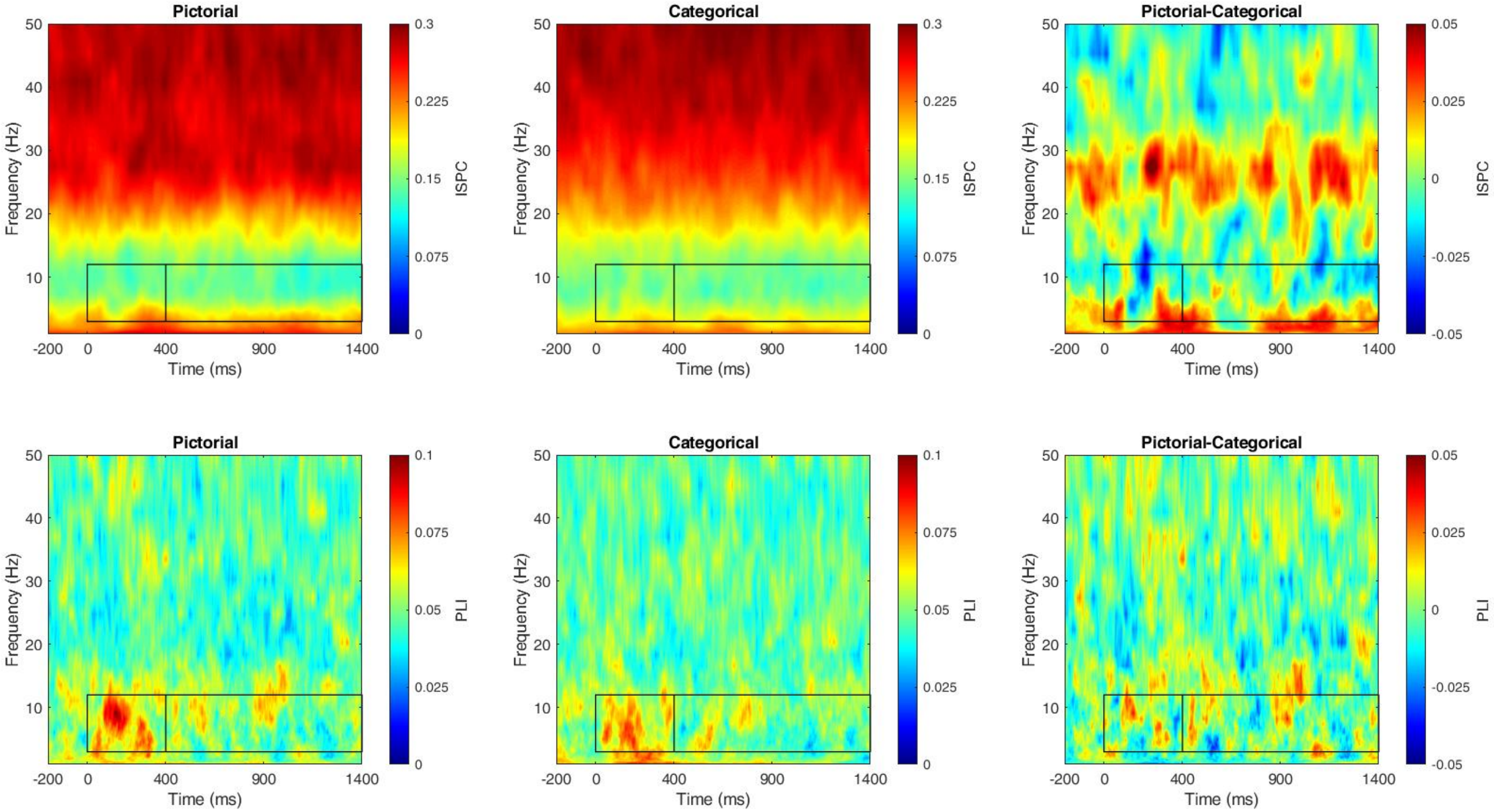


Figure 11. Posterior-Temporal Synchrony for Experiment 1. The top row depicts the ISPC between Iz and T8 electrodes in the pictorial cue (left), the categorical cue (center), and the difference between the two(right). The bottom row depicts the PLI. The two boxes drawn on each plot indicate the cue and RI in the theta-alpha frequency band, respectively.

Brain-to-Behavior Relationship: Guidance and Frontal-Posterior Synchrony

A two (good guidance versus bad guidance) by two (pictorial versus categorical cue) mixed factor ANOVA was performed to assess the relationship between guidance and frontal-posterior synchrony. If larger frontal-posterior synchrony indicates a stronger attentional template, frontal-posterior synchrony should be stronger in good guidance trials than bad ones. Furthermore, it should be stronger with pictorial cues irrespective of the type of guidance. This would demonstrate that the attentional template is not contained within any specific brain region but is neural communication in which the frontal regions bias early visual areas to exert top-down control when processing the search display. This analysis was specific to the alpha and theta frequency bands. As discussed previously, alpha synchrony has been implicated in attentional mechanisms (Palva & Palva, 2010; de Vries et al., 2017; van Driel et al., 2017) and theta synchrony has been implicated in memory-related processes (Sarnthein et al., 1998, Sauseng et al., 2004; Summerfield & Mangels, 2005). Both alpha and theta were expected to result in the same pattern of results. There were four time-frequency windows of interest: alpha-cue (8-12 Hz, 0 ms to 400 ms), alpha-RI (8-12 Hz, 401 ms to 1400 ms), theta-cue (3-7 Hz, 0 ms to 400 ms), and theta-RI (3-7 Hz, 401 ms to 1400 ms) using the same Fpz and Iz electrodes used in the frontal-posterior synchrony analysis. A summary of the results can be found in Table 4.

Alpha-Cue

Inconsistent with the hypotheses, synchrony was larger before bad guidance trials (ISPC: F (1, 57) = 4.57, p = .04, η_p^2 = .07; PLI: F (1, 57) = 9.43 p = .003, η_p^2 = .14) but there was no difference between the pictorial and categorical cues (ISPC: F (1, 57) = 1.44, p = .24, η_p^2 = .03; PLI: F (1, 57) = 1.08, p = .30, η_p^2 =.02). There was, however, a significant interaction between guidance and cue type (ISPC: *F* (1, 57) = 10.42, *p* = .002, η_p^2 = .16; PLI: *F* (1, 57) = 33.18, *p* < .001, η_p^2 = .37). Paired samples t-test showed slightly different patterns between the ISPC and the PLI results. ISPC results indicated synchrony was significantly stronger during pictorial cues before bad guidance trials, *t* (25) = -3.01, *p* = .006, *d* = -.59. Synchrony before good or bad guidance trials during categorical cues did not differ, *t* (32) = 1.01, *p* = .32, *d* = .18. PLI results also indicated synchrony was stronger before bad guidance trials during pictorial cues, *t* (25) = -4.64, *p* < .001, *d* = -.91. However, the opposite pattern was observed in the categorical cue condition, *t* (32) = 2.83, *p* = .004, *d* = .49; synchrony was stronger before good guidance trials. Independent samples t-tests showed no difference in synchrony during pictorial and categorical cues that resulted in good guidance with ISPC, *t* (57) = .21, *p* = .84, *d* = .05, or PLI, *t* (57) = -1.51, *p* = .14, *d* = -.40. In the bad guidance trials, synchrony was stronger during pictorial cues relative to categorical cues (ISPC: *t* (57) = 1.99, *p* = .05, *d* = .52; PLI: *t* (57) = 2.73, *p* < .01, *d* = .72). See Figure 12.

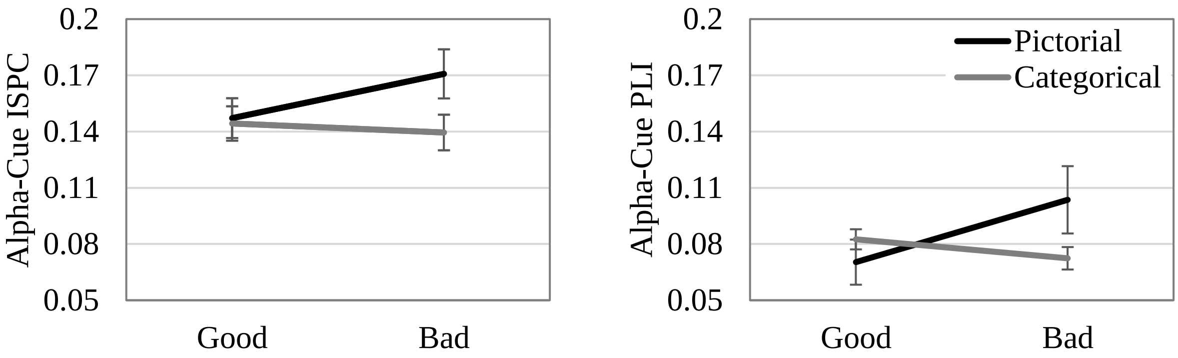


Figure 12. Alpha-Cue ISPC and PLI for Experiment 1. Mean ISPC and PLI per condition in the alpha-cue, time-frequency window. Error bars indicate the SEM.

Alpha-RI

With ISPC, there was no significant difference between good and bad guidance, *F* (1, 57) = 2.67, *p* = .11, η_p^2= .05, and no significant difference between cue types, *F* (1, 57) = 2.67, *p* = .11, η_p^2= .05. However, with PLI, synchrony was stronger before bad guidance trials, *F* (1, 57) = 13.40, *p* < .001, η_p^2 = .19, but no significant difference was found between cue types, *F* (1, 57) = .96, *p* = .33, η_p^2 =.02. There was however, a signficant interaction with both measures (ISPC: *F* (1, 57) = 5.91, *p* = .02, η_p^2 = .09; PLI: *F* (1, 57) = 33.92, *p* < .001, η_p^2 = .37). Paired samples t-tests showed stronger synchrony before bad guidance trials in the pictorial cue condition with both measures (ISPC: *t* (25) = -1.91, *p* = .03, *d* = -.38; PLI: *t* (25) = -5.38, *p* < .001, *d* = -1.06). In the categorical cue condition, PLI indicated stronger synchrony before good guidance trials, *t* (32) = 1.96, *p* = .03, *d* = .34 but not with ISPC, *t* (32) = 1.33, *p* = .19, *d* = .23. Independent samples t-tests revealed no differences in synchrony between pictorial and categorical during the RI before good guidance trials with ISPC, *t* (57) = .33, *p* = .74, *d* = .09, or PLI, *t* (57) = -.97, *p* = .34, *d* = -.26. Before bad guidance trials, synchrony was stronger after pictorial cues relative to categorical cues. However, this was only significant with PLI, *t* (57) = 2.47, *p* < .05, *d* = .65, but not ISPC, *t* (57) = 1.50, *p* = .14, *d* = .39. See Figure 13.

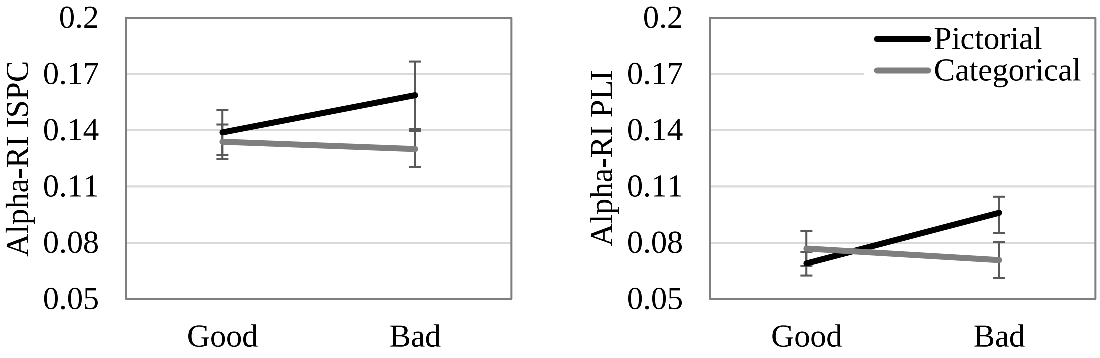


Figure 13. Alpha-RI ISPC and PLI for Experiment 1. Mean ISPC and PLI per condition in the alpha-RI, time-frequency window. Error bars indicate the SEM.

Theta-Cue

With ISPC, there was no significant effect of guidance type, *F* (1, 57) = .41, *p* = .53, η_p^2 = .01, or cue type, *F* (1, 57) = 1.67, *p* = .20, η_p^2 = .03. With PLI, synchrony was stronger prior to bad guidance trials, *F* (1, 57) = 8.11, *p* = .006, η_p^2 = .13, and synchrony was stronger in the pictorial cue condition, *F* (1, 57) = 6.61, *p* = .03, η_p^2=.10. However, there was a significant interaction with both measures (ISPC: *F* (1, 57) = 5.46, *p* = .02, η_p^2 = .02; PLI: *F* (1, 57) = 41.98, *p* < .001, η_p^2 = .42. Paired samples t-tests indicate sychrony was stronger prior to good guidance trials in the categorical cue condition with both measures (ISPC: *t* (32) =2.23, *p* = .03, *d* = .39; PLI: *t* (32) = 2.96, *p* = .006, d = .52). In the pictorial cue condition, synchrony was stronger prior to bad guidance trials although this was only observed with PLI, *t* (25) = -5.72, *p* < .001, *d* = -1.22, ISPC: *t* (25) = -1.46, *p* = .26, *d* = -.23. Independent samples t-tests showed prior togood guidance trials, synchrony was stronger during categorical cues relative to pictorial cues. However, this was only significant with PLI, *t* (57) = -2.30, *p* = .03, *d* = -.60 (ISPC, *t* (57) = .41, *p* = .67, *d* = .11). In the bad guidance trials, synchrony was stronger during pictorial cues relative to categorical cues with both, ISPC: *t* (57) = 1.97, *p* = .05, *d* = .52, and PLI: *t* (57) = 6.15, *p* < .001, *d* = 1.61. See Figure 14.

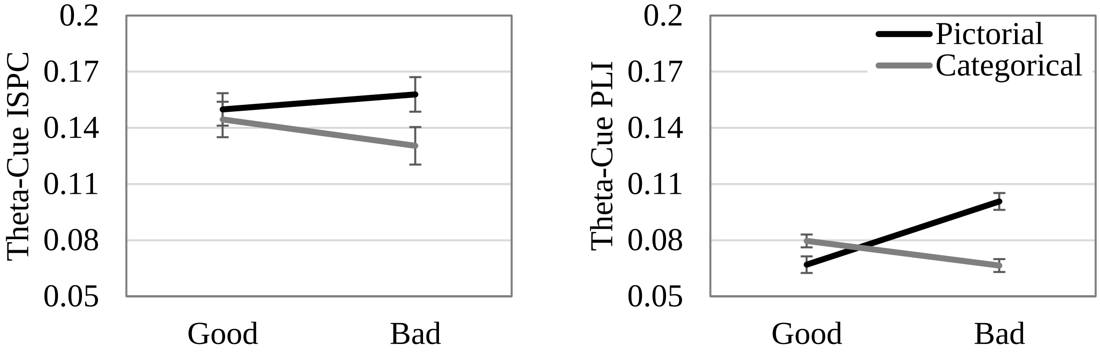


Figure 14. Theta-Cue ISPC and PLI for Experiment 1. Mean ISPC and PLI per condition in the theta-cue, time-frequency window. Error bars indicate the SEM.

Theta-RI

With ISPC, synchrony was stronger before bad guidance trials compared to good guidance trials, *F* (1, 57) = 5.69 *p* = .02, η_p^2 = .09. Cue type, *F* (1, 57) = 2.02, *p* = .16, η_p^2=.03, and the interaction, *F* (1, 57) = 2.74, *p* = .10, η_p^2 = .05, were not significant. With PLI, there was stronger synchrony before bad guidance trials, *F* (1, 57) = 17.49 p < .001, η_p^2 = .24, but there was no effect of cue type, *F*(1, 57) = 1.73, *p* = .19, η_p^2=.03. The interaction was also significant, *F* (1, 57) = 47.09, *p* < .001, η_p^2 = .45. Paired samples t-tests indicate stronger synchrony before bad guidance trials in the pictorial cue condition, *t* (25) = -6.17, *p* < .001, *d* = -1.21, but the opposite effect in the categorical cue condition, *t* (32) = 2.48, *p* = .009, *d* = .43. Independent samples t-tests showed, before good guidance trials, synchrony was stronger after categorical cues relative to pictorial cues, *t* (57) = -4.05, *p* < .001, *d* = -1.06. Before bad guidance trials, synchrony was stronger after pictorial cues relative to categorical cues, *t* (57) = 4.61, *p* < .001, *d* = 1.21. See Figure 15.

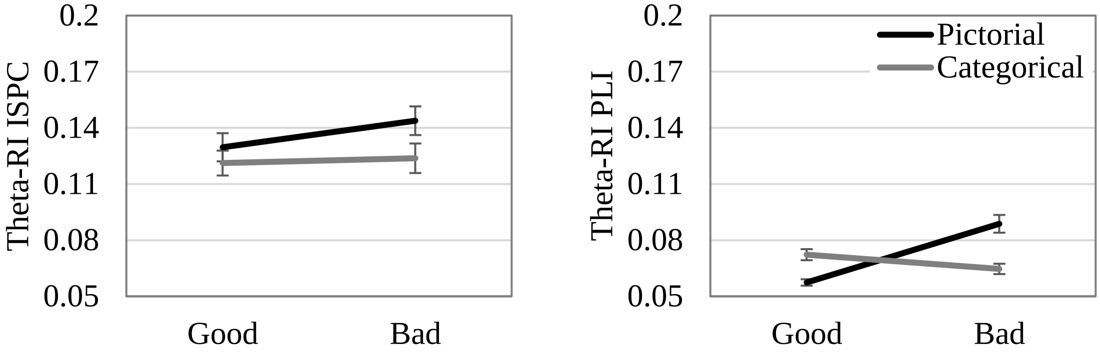


Figure 15. Theta-RI ISPC and PLI for Experiment 1. Mean ISPC and PLI per condition in the theta-RI, time-frequency window. Error bars indicate the SEM.

Table 4. Summary of Brain-Behavior Results for Experiment One.

Time-Frequency Window	ISPC	PLI	Consistent
Alpha-Cue			
Main Effects			
Guidance	Good < Bad	Good < Bad	✓
Cue Type	*n.s.*	*n.s.*	✓
Interaction			
Paired T-tests			
Pictorial	Good < Bad	Good < Bad	✓
Categorical	*n.s.*	Good > Bad	✗
Independent T-tests			
Good	*n.s.*	*n.s.*	✓
Bad	Pictorial > Categorical	Pictorial > Categorical	✓
Alpha-RI			
Main Effects			
Guidance	*n.s.*	Good < Bad	✗
Cue Type	*n.s.*	*n.s.*	✓
Interaction			
Paired T-tests			
Pictorial	Good < Bad	Good < Bad	✓
Categorical	*n.s.*	Good > Bad	✗
Independent T-tests			
Good	*n.s.*	*n.s.*	✓
Bad	*n.s.*	Pictorial > Categorical	✗
Theta-Cue			
Main Effects			
Guidance	*n.s.*	Good < Bad	✗
Cue Type	*n.s.*	Pictorial > Categorical	✗
Interaction			
Paired T-tests			
Pictorial	*n.s.*	Good < Bad	✗
Categorical	Good > Bad	Good > Bad	✓
Independent T-tests			
Good	*n.s.*	Pictorial < Categorical	✗
Bad	Pictorial > Categorical	Pictorial > Categorical	✓
Theta-RI			
Main Effects			
Guidance	Good < Bad	Good < Bad	✓
Cue Type	*n.s.*	*n.s.*	✓
Interaction	*n.s.*		
Paired T-tests			
Pictorial		Good < Bad	✗
Categorical		Good > Bad	✗
Independent T-tests			
Good		Pictorial < Categorical	✗
Bad		Pictorial > Categorical	✗

Exploratory Analysis

Because of the unexpected results from the brain-behavior analysis, an exploratory analysis was conducted to further investigate the observed effect. First, a mixed factor ANOVA was used to compare good and bad guidance by cue type to establish if guidance affected the attentional template (as measured by accuracy). If guidance is a reliable oculomotor measure of the quality attentional template, it should affect search performance; if guidance is good, accuracy should also be good, if guidance is bad, accuracy should be bad. Second, the brain-behavior analysis was extended to include frontal-temporal synchrony and posterior-temporal synchrony to determine if the pattern of results previously observed were specific to frontal-posterior synchrony or indicative of a larger pattern of brain activity. Because this analysis was exploratory, only PLI was used to estimate synchrony per Cohen's (2015) recommendation. The analysis was performed in the same manner as above, using only the alpha-cue and alpha-RI time-frequency windows but with the frontal-temporal and posterior-temporal electrodes.

Accuracy by Guidance

Accuracy was significantly higher for good guidance trials compared to bad guidance trials, F (1, 57) = 46.49, $p < .001$, $\eta_p^2 = .45$. the interaction was also significant, F (1, 57) = 9.47, $p = .003$, $\eta_p^2 = .14$. Paired samples t-tests showed accuracy was significantly higher when guidance was good with both pictorial, t (25) = -4.98, $p < .001$, d = -.98, and categorical cues, t (32) = -4.44, $p < .001$, d = - .77. Independent samples t-tests showed accuracy was significantly higher with categorical cues in the bad guidance trials, t (57) = -2.23, p = .03, d = -.59. In good guidance trials, accuracy did not differ with pictorial and categorical cues, t (57) = .98, $p < .33$, d

= .26. Taken together, these results suggest that guidance did affect accuracy making guidance a reliable measure of the quality attentional template. See Figure 16.

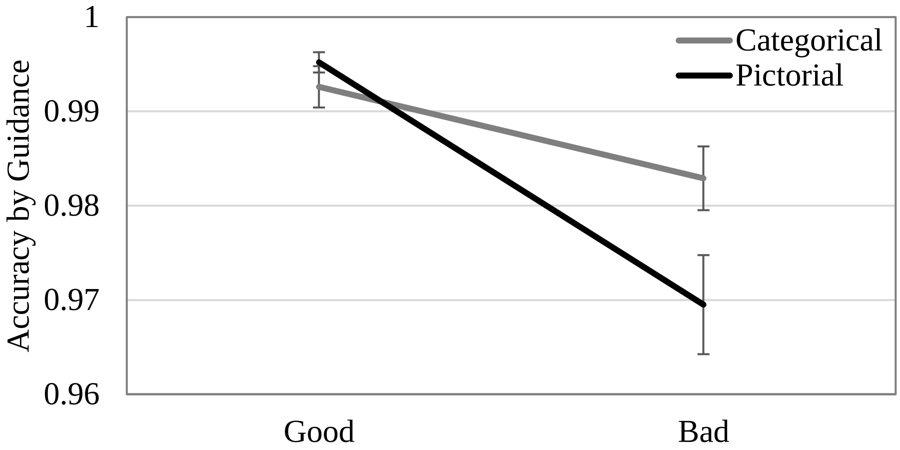


Figure 16. Accuracy by guidance for Experiment One. Error bars indicate the SEM.

Frontal-Temporal

Alpha-Cue

Electrodes Fpz and T8 were used for this analysis. Synchrony was stronger during the cue before bad guidance trials, F (1, 57) = 7.65, p = .008, η_p^2 = .12. There was no difference in synchrony between pictorial and categorical cues, F (1, 57) = .73, p = .40, η_p^2 = .01. The interaction was significant, F (1, 57) = 50.08, $p < .001$, η_p^2 = .47. Paired samples t-tests demonstrate a cross-over interaction in which there is stronger synchrony before bad guidance trials in the pictorial cue condition, t (25) = -5.98, $p < .001$, d = -1.17, but also stronger synchrony before good guidance trials in the categorical cue condition, t (32) =3.56, p = .001, d = .62. Independent samples t-tests showed synchrony was stronger during categorical cues before good guidance trials, relative to pictorial cues, t (57) = -1.98, p = .05, d = -.52. Conversely, synchrony was stronger during pictorial cues relative to categorical cues before bad guidance trials, t (57) = 3.16, p = .003, d = .83. See Figure 17.

Alpha-RI

Synchrony was stronger during the RI before bad guidance trials, F (1, 57) = 14.58, $p <$ .001, η_p^2 = .20. There was no difference in synchrony during the RI between pictorial and categorical cues, F (1, 57) = .15, p = .70, η_p^2 = .003. The interaction was significant, F (1, 57) = 58.86, $p <$ .001, η_p^2 = .51. Paired samples t-tests demonstrate a cross-over interaction in which there is stronger synchrony before bad guidance trials in the pictorial cue condition, t (25) = -7.13, $p <$ .001, d = -1.40, but stronger synchrony before good guidance trials in the categorical cue condition, t (32) =3.10, p = .004, d = .54. Independent samples t-tests showed before good guidance trials, synchrony was stronger after categorical cues, relative to pictorial cues, t (57) = -2.39, p = .02, d = -.63. Conversely, before bad guidance trials, synchrony was stronger after pictorial cues relative to categorical cues, t (57) = 2.81, p = .007, d = .74. See Figure 17.

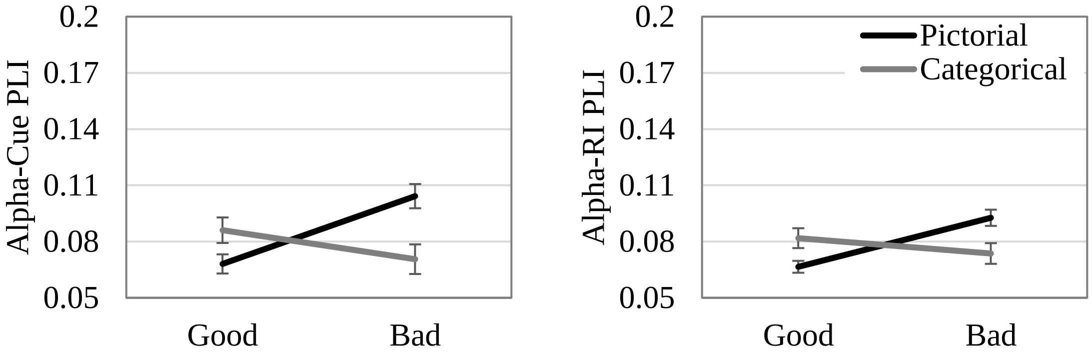


Figure 17. Frontal-Temporal PLI for Alpha Cue and RI for Experiment 1. Mean PLI per condition in the Alpha Cue and RI time-frequency windows. Error bars indicate the SEM.

Posterior-Temporal

Alpha-Cue

Electrodes Iz and T8 were used for this analysis. Synchrony was stronger during the cue before bad guidance trials, F (1, 57) = 9.49, p = .003, η_p^2 = .14. Synchrony was also stronger during the cue in the pictorial cue condition, F (1, 57) = 4.16, p < .05, η_p^2 = .07. The interaction was significant, F (1, 57) = 23.68, p < .001, η_p^2 = .29. Paired samples t-tests demonstrated a cross-over interaction in which there is stronger synchrony before bad guidance trials in the pictorial cue condition, t (25) = -4.07, p < .001, d = -.80, but stronger before good guidance trials in the categorical cue condition, t (32) = 3.08, p = .05, d = .35. Independent samples t-tests showed synchrony was stronger during categorical cues before good guidance trials, relative to pictorial cues, t (57) = -1.34, p = .03, d = -.35, and synchrony was stronger during pictorial cues before bad guidance trials, relative to categorical cues, t (57) = 4.08, p < .001, d = 1.07. See Figure 18.

Alpha-RI

Synchrony was stronger during the RI before bad guidance trials, F (1, 57) = 32.86, p < .001, η_p^2 = .37, and stronger in the pictorial cue condition, F (1, 57) = 5.12, p < .05, η_p^2 = .08. The interaction was also significant, F (1, 57) = 103.38, p < .001, η_p^2 = .65. Paired samples t-tests demonstrate a cross-over interaction in which there is stronger synchrony before bad guidance trials in the pictorial cue condition, t (25) = -12.06, p < .001, d = -2.37, but stronger synchrony before good guidance trials in the categorical cue condition, t (32) =3.08, p = .004, d = .54. Independent samples t-tests showed synchrony was stronger after categorical cues before good guidance trials, relative to pictorial cues, t (57) = -2.80, p = .007, d = -.73, and stronger after pictorial cues before bad guidance trials relative to categorical cues, *t* (57) = 6.21, *p* < .001, *d* = 1.63. See Figure 18.

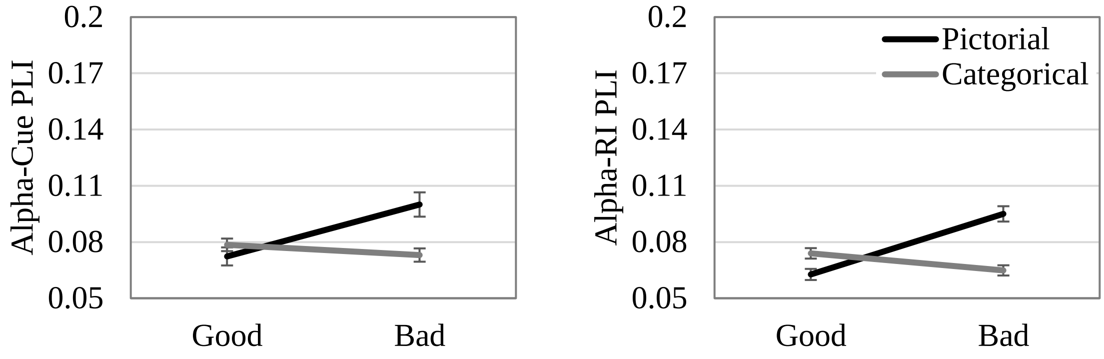


Figure 18.Posterior-Temporal PLI for Alpha Cue and RI for Experiment 1. Mean PLI per condition in the Alpha Cue and RI time-frequency windows. Error bars indicate the SEM.

Discussion

Retrieval of LTM information is a necessary assumption built into all models of categorical search. However, the retrieval of this information for attentional biasing during search has not been shown with any neurophysiological markers. This experiment aimed to compare the neural activity of a pictorial cue in which participants were given useful perceptual information and a categorical cue in which the participants were not given useful perceptual information but instead had to rely on LTM.

The hypotheses for this experiment were as follows. For the manual responses (accuracy and RT) and eye movement metrics (guidance and verification time), pictorial cues were expected to result in better search performance relative to categorical cues. Consistent with prior work, pictorial cues resulted in faster RTs, stronger search guidance, and faster verification time relative to categorical cues (e.g., Yang & Zelinsky, 2009; Schmidt & Zelinsky, 2009). However, accuracy did not differ between cue types but with accuracy averaging 99% in both conditions, there was a ceiling effect.

Regarding the local power analyses, frontal theta power was expected to be larger for pictorial cues than categorical cues, suggesting a pictorial cue may be treated as an episodic memory trace (Klimesch et al., 1996; Klimesch et al., 1997c; Klimesch et al., 2008). For both cues, posterior alpha suppression was expected to be larger in the contralateral hemisphere relative to the ipsilateral hemisphere (with respect to the cue) which would indicate more attention allocated to the task-relevant side compared to the task-irrelevant side (Medendorp et al., 2007; van Dijk et al., 2010; Reinhart & Woodman, 2014; de Vries et al., 2017; van Driel et al., 2017). It was also hypothesized that this effect would be larger with categorical cues because they require more semantic processing (Klimesch et al., 1997a). Lastly, greater posterior gamma-band activity has been associated with feature binding (Keil et al., 2001; Engel & Singer, 2001) and was therefore hypothesized to occur early in the RI after a pictorial cue, indicating that the stimulus is being maintained as a bound object (blue pen) rather than individual features (something blue, long, cylindrical). Conversely, larger posterior gamma-band activity was hypothesized to occur later in the RI with categorical cues indicating that semantic information was extracted and bound into an exemplar of the target category (Keil et al., 2001; Engel & Singer, 2001).

Unfortunately, most of these hypotheses were not supported by the data. There was, however, a significant lateralized posterior alpha suppression effect; there was more posterior alpha suppression in the contralateral hemisphere relative to the ipsilateral hemisphere for pictorial cues suggesting participants attended to the cued side of the screen more than the un-cued side of the screen. Perhaps in the categorical cue condition, participants could not ignore the uncued side of the screen as effectively due to the automaticity frequently seen with reading (see Stroop effect; Stroop, 1992).

When comparing the patterns of synchrony resulting from pictorial and categorical cues, the model predicted stronger synchronization between frontal and posterior regions with pictorial cues as there should be a bi-directional flow of information; a low spatial frequency version of the perceptual information processed in the posterior visual areas is rapidly transferred to frontal areas for interpretation and then frontal regions determine how to bias visual areas. Frontal-temporal synchrony was predicted to be larger with categorical cues as categorical information would need to be extracted from the temporal areas and transferred to frontal areas to bias early visual areas. Posterior-temporal synchrony was anticipated to be stronger for categorical cues as the perceptual information from the cue must necessarily be interpreted in the temporal areas to extract CCFs. Unfortunately, these hypotheses were not substantiated.

Although frontal-posterior synchrony did not differ between the two cue types, the brain-behavior analysis was performed to determine if frontal-posterior synchrony would predict later search performance, specifically search guidance. Search guidance was quantified by the direction of the first search saccade; if the first search saccade was directed towards the target, this was considered good guidance, if the first search saccade was directed towards a distractor, this was considered bad guidance. Guidance was chosen because, if guidance is good, it can be assumed that the information provided in the cue resulted in a strong attentional template and was either well-preserved or well-utilized. The opposite can be assumed for bad guidance trials.

To confirm within this experiment, accuracy within each cue type was separated by good and bad guidance. Overall accuracy was higher when guidance was good. However, in good guidance trials, accuracy did not differ between conditions. Conversely, in bad guidance trials, accuracy was higher with categorical cues suggesting a bad template had a larger effect on pictorial cues. If frontal-posterior alpha synchrony is indicative of attentional biasing, as had been previously reported (Palva & Palva, 2010; de Vries et al., 2017; van Driel et al., 2017), it should be stronger in good guidance trials relative to bad guidance trials and stronger with pictorial cues relative to categorical cues. This pattern should have also extended to frontal-posterior theta synchrony as a potential indicator of the memory component of the attentional template. Because more information is provided in a pictorial cue, the memory trace should be larger than the categorical cue. This would provide an excellent neurophysiological explanation for the pictorial advantage observed when comparing pictorial and categorical cues. If alpha and theta synchrony between frontal and posterior regions is stronger with pictorial cues, perhaps it indicates stronger attentional biasing of early visual areas when participants have access to precise perceptual information.

Although this analysis yielded significant results, the pattern of results was inconsistent with the hypotheses. Furthermore, it is important to note that the significant results in the PLI analyses did not always reach significance when measured by ISPC, although the pattern was similar (see Table 4 for the summary). Because ISPC and PLI are quantifying synchrony in slightly different ways, (ISPC measures the clustering of phase angle differences, PLI measures the portion of phase angle differences that are positive or negative) it is not uncommon that they yield slightly different, statistically significant results (Cohen, 2015; Gomez-Ramierz et al., 2017; Knyazeva et al., 2021). Given the inconsistency in significance (not directionality), significant findings with both measures will be considered strongly supported, whereas those only found significant with one measure will be considered weakly supported.

Previous research has suggested frontal-posterior alpha synchrony is related to attentional mechanisms (Palva & Palva, 2010; de Vries et al., 2017; van Driel et al., 2017), whereas frontal-posterior theta synchrony is related to memory processes (Sarnthein et al., 1998, Sauseng et al., 2004; Summerfield & Mangels, 2005). Interestingly, both yielded similar patterns of results which is consistent with the idea that the attentional template requires both attentional mechanisms and memory (see Olivers et al., 2011). During the cue, it can be assumed that the neural activity is largely related to processing the cue. In the pictorial cue condition, there was more frontal-posterior alpha and theta synchrony before bad guidance trials which may suggest the more the participant attended to/processed and encoded the cue (stronger alpha and theta synchrony), the more likely it was that the first saccade would be directed towards a distractor. This pattern carried over to the RI which is likely related to the maintenance of the attentional template. This effect was consistently observed in the alpha cue and RI time-frequency windows with ISPC and PLI whereas the effects in the theta time-frequency windows were weakly supported as they were only observed with PLI. Conversely, in the categorical cue condition, the more the participant processed and maintained the cue (stronger alpha and theta synchrony during the cue and RI), the more likely the first saccade would be directed toward the target. This effect was consistently observed in the theta-cue time-frequency window while the alpha cue and RI, and theta-RI time frequency intervals were weakly supported as they were only observed with PLI.

Another interesting finding was revealed when comparing pictorial and categorical cues within good guidance trials and bad guidance trials. When guidance was good, there was no difference in alpha synchrony with pictorial or categorical cues (cue or RI, strongly supported). Conversely, in the theta time-frequency windows, there was stronger synchrony with categorical cues (weakly supported). In other words, when the attentional template was “good,” there was not necessarily a difference in attention (alpha) but there may have been a difference in memory (theta); specifically, there was more memory utilization with categorical cues which led to a better attentional template (as measured by guidance). When guidance was bad, synchrony was stronger in all four time-frequency windows with pictorial cues suggesting more attention and memory utilization during the cue (strongly supported) and RI (weakly supported).

The overall pattern observed in the pictorial cue condition is consistent with several other studies demonstrating a negative relationship between CDA and search performance (Carlisle et al., 2011; Gunseli et al., 2014a; Gunseli et al., 2014b; Schmidt et al., 2014). In Schmidt et al. (2014), they found that larger CDA preceded trials in which the first saccade was directed toward a distractor. More importantly, they found that early CDA was similar before good or bad guidance trials. However, over time, CDA before good guidance trials lessened over the RI, whereas CDA before bad guidance trials stayed the same. They theorized this could indicate a consolidation process that led to a more simplified and effective attentional template. Because the pictorial search was easy and could be completed categorically (looking for any teddy bear amongst non-teddy bears), perhaps participants did not need to process, encode, and maintain much detailed information from the cue. When they did, perhaps this created more room for error during search. In other words, the greater number of features extracted from the cue may increase the chances of feature overlap with the distractors. Conversely, if only the most relevant or discriminative feature(s) are chosen, there is a decreased chance of feature overlap.

With categorical cues, participants did not need to process, encode, and maintain the details of the cue to the extent that pictorial cues required. Rather participants needed to read and comprehend the word and then call to mind the features from the category. Unlike pictorial cues, there was no opportunity to extract and maintain too many features from the cue. With that in mind, the amount of synchrony before good guidance trials may indicate participants relaying just the right amount of information in preparation for the search. In bad guidance trials, less synchrony may indicate insufficient information to accurately direct attention to the target. Furthermore, some evidence suggests frontal-posterior theta synchrony is specifically related to memory retrieval (Summerfield & Mangels, 2005). Not only was there more theta synchrony in good guidance trials in comparison to bad guidance trials (cue: ISPC and PLI, RI: PLI only), but in good guidance trials, there was more synchrony in comparison to pictorial cues (cue and RI: PLI only). This provides some evidence of memory retrieval during the cue and RI during categorical search.

The brain-behavior analysis was extended to further investigate this unexpected dissociation between pictorial and categorical cues to include the other long-range connections outlined in the hypothesized models, frontal-temporal and posterior-temporal. Both long-range connections exhibited a similar pattern as the frontal-posterior alpha synchrony results. More processing, encoding (i.e., during the cue), and maintenance (i.e., during the RI) of a pictorial cue resulted in bad guidance, whereas more processing, encoding, and maintenance of a categorical cue resulted in good guidance. Unfortunately, little to no work has looked at alpha synchrony between frontal-temporal (some work has suggested it may be related to spatial attention, Bagherzadeh et al., 2020) and posterior-temporal areas, making it difficult to interpret these findings with any degree of certainty. Additional studies would have to be conducted to confirm this as this was an exploratory analysis.

CHAPTER FIVE: EXPERIMENT TWO

In general, when assessing neural activity, the goal is often to match the stimuli across conditions as closely as possible while changing the circumstances required for processing the stimuli (Luck, 2014). In Experiment One, the cues differed perceptually which may have contributed to differences in neural activity. In this experiment, the cues were perceptually equivalent, but the type of memory trace differed. Like Experiment One, participants in the categorical cue condition should have had to rely on LTM. In contrast, participants in the specific cue condition should have had to rely on shorter-term, episodic memory traces created during the memory encoding phase at the beginning of the experiment (see Figure 19). The purpose of the specific cue condition was to have a condition conceptually similar to the pictorial cue condition (in which only one specific item was always the target) but visually similar to the categorical cue condition from Experiment One. This condition served as an intermediary step between pictorial and categorical cues. Because the specific condition was expected to mirror the pictorial condition, the hypotheses, and rationale for the hypotheses, were similar to Experiment One, except for posterior gamma power and temporal-posterior synchrony. Posterior gamma was hypothesized to play a role in “assembling” an attentional template by extracting features from LTM and binding them into a usable percept. This process was expected to be similar with both conditions, and thus posterior gamma activity was not assessed in this study. Temporal-posterior synchrony was hypothesized to be indicative of word processing and, in both conditions, the cue was a word and thus was not expected to be different. Accordingly, temporal-posterior synchrony was also not assessed. A summary of all of the hypotheses for Experiment Two can be found in Table 5.

Table 5. Hypotheses for Experiment Two.

Analysis	Specific	Categorical
Manual		
Accuracy	More	Less
RT	Faster	Slower
Eye Metrics		
Guidance	Stronger	Weaker
Verification Time	Faster	Slower
Power		
Frontal Theta	More	Less
Posterior Alpha	Less	More
Synchrony		
Frontal-Posterior	Stronger	Weaker
Frontal-Temporal	Weaker	Stronger
Brain-Behavior		
Frontal-Posterior/Guidance	Stronger	Weaker

Methods

Experiment two is identical to Experiment One except for the following exceptions.

Participants

This experiment was a reanalysis of an experiment designed and collected by Schmidt and colleagues at Stony Brook University. Seventeen participants were recruited from Stony Brook University. 67% were female and the average age was 21.7 years old. Participants had normal or corrected-to-normal vision and were English-speaking by self-report. Participants received course credit for completing the experiment. The Stony Brook University IRB approved the experimental protocol, and the participant gave verbal informed consent before participation.

Design and Procedure

The design of Experiment Two was identical to Experiment One except the two conditions, categorical text cues and specific text cues, were within-subjects. In the categorical cue condition, the text cue indicated the category of the target for the upcoming trial, identical to Experiment One. In the specific text cue condition, the text cue corresponded to a specific stimulus studied and memorized before the task began. Also, there were fewer categories, and thus more category target repeats to match the number of targets in the specific cue condition.

Memory Encoding Phase

Participants were given a printout with a table of all possible categorical and specific text cues. The corresponding image was in the cell below the text cue if the text cue was specific. No image would be in the cell if the text cue was categorical. Participants were instructed to study the list for the duration of the EEG setup (approximately 30 minutes, see Figure 19). At the end of the setup, the research assistant tested the participant's memory of the table by saying the text cue and asking if the text cue was categorical or specific. If it was a specific text cue, participants were then asked to describe the corresponding stimulus verbally. Participants could start the search task if they could accurately describe the stimulus's shape, orientation, and color. If they incorrectly identified the type of cue (categorical or specific) or stimulus description, they were asked to study the list and were tested again. This was repeated until 100% accuracy was achieved.

apple	bench	bird	book	boot	broom	brush	bug
?			?		?		
cake	car	cat	chair	clock	dog	drum	fish
?	?			?			?
fork	frame	frog	gun	hat	iron	key	knife
?	?			?		?	
lamp	lock	mask	moth	pan	pipe	plate	purse
?	?			?	?		
rifle	shell	sofa	sword	table	tank	tool	truck
	?		?	?	?	?	

Figure 19. *Text cue memorization sheet for participants. The cells that contained an image indicated that the category label shown would be the exact target in the search display. The cells that contained a question mark indicated a categorical cue in which 1 of 10 exemplars from the category could be the target in the search display (participants were not informed of the number of exemplars). This resulted in a single target for all specific text cues and a unique target on every trial in the categorical cue condition.*

Search task

The search task procedure was identical to Experiment One except for cue type, described in detail in the Stimuli section. Specific and categorical text cues trials were interleaved.

Stimuli

The stimuli for this experiment were also obtained from the Hemera Photo Object database and other web sources. 40 categories were used in the experiment which were randomized and counterbalanced between the categorical cue condition and the specific text cue condition. All text cues were from a basic-level category. Categorical target objects were trial unique and specific cue target objects were repeated ten times. Distractors were picked randomly but were chosen from basic-level categories different from the target categories. The length of the text cues ranged between three (1.35°) to five letters (3.3°). Items in the search display were each resized to 1.35°. Text cues were counterbalanced across participants. Each category appeared in the categorical and specific cue conditions approximately the same number of times (though this balancing was not complete with 17 participants).

Data Preprocessing

The data were preprocessed in the same manner as Experiment One. After artifact rejection, two participants were excluded. In the specific cue condition, an average of 12% (minimum: 5%, maximum: 22%) of the trials were discarded. In the categorical cue condition, an average of 12% (minimum: 4%, maximum: 22%) of trials were discarded. This left 15 participants in the experiment.

Results

Accuracy and Response Time

Paired samples t-test revealed no differences in accuracy, t (14) = 1.12, $p = .28$, $d = .29$ but faster RTs with specific texts cues, t (14) = -26.23, $p < .001$, $d = -6.77$. Means and standard deviations can be found in Table 6.

Eye Metrics

Search guidance was stronger, t (14) = 7.12, $p < .001$, $d = 1.84$, and target verification was faster, t (14) = -17.21, $p < .001$, $d = -4.44$, with specific text cues relative to categorical text cues. The means and the standard deviations can be found in Table 6. These findings demonstrate that a specific text cue resulted in superior search performance across a range of measures.

Table 6. Means and Standard Deviations for Experiment Two.

Metric	Specific Cues	Categorical Cues
Accuracy (%)	.99 (.01)	.99 (.01)
RT (ms)	954 (151)	11801(155)
Initial Saccade Direction (%)	.57 (.11)	.45 (.07)
Verification Time (ms)	444 (98)	565 (97)

Note. Standard deviations are in parentheses.

Power Analysis

Electrodes were chosen in the same manner as Experiment One, resulting in the same electrode selection. See Figure 20.

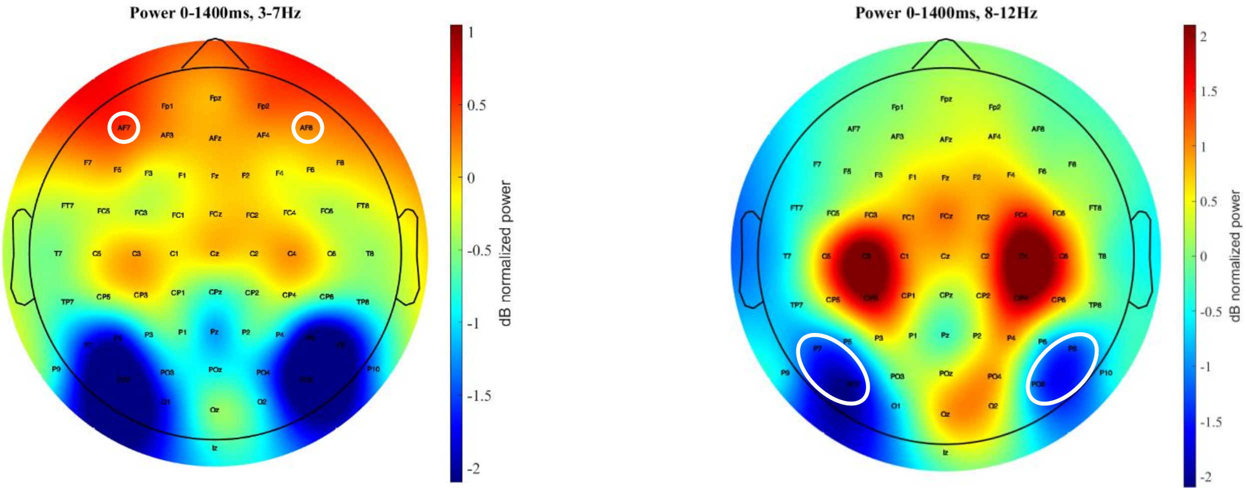


Figure 20. Total Power Maps for Experiment Two. Each map shows the total dB normalized power, averaged over all participants, and the time (cue and RI) and frequency (theta and alpha) specified above each topographical map. White circles on each map indicate the presumed peak of power at the given frequency band during the specified time interval.

Theta

Frontal theta power was expected to be larger for specific text cues than categorical cues because theta enhancement is indicative of encoding new episodic memory traces (Klimesch, 1999; 2012). However, there were no significant differences between specific text cues and categorical cues (largest nonsignificant pixel, cue: $Z = -1.30$, $p = .19$, RI: $Z = -1.40$, $p = .16$). See Figure 21.

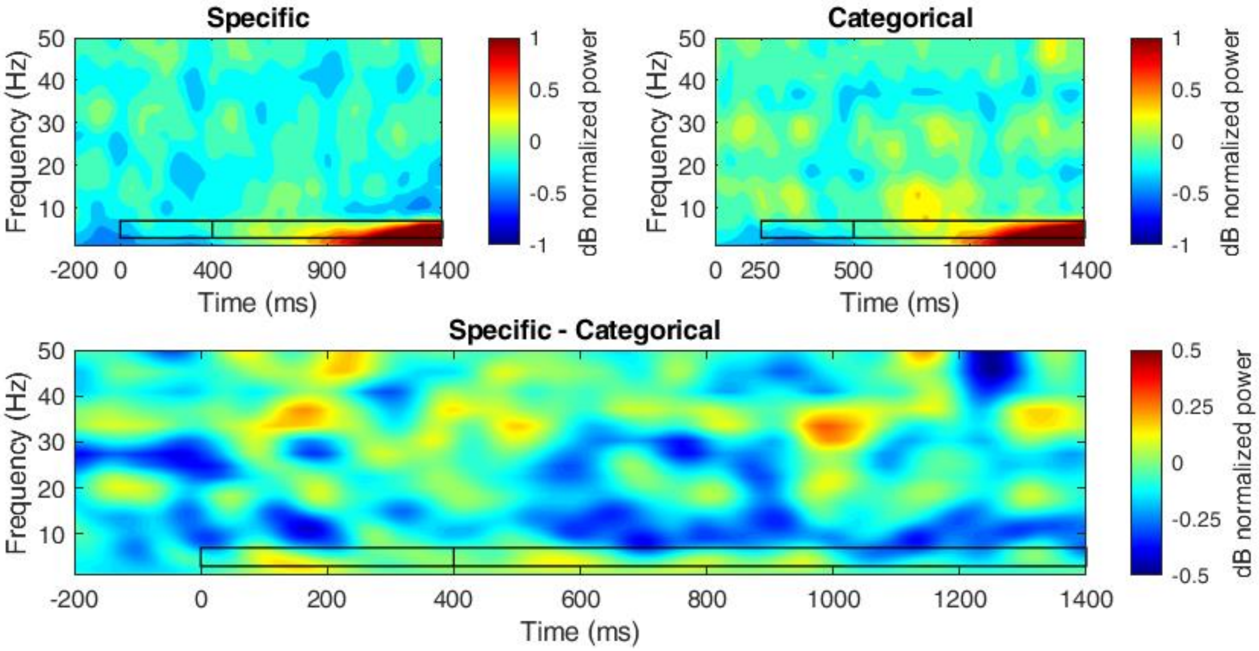


Figure 21. *Theta Power for Experiment Two. Average power dB normalized power at AF7 and AF8 in the specific cue condition (top left), in the categorical cue condition (top right), and the difference between the specific and categorical cue conditions (bottom row). The boxes drawn on each plot indicate the cue and RI in the theta frequency band, respectively.*

Alpha

Posterior alpha suppression was expected to be larger with categorical cues relative to specific text cues as alpha suppression increases with semantic processing demands (Klimesch et al., 1997b; Klimesch et al., 1997a). Furthermore, this effect will be lateralized (due to the lateralized cue screen), resulting in larger alpha suppression in the contralateral hemisphere (relative to the cue; Medendorp et al., 2007; van Dijk et al., 2010; Reinhart & Woodman, 2014; de Vries et al., 2017; van Driel et al., 2017). However, there were no significant differences for either hypothesis (contra – ipsi, specific cue: largest nonsignificant pixel, $Z = -1.49$, $p =.14$, RI: largest nonsignificant pixel, $p = .36$; categorical cue: largest nonsignificant pixel, $Z = -1.48$, $p = .14$, RI: largest nonsignificant pixel, $p = .35$; specific- categorical, largest nonsignificant pixel, cue: $Z = -.68$, $p = .50$, RI: $Z = 1.01$, $p = .31$). See Figure 22.

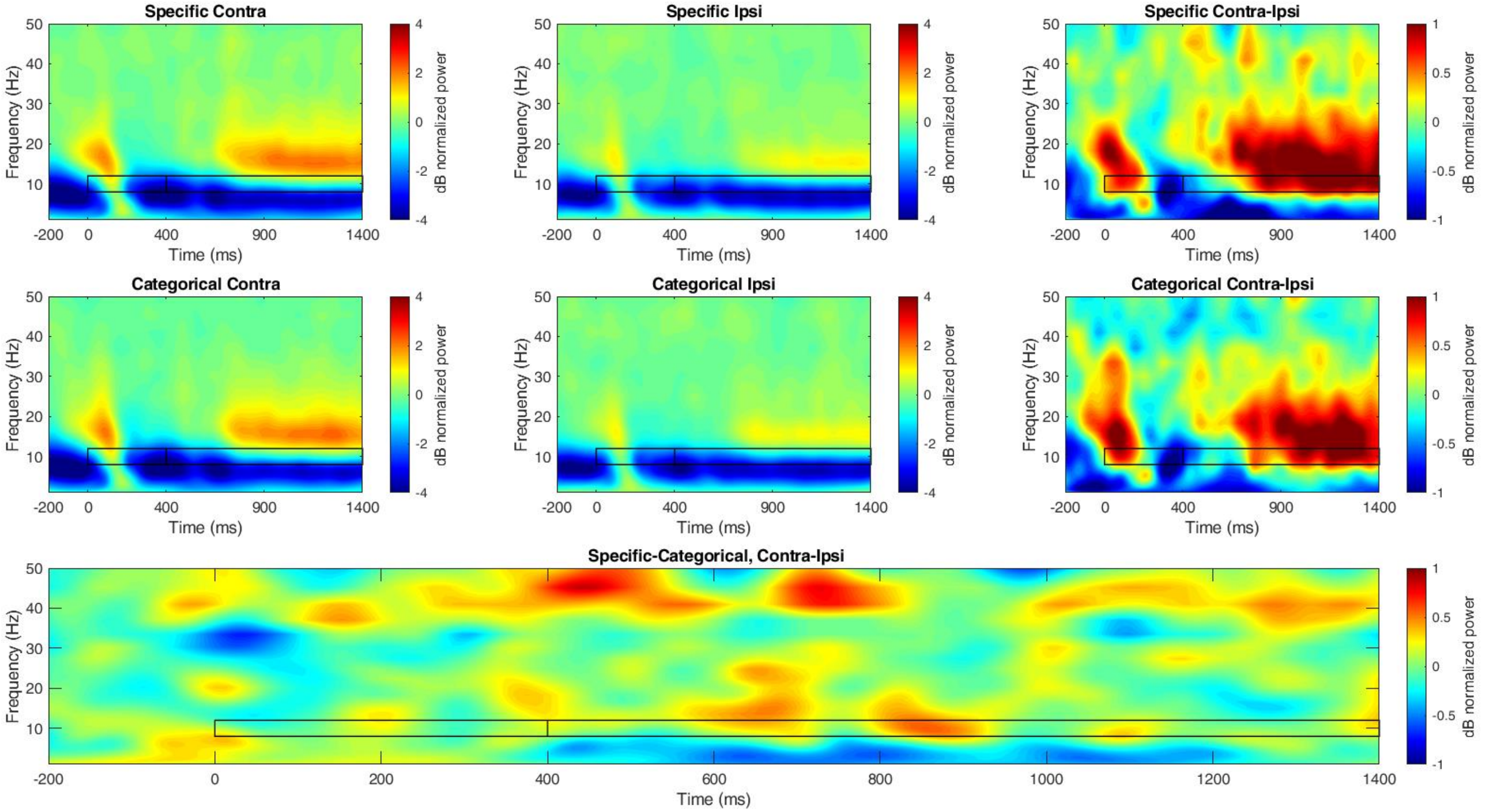


Figure 22. Alpha Power for Experiment Two. Plots in the top row are average dB normalized power in the specific cue condition, and plots in the middle row are power in the categorical cue condition. Contra plots are averaged from the P8 and PO8 electrodes, and Ipsi plots are averaged from the P7 and PO7 electrodes. Contra- Ipsi plots are a subtraction of the average of Contra plots and Ipsi plots. The bottom row is a subtraction of the Specific and Categorical Contra-Ipsi plots. The boxes drawn on each plot indicate the cue and RI in the theta frequency band, respectively.

Synchrony

Electrodes for this analysis were chosen in the same manner as Experiment One. See Figure 23.

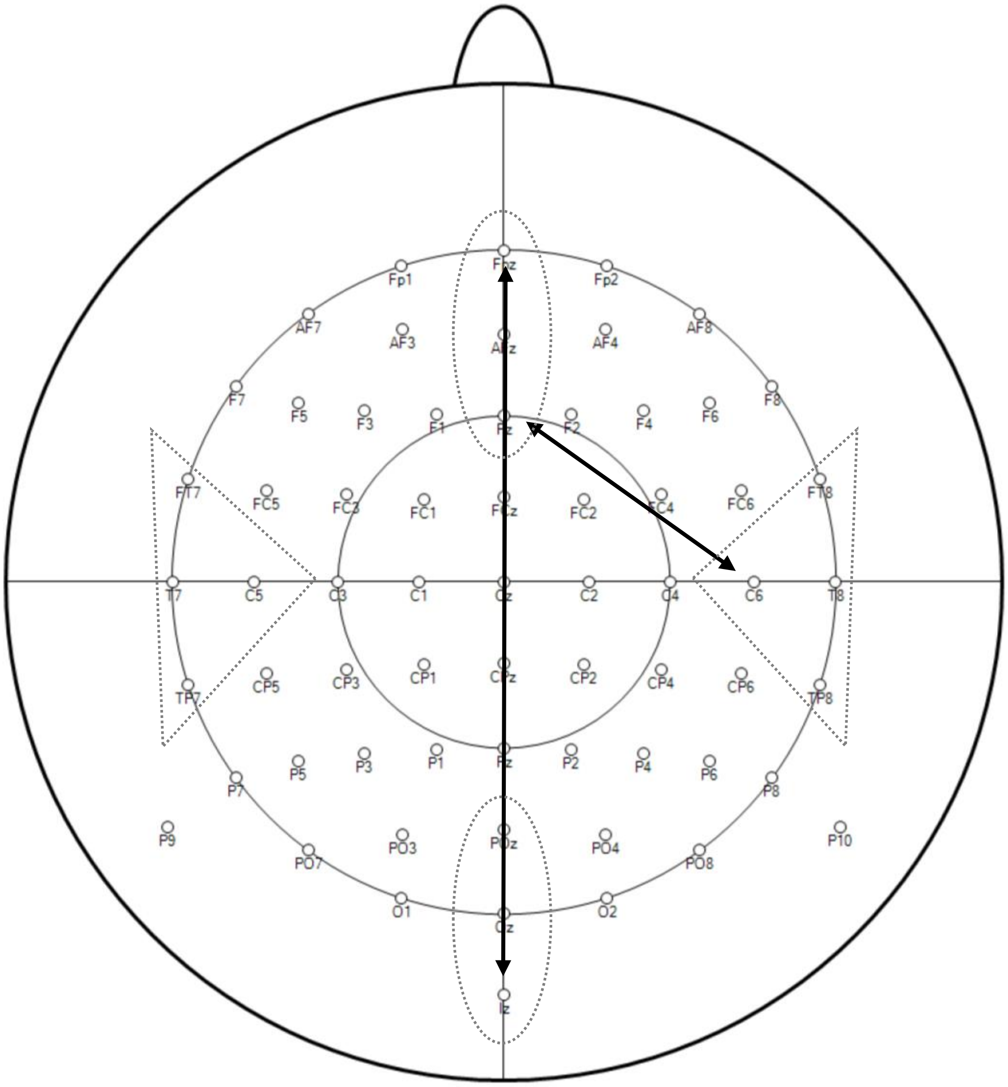


Figure 23. Head map of Peak Synchronous Activity for Experiment Two. This figure depicts the strongest frontal-posterior (Fpz-Iz) and frontal-temporal (Fz-C6) connections out of a pre-selected subset of electrodes, circled in gray.

Frontal-Posterior

Like Experiment One, Fpz and Iz were the stronger frontal-posterior connection. Because participants should have specific knowledge of the target details in the specific text cue condition, top-down control was expected to be stronger, and thus frontal-posterior synchrony was also expected to be stronger. No differences were observed with ISPC (largest nonsignificant cluster, cue: $p = .97$, RI: $p = .99$) or PLI (largest nonsignificant cluster, cue: $p = .24$, RI: $p = .49$), nor were any other significant differences observed. See Figure 24.

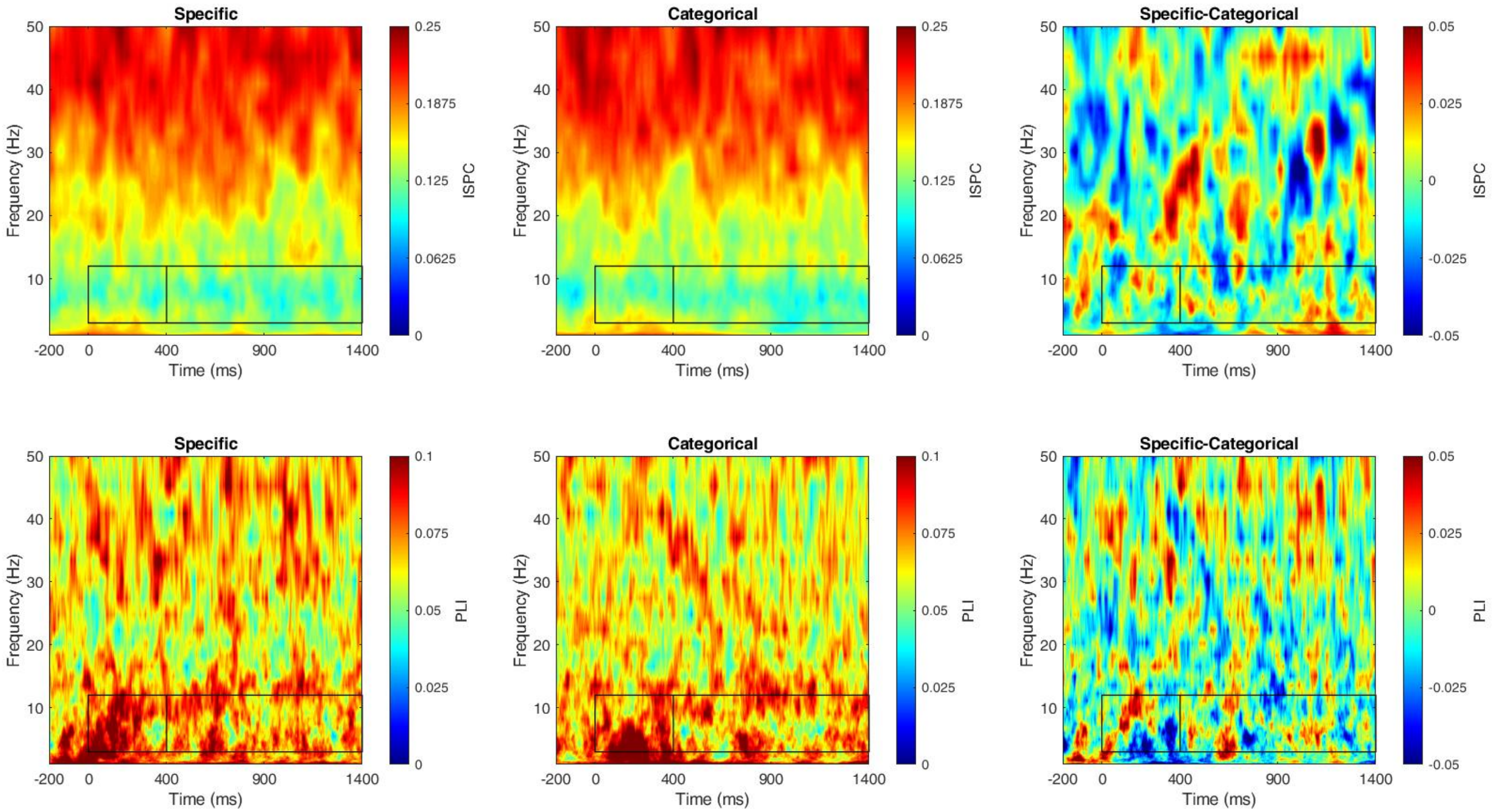


Figure 24. *Frontal-Posterior Synchrony for Experiment Two. The top row depicts the ISPC between Fpz and Iz electrodes in the specific (left), the categorical cue (center), and the difference between the two (right). The bottom row depicts the PLI.*

Frontal-Temporal

The strongest frontal-temporal connection was Fz and C6. Frontal-Temporal synchrony was expected to be larger with categorical cues as there is a greater dependence on categorical information extracted from temporal regions to provide frontal areas with information to exert top-down attentional biasing for search. However, there were no significant differences in ISPC (largest nonsignificant cluster, cue: $p = .93$, RI: $p = .88$) or PLI (largest nonsignificant cluster, cue: $p = .22$, RI: $p = .44$). See Figure 25.

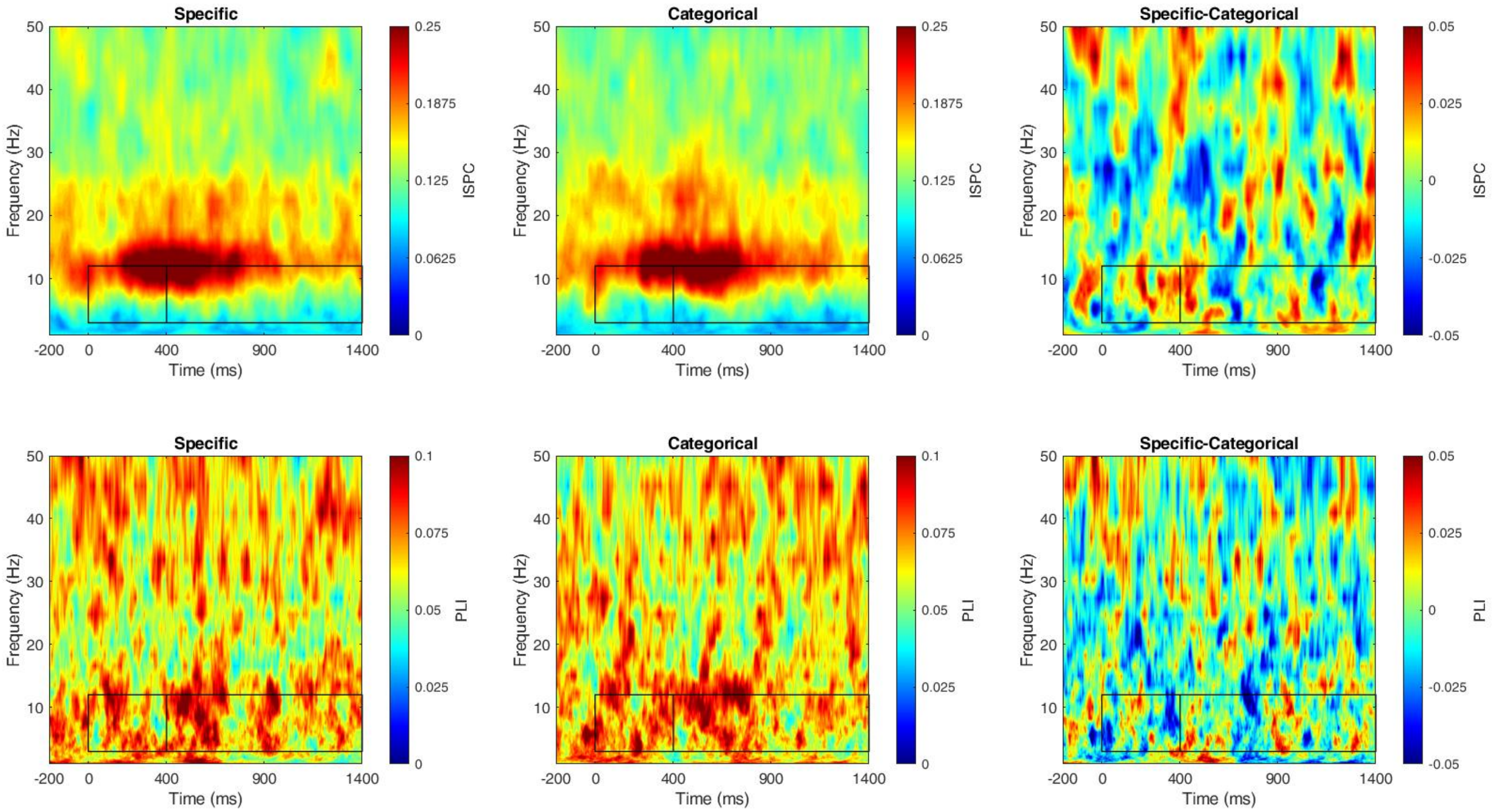


Figure 25. Frontal-Temporal Synchrony in Experiment Two. The top row depicts the ISPC between Fz and C6 electrodes in the pictorial (left,) the categorical cue (center), and the difference between the two (right). The bottom row depicts the PLI.

Brain-to-Behavior Relationship: Guidance and Frontal-Posterior Synchrony

Based on the model, it was expected that a two (good guidance or bad guidance) by two (specific text cue or categorical cue) mixed factor ANOVA should produce a main effect of guidance, in which frontal-posterior synchrony is more robust in good guidance trials relative to bad guidance trials regardless of cue type and a main effect of cue in which frontal-posterior synchrony is more robust with specific text cues irrespective of the type of guidance. However, based on the results of Experiment One, it was expected that specific text cues would resemble the results from pictorial cues, and the categorical cues would replicate, resulting in a similar set of interactions as Experiment One. A summary of the ISCP and PLI results can be found in Table 7. The frontal-posterior electrodes from the synchrony analysis from Experiment Two (Fpz and Iz) and time-frequency windows from Experiment One were used for this analysis.

Alpha-Cue

No significant effects were observed (guidance, ISPC: F (1, 14) = .07, p = .80, η_p^2 = .01, PLI: F (1, 14) = .06, p = .81, η_p^2 = .004; cue type, ISPC: F (1, 14) = .19, p = .67, η_p^2 = .01, PLI: F (1, 14) = 1.73, p = .21, η_p^2= .11; interaction, ISPC: F(1, 14) = .06, p = .81, η_p^2 = .01, PLI: F (1, 14) = .25, p = .63, η_p^2 = .02). See Figure 26.

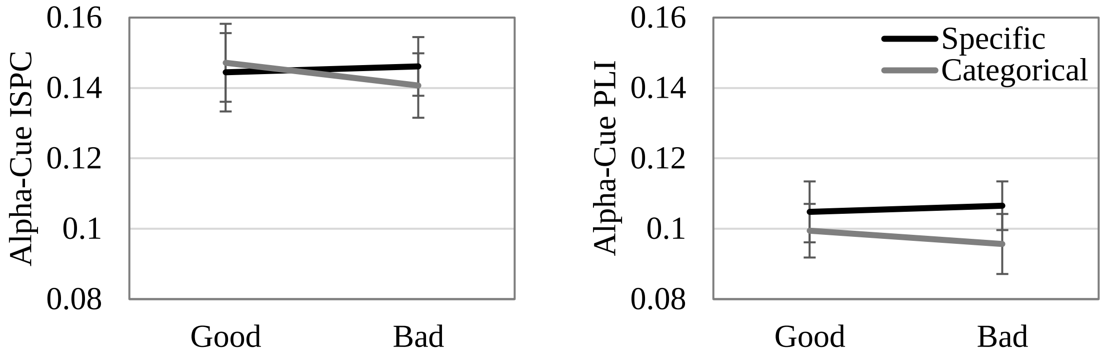


Figure 26. Alpha-Cue ISPC and PLI for Experiment Two. Mean ISPC and PLI per condition in the alpha-cue, time-frequency window. Error bars indicate the SEM.

Alpha-RI

No significant effects were observed (guidance, ISPC: *F* (1, 14) = 1.17, *p* = .30, η_p^2 = .08, PLI: *F* (1, 14) = .13, *p* = .72, η_p^2 = .01; cue type, ISPC: *F* (1, 14) = .02, *p* = .88, η_p^2= .002, PLI: *F* (1, 14) = .68, *p* = .43, η_p^2= .05; interaction, ISPC: *F* (1, 14) = .98, *p* = .34, η_p^2 = .07, PLI: *F* (1, 14) = 1.30, *p* = .27, η_p^2 = .09). See Figure 27.

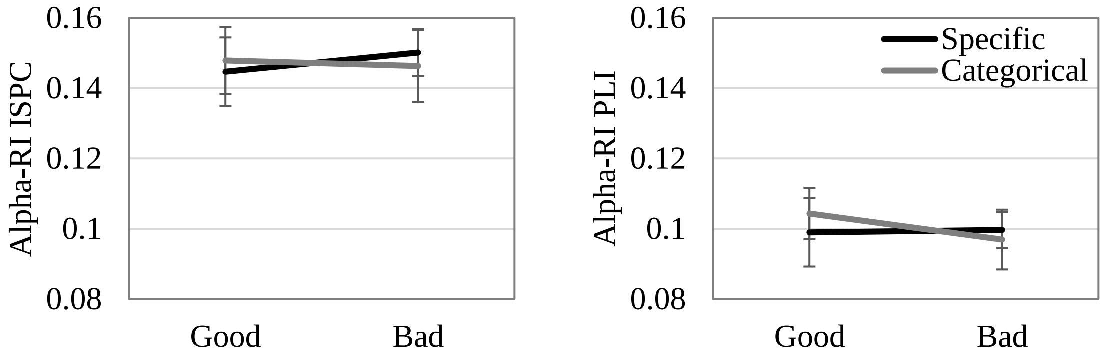


Figure 27. Alpha-RI ISPC and PLI for Experiment Two. Mean ISPC and PLI per condition in the alpha-RI, time-frequency window. Error bars indicate the SEM.

Theta-Cue

No significant effects were observed (guidance, ISPC: *F*(1, 14) = .14, p = .71, η_p^2 = .01, PLI: *F* (1, 14) = .002, *p* = .97, η_p^2 < .001; cue type, ISPC: *F* (1, 14) = 1.06, p = .32, η_p^2= .07, PLI: F(1, 14) = 1.62, p = .22, η_p^2= .10; interaction ISPC: *F*(1, 14) = 1.54, *p* = .24, η_p^2 = .10, PLI: *F* (1, 14) = 1.03, *p* = .33, η_p^2 = .07). See Figure 28.

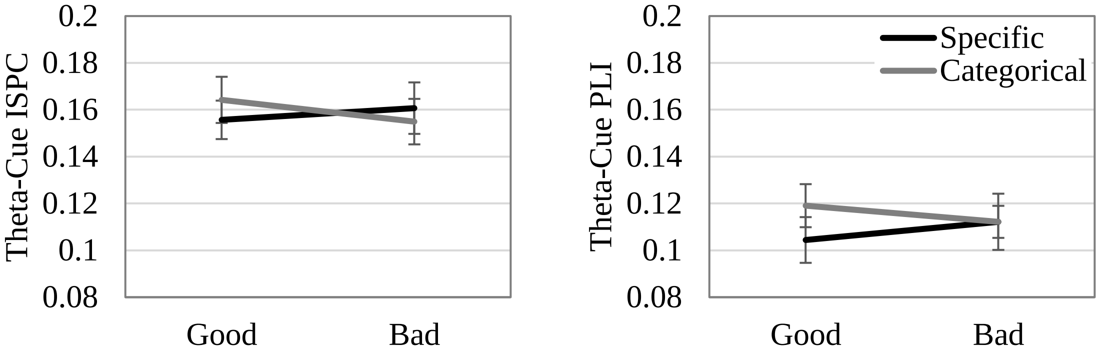


Figure 28. Theta-Cue ISPC and PLI for Experiment Two. Mean ISPC and PLI per condition in the theta-cue, time-frequency window. Error bars indicate the SEM.

Theta-RI

No significant effects were observed with ISPC (guidance: *F*(1, 14) = .33, p = .58, η_p^2 = .02, cue type: *F* (1, 14) = .96, p = .35, η_p^2= .06, interaction: *F*(1, 14) = 2.87, *p* = .11, η_p^2 = .17). With PLI, there was only a significant interaction, *F* (1, 14) = 11.68, *p* = .004, η_p^2 = .46 (guidance: *F* (1, 14) =.85, *p* = .37, η_p^2 = .06; cue type: *F* (1, 14) = .04, *p* = .85, η_p^2= .003). Paired samples t-test indicated stronger synchrony before good guidance trials in the categorical cue condition, *t* (14) = 3.03, *p* = .01, *d* = .78, but not the specific cue condition, *t* (14) = -.80, *p* = .44, *d* = -.21. Independent samples t-tests showed, before good guidance trials, synchrony was stronger after categorical cues relative to specific cues, *t* (15) = -3.68, *p* = .002, *d* = -.92. Before a bad guidance trial, synchrony was stronger after specific cues relative to categorical cues, *t* (15) = 2.45, *p* = .03, *d* = .61. See Figure 29.

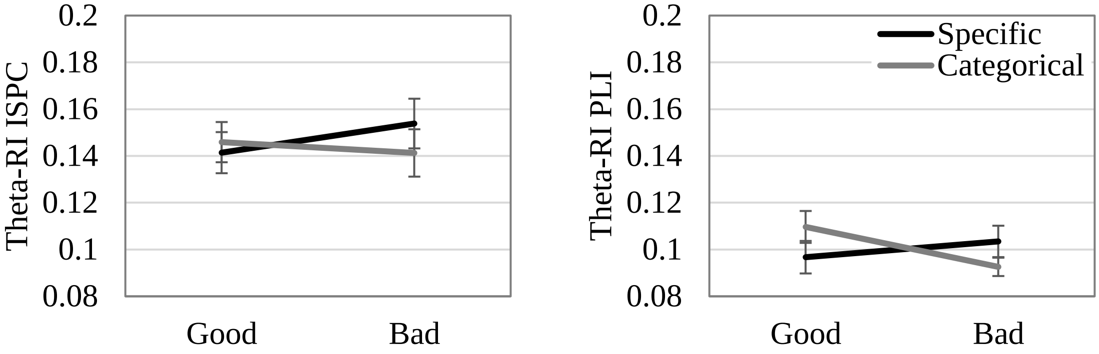


Figure 29. Theta-RI ISPC and PLI for Experiment Two. Mean ISPC and PLI per condition in the Theta-RI, time-frequency window. Error bars indicate the SEM.

Table 7. Summary of Brain-Behavior Results from Experiment Two

Time-Frequency Window	ISPC	PLI	Consistent
Alpha-Cue			
Main Effects			
Guidance	*n.s.*	*n.s.*	✓
Cue Type	*n.s.*	*n.s.*	✓
Interaction	*n.s.*	*n.s.*	✓
Alpha-RI			
Main Effects			
Guidance	*n.s.*	*n.s.*	✓
Cue Type	*n.s.*	*n.s.*	✓
Interaction	*n.s.*	*n.s.*	✓
Theta-Cue			
Main Effects			
Guidance	*n.s.*	*n.s.*	✓
Cue Type	*n.s.*	*n.s.*	✓
Interaction	*n.s.*	*n.s.*	✓
Theta-RI			
Main Effects			
Guidance	*n.s.*	*n.s.*	✓
Cue Type	*n.s.*	*n.s.*	✓
Interaction	*n.s.*		
Paired T-tests			
Specific		*n.s.*	✗
Categorical		Good > Bad	✗
Independent T-tests			
Good		Specific < Categorical	✗
Bad		Specific > Categorical	✗

Discussion

Because specific cues should be more similar to pictorial cues, specific cues were expected to result in stronger search performance. Specific cues did result in better search performance: faster RTs, stronger guidance, and faster verification times. However, accuracy did not differ between cue types due to a ceiling effect as both were at 99% accuracy.

In the power analyses, frontal theta power was expected to be larger for specific cues because it was hypothesized that specific cues would be similar to an episodic memory trace

(Klimesch et al., 1996; Klimesch et al., 1997c; Klimesch et al., 2008; Bastiaansen et al., 2005; Salisbury & Taylor, 2012). This is because participants were told to memorize the stimuli corresponding to each specific cue and thus would not have to rely on semantic memory. Because posterior alpha suppression increases with semantic processing (Klimesch et al., 1997b; Klimesch et al., 1997a), it was hypothesized that it would be larger for categorical cues. Unfortunately, no differences were found in the power analyses.

In the synchrony analysis, frontal-posterior was expected to be stronger in the specific cue condition because participants had specific knowledge of the target details. Conversely, frontal-temporal synchrony was expected to be larger for categorical because of increased semantic processing demands. In both cases, no such patterns were observed differences between specific and categorical cues.

In the brain-to-behavior analysis, the unexpected results from Experiment One were expected to replicate in Experiment Two; generally, specific text cues were expected to result in strong synchrony before a bad guidance trial whereas the opposite was expected with categorical cues. Unfortunately, this analysis mostly yielded null results. One significant interaction was replicated in the theta-RI time-frequency window, but only with PLI. The follow-up t-tests replicated the relationship between good and bad guidance trials with categorical cues in which there was stronger synchrony before good guidance trials. It also replicated the relationship between pictorial and categorical cues in good guidance trials and bad guidance trials in which categorical cues resulted in stronger synchrony prior to good guidance trials and specific cues in stronger synchrony prior to bad guidance trials. This bolsters support for these findings in Experiment One despite only being observed with PLI in both experiments. Furthermore, the numerical pattern of nonsignificant results from this analysis mirrored the results in Experiment One. Specifically, the crossover interaction in which stronger synchrony preceded bad guidance trials in the specific cue condition and stronger synchrony preceded good guidance trials in the categorical cue condition. In that vein, specific cues more closely resemble pictorial cues, but nothing can be inferred because this was nonsignificant.

A limitation of this study is that participants can treat the specific text cue as a categorical cue. However, if this was the case, search performance and the neural dynamics should look similar between cue types. On the contrary, search performance differed, but the neural dynamics did not, suggesting the cues were treated differently to some degree. In the specific cue condition, the participant knew the exact shape, color, and orientation of the target, whereas, in the categorical cue condition the participant needed to “guess” based on the characteristics of the category. In terms of neural activity, perhaps these analyses did not or could not distinguish between these two possibilities. However, knowing the exact target features versus guessing the target features would certainly lead to a search benefit.

CHAPTER SIX: GENERAL DISCUSSION

For categorical search to produce guidance, participants must retrieve the perceptual features that pertain to the target category from LTM to direct attention to the target. However, to date, no neurophysiological data confirm this process. The goal of this dissertation was to identify potential neural markers of categorical representations that are used for visual search. In Experiment One, participants completed a pictorial or categorical search. This experiment compared the EEG activity elicited from a pictorial cue to that of a categorical cue. Because the behavioral and neurophysiological literature regarding pictorial cues is more well-established, it should have provided a solid foundation for hypotheses and points of comparison for categorical cues.

In the pictorial cue condition, lateralized posterior alpha suppression was observed, in which alpha suppression was larger in the contralateral posterior electrodes, consistent with previous findings (Medendorp et al., 2007; van Dijk et al., 2010; Reinhart & Woodman, 2014; de Vries et al., 2017; van Driel et al., 2017). Unfortunately, the rest of the hypotheses were not confirmed. The biggest obstacle to investigating categorical attentional templates, and even real-world pictorial templates, is the sparse literature. Consequently, many of the hypotheses were based on literature tangentially related to these types of representations (i.e., semantic memory processing; Klimesch et al., 1997a; Klimesch et al., 1997b; Schnack et al., 2003; Bastiaansen et al., 2005; Salisbury & Taylor, 2012). Critically, paradigms designed to test semantic memory, or working memory more generally, do not involve the attentional mechanisms required to direct, or guide, spatial attention suggesting that attentional templates may be unique to visual search and highly specific, making much of the background literature less applicable.

Another large discrepancy between the pictorial and text cue conditions, and the broader neurophysiological literature, is the difference between simple and real-world stimuli. Although the previous literature used pictorial representations of the target, typically, simple stimuli were used (Di Russo et al., 2003; Sauseng et al., 2004; Vogel & Machizawa, 2004; Sauseng et al., 2005; Vogel et al., 2005; Medendorp et al., 2007; Palva et al., 2010; van Dijk et al., 2010; Carlisle et al., 2011; Woodman & Arita, 2011; Gunseli et al., 2014a; Gunseli et al., 2014b; Fukuda et al., 2015; Fukuda et al., 2016; van Driel et al., 2017 de Vries et al., 2017; Rajsic et al., 2019). In these experiments, the cues were real-world objects or words naming the real-world object categories. For various reasons, real-world stimuli may result in different patterns of brain activity. Real-world stimuli are more complex, visually and categorically. Visually, a real-world stimulus contains many features, making it difficult to quantify how features are selected and difficult to know which ones are selected for attentional biasing. Furthermore, previous work has indicated that a subset of visual features, such as color and orientation, are most effective at guiding attention (Wolfe & Horowitz, 2004; Wolfe & Horowitz, 2017). Studies using simple stimuli typically use a single or a small set of target-defining features, such as shape, color, or orientation, making it clear what feature(s) was selected and its utility in guiding attention.

Additionally, real-world stimuli not only have visual properties, but they also have categorical properties. While simple stimuli can technically be classified into categories, in most cases, categorical information is not useful (but see, e.g., Jonides & Gleitman, 1972; Wolfe et al., 1992). Conversely, when using real-world stimuli, their categorical properties allow participants to use this information during search, especially when the distractors are from different categories. Instead of focusing on the exact features visible during the cue, participants can use more general features common to the target category (i.e., find any teddy bear amongst non-teddy bears). The availability of multiple strategies (i.e., encode/maintain the target features or encode/maintain the target category) to complete the search likely introduces noise into the data that may make it hard to reproduce previous findings that utilized simple stimuli. Although this makes this research more difficult, it is important to establish and characterize the differences between the neural response to simple stimuli versus more complex items.

Much of what is known about visual attention is derived from simple stimuli, but these complex items are more relevant to visual attention in everyday life. The fact that this data shows a negative relationship between guidance and frontal-posterior synchrony with real-world stimuli, while previous research using simple stimuli showed a positive relationship between RT and frontoparietal synchrony (van Driel et al., 2017) highlights the importance of conducting visual search studies with more realistic stimuli. Accordingly, future work should directly compare the neural dynamics of pictorial search with simple stimuli versus real-world stimuli. Although previous simple stimuli studies have demonstrated a positive relationship between alpha/theta frontoparietal synchrony and search performance (as measured by RT, van Driel et al., 2017), this relationship has not been demonstrated with guidance. If the relationship between synchrony and guidance is also positive, then the complexity of features and/or the categorical information may be related to the negative relationship between synchrony and guidance observed in the pictorial condition.

It is worth noting differences only emerged when separating trials in which the attentional template was “good" from trials in which it was “bad.” The pattern of synchronous activity was often the complete opposite. With this in mind, future work should consider separating their data in a similar fashion. In the case of these studies, initial saccade direction is especially useful as it is a very early measure of attention (Chen & Zelinsky, 2006). Other guidance measures, such as RTs and scan path ratios, may be influenced by later processing in the search display (Hollingworth, 2005; Castelhano & Henderson, 2007).

Experiment Two compared categorical cues and specific text cues. The purpose of this experiment was two-fold: 1) replicate the categorical cue condition results from Experiment One and 2) provide an intermediate condition that was perceptually matched to the categorical cue condition while replicating the specific target identity of the pictorial cues. By perceptually matching the categorical cue condition (i.e., both were text), it would be possible to determine if the hypothesized differences between pictorial and categorical cues were due to the conceptual (an exact target versus a category) or the perceptual (an image versus text) differences. If the specific cue condition looked similar to the pictorial cue condition, the differences observed in Experiment One were likely due to the conceptual differences; pictorial cues pertained to a single item, whereas categorical cues pertained to a wide array of items recalled from LTM. If the specific cue condition looked more like the categorical cue condition, the differences between pictorial and categorical cues were likely due to perceptual differences (images vs. words).

Although search performance was stronger for specific cues, there were minimal differences in neural activity; most categorical cue results did not replicate and there were very few differences between cue types. Although this experiment yielded largely nonsignificant results, the patterns were promising. In the brain-behavior analysis, many results from the theta-RI were replicated and the relationship between specific and categorical cues mirrored that of the relationship between pictorial and categorical cues. Like the categorical cue condition in Experiment One, synchrony was stronger before good guidance trials (compared to bad), and in those trials, categorical cues resulted in stronger synchrony (compared to specific). In bad guidance trials, specific cues resulted in stronger synchrony. Although these results were only observed with PLI, the consistency between both studies suggests a rather robust effect. In the rest of the analyses, the pattern of categorical results was numerically very similar to Experiment One, and the pattern of specific cue results was numerically very similar to pictorial cues. However, a larger issue with this experiment was the small sample size. According to a post hoc power analysis, the preferred sample size would have been closer to 36 participants (using the PLI results from the brain-behavior analysis in Experiment One to estimate effect sizes). Moreover, participants only completed half the number of trials (relative to Experiment One) due to the within-subjects design. Perhaps this experiment would have been more successful with the larger sample size and a greater number of trials.

Future work should run a revised version of Experiment Two with the following changes. First, data should be collected from the appropriate number of participants. Second, this experiment should increase the number of trials for each cue condition. Lastly, the level of difficulty should be increased in each condition. A limitation of both studies was the high accuracy in each condition, likely caused by the ease and simplicity of the tasks. In both experiments, the search display was comprised of one target and three distractors, each from distinct categories. This would result in a very easy search. It is likely that participants did not need to remember the exact details of the target (pictorial or specific cues) or did not need to extract a large amount of CCFs (categorical cues). This could explain why there were performance differences but minimal brain activity differences. The level of difficulty can be increased by including within-category distractors thereby increasing the utility of the cue. In all conditions, cues could be at the subordinate level and distractors could be pulled from the corresponding basic level category (i.e., cued with a picture of or the word husky, non-husky dogs as distractors). Furthermore, this would eliminate the possibility of participants in the specific cue condition using a categorical strategy. Hopefully, with these changes, the differences between the cue types will be more apparent.

Although the models and corresponding hypotheses set forth were far from the actual results, what do the results we have tell us about the attentional template? It was argued earlier that if neural activity were considered the "attentional template," it would likely positively correlate with subsequent search performance. Regarding pictorial cues, frontal-posterior alpha (strongly supported) and theta synchrony (weakly supported), along with frontal-temporal and posterior-temporal alpha synchrony, were negatively correlated with search guidance. If a positive relationship is required, these results suggest alpha or theta synchrony (in the connections tested) does not measure the attentional template. Conversely, frontal-posterior alpha (weakly supported) and theta (strongly supported during the cue, weakly during the RI in Experiment One and two) synchrony was positively correlated with search performance in the categorical cue condition. This relationship opens the possibility that these connections may reflect at least some aspect of the attentional template when categorical features must be retrieved from LTM. Alternatively, perhaps frontal-posterior synchrony does measure the attentional template but is independent of performance. In other words, it cannot distinguish between a good template and a bad template but rather indexes the amount of information contained within a template (similar to CDA). More specifically, frontal-posterior alpha synchrony may index the attentional components and frontal-posterior theta synchrony may index the memory components of a template. However, much more work would be needed to say this with certainty.

Novel Study Proposal

During the proposal phase of this dissertation, the committee requested a novel study be proposed and outlined in detail, as the experiments in this study were previously designed and collected by Schmidt and colleagues at Stony Brook University. Accordingly, the following study should be conducted to gather corroborating evidence for the interpretation of these results.

This study aims to establish whether stronger frontal-posterior alpha and theta synchrony are indicative of a categorical attentional template by employing a load manipulation; if frontal-posterior alpha and theta synchrony is or is related to the attentional template, it should increase with load.

Participants

Per the power analysis conducted for Experiment Two, data from at least 40 participants should be collected.

Design and Procedure

The study will have three conditions, one single categorical cue (black boots), two categorical cues from the same category (i.e., black boots, brown boots), and two categorical cues from different categories (i.e., black boots, red cup). To ensure that participants use the color and the categorical information provided in the cue(s), the distractors in the search display will be different colored exemplars from two target categories. Furthermore, to minimize potential perceptual differences in the search displays, the search displays will be held constant across conditions. For example, the search display would consist of two non-black or brown boots and two non-red cup distractors and would be used three times, once in each condition. The three conditions will be randomized and interleaved. All experimental parameters (timing, type of stimuli, etc.) would be the same as these experiments, except the cue screens in this experiment will not be lateralized. Instead, the cue(s) will be placed in the center of the screen as the effects observed were not lateralized. Each condition will have 210 trials to further ensure sufficient power.

Apparatus

This study will use eye tracking and EEG.

Data Analyses

For the behavioral data, accuracy, RT, and guidance as measured by initial saccade direction will be evaluated. The brain-behavior analysis will be applied to the EEG data using the same analysis parameters.

Hypotheses

Accuracy should be similar in all three conditions. The lack of an effect in accuracy will ensure that any possible neural differences are not due to differences in difficulty, which is preferable. However, RT and guidance should be best with a single cue, followed by the two-same, followed by the two-different.

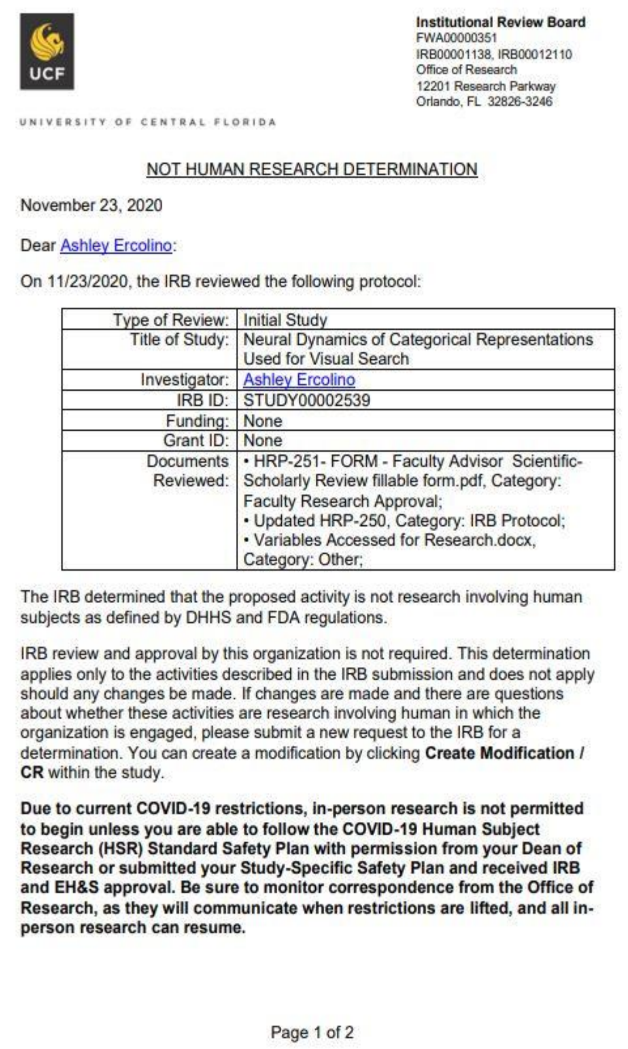
In the brain-behavior analysis, trials will be separated by good and bad guidance. Like the findings in Experiment One, the relationship between categorical guidance and frontal-posterior alpha and theta synchrony is expected to be positive in all three conditions. However, if alpha and theta synchrony is indicative of a categorical attentional template, synchrony should increase as more information is needed and stored for attentional biasing. Accordingly, a single categorical cue should exhibit less synchrony than two categorical cues, same or different. The most interesting comparison will be between two-same and two-different categorical cues. Although there are two cues in both conditions, there is only one category and two colors in the two-same condition, whereas two-different is two categories and two colors. If frontal-posterior alpha and theta synchrony are only sensitive to basic visual features such as color, there should be no difference between the two conditions. However, if frontal-posterior synchrony is sensitive to categorical information, two-different should result in stronger frontal-posterior alpha and theta synchrony.

Conclusion

In conclusion, these results demonstrated an interesting dissociation between pictorial and categorical cues. Results suggested less attention (frontal-posterior alpha synchrony, strongly supported) and less memory (frontal-posterior theta synchrony, weakly supported) usage during and after a real-world pictorial cue results in stronger search guidance whereas more attention (weakly supported) and more memory usage during (strongly supported) and after (moderately supported) a categorical cue results in stronger search guidance. Before good guidance trials, attention during the cue and RI did not differ between pictorial and categorical cues in either synchrony measure. However, there was more memory, perhaps memory retrieval, during and after a categorical cue compared to pictorial cues (weakly supported). When guidance was bad, there was more attention and memory with pictorial cues compared to categorical cues (strongly supported during the cue and weakly supported during the RI).

Although the pictorial results were surprising, what do these findings say specifically about the neural dynamics of categorical representations used for visual search? When considering only the most strongly supported findings, it is clear that frontal-posterior theta synchrony during the cue is positively related to strong categorical search performance. If frontal-posterior theta synchrony is, in fact, indicative of memory encoding and retrieval as has been previously shown in the literature in other contexts (Sarnthein et al., 1998, Sauseng et al., 2004; Summerfield & Mangels, 2005), these findings are the first of its kind to identify a neural marker related to the retrieval of categorical information used to direct attention during search.

APPENDIX IRB APPROVAL



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NOT HUMAN RESEARCH DETERMINATION

November 23, 2020

Dear Ashley Ercolino:

On 11/23/2020, the IRB reviewed the following protocol:

Type of Review:	Initial Study
Title of Study:	Neural Dynamics of Categorical Representations Used for Visual Search
Investigator:	Ashley Ercolino
IRB ID:	STUDY00002539
Funding:	None
Grant ID:	None
Documents Reviewed:	• HRP-251- FORM - Faculty Advisor Scientific-Scholarly Review fillable form.pdf, Category: Faculty Research Approval; • Updated HRP-250, Category: IRB Protocol; • Variables Accessed for Research.docx, Category: Other;

The IRB determined that the proposed activity is not research involving human subjects as defined by DHHS and FDA regulations.

IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities are research involving human in which the organization is engaged, please submit a new request to the IRB for a determination. You can create a modification by clicking **Create Modification / CR** within the study.

Due to current COVID-19 restrictions, in-person research is not permitted to begin unless you are able to follow the COVID-19 Human Subject Research (HSR) Standard Safety Plan with permission from your Dean of Research or submitted your Study-Specific Safety Plan and received IRB and EH&S approval. Be sure to monitor correspondence from the Office of Research, as they will communicate when restrictions are lifted, and all in-person research can resume.

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If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Kamille C. Birkbeck

Kamille Birkbeck
Designated Reviewer

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