Are All Relational Judgments the Same?
An Investigation of Two Decision Models Using Event-Related-Potentials

by

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Abstract

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Two neurocognitive models of decision-making, Iterative Reprocessing (IR) and Accumulator models have been proposed to explain subjective conceptual and objective perceptual judgments, respectively. To date, there is little evidence from humans in support of the central tenet of both models that there is a direct relation between duration of evaluative processing and judgment difficulty. Further, it is not known if a single model can explain all types of judgments. To compare the timing and location of neural activations underlying decision-making, event-related potentials (ERPs) were recorded while participants completed judgments in a 2-by-2 factorial design with factors of Judgment Type (Objective, Subjective) and Domain (Semantic, Perceptual). To assess the effect of difficulty on evaluative processing, difficulty was manipulated for Objective judgments. Confirming the finding of Johnson and colleagues (2011) both Early and Late LPCs were elicited by all judgments creating an evaluative processing interval. The duration of ERPs reflecting evaluative processing (i.e., accumulation, working memory, selection, monitoring) increased as a function of judgment difficulty for Objective Semantic and Perceptual judgments, providing some of the first direct evidence that duration of this processing is related to difficulty. A comparison of the judgments examined here revealed two networks underlying decision-making; however, these networks did not divide based on judgment type or domain. Instead, judgments differed on whether the details on which the decision was based were analyzed based on global or local properties. The division between networks involve whether judgments can be decided by fitting things together into a whole (e.g., global) (Objective Perceptual, Subjective Perceptual, Subjective Semantic) or can be decided based on only a few details (e.g., local) (Objective Semantic). Processing in the local network is consistent with the IR model, while the global network is consistent with Accumulator models. Results indicate the IR model does not account for explicit subjective conceptual judgments, but can account for Objective Semantic judgments. Further, the study validates that Accumulator models' account for Objective Perceptual judgments and expands this model to both Subjective Perceptual and Semantic judgments, suggesting that these models may provide accurate accounts of most types of decisions that humans make every day.

Acknowledgments

“An optimistic attitude is half of success” – a useful reminder from a fortune cookie message from a dinner at lab that has not left the corner of my monitor for many years

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Relational judgments are decisions that involve comparisons of two or more objects on a specific dimension. These judgments are made frequently, such as when one wants to determine which of two objects is larger or to determine if the item you want to buy is more expensive at this store or another store. Relational judgments are not only a vital part of everyday life but also vary as to whether they are based primarily on perceptual information (perceptually-based decisions) or require retrieval of previously created memories (conceptually-based decisions). Moreover, in contrast to the above examples, which have objective (i.e., veridical) answers, relational judgments can also be subjective, such as when people decide which of two objects they prefer (e.g., chocolate chip vs. oatmeal raisin cookies), for which there are no veridical answers. Thus, relational judgments can vary along the dimensions of domain (conceptual, perceptual) and judgment type (objective, subjective).

The ubiquity and importance of relational and other types of judgments has made them a central topic of psychological research over the past 50 years (e.g., Tversky & Kahneman, 1981; see Ernst & Paulus, 2005; Gold & Shadlen, 2007; Nakko, Ohira, & Northoff, 2012 for reviews). Nevertheless, there are many unanswered questions about how decisions are made. Thus, the present research was designed to answer questions about the nature and timing of the cognitive processes underlying relational judgments. The following literature review is limited to research on types of conscious judgments (see Fazio & Olson, 2003 for a review of research on other types of judgments).

Research on decision-making has found that many types of decisions rely on the same or similar cognitive processes. Early models tended to be relatively simple and relied on behavioral data to identify the nature and sequence of the cognitive processes involved. Consequently, a general characteristic of these behavioral models was that they reduced decision making to a few processing stages. For example, Fellows (2004) divided decision making into three stages: identification/generation of options, evaluation of options, and response selection. The advent of powerful functional neuroimaging techniques has allowed researchers to extend behavioral models by providing information on the relation between cognitive processing and brain activity. Accordingly, more recent neurocognitive models have become increasingly complex as they incorporate data from both behavioral and brain function to illustrate how various cognitive processes involved in decision-making are instantiated in the brain.

At least two general types of neurocognitive models have been proposed to explain the processes and brain mechanisms underlying conceptual and perceptual decision making. In the conceptual domain, Cunningham and colleagues (Cunningham & Zelazo, 2007; Cunningham, Zelazo, Packer, & Bavel, 2007) proposed the Iterative Reprocessing (IR) model to explain how subjective judgments about attitudes can be modified in real time through repeated memory retrievals and analysis to accommodate information about current goals and circumstances. The central component of the IR model is an iterative loop in which retrieved memories can be analyzed and modified in a cycle that is repeated as often as necessary to reach the evaluative judgment that best fits the current circumstances. In their model, the amount of reprocessing (i.e., number of cycles through the iterative loop) required to reach an evaluation, and thus the time required, increases with the complexity of the evaluation. In the perceptual domain, Accumulator models have been proposed, which posit that objective perceptual judgments are reached by accumulating perceptual information until a decision threshold is reached (Smith & Ratcliff, 2004; Usher & McClelland, 2001). In these models, judgment speed is determined by the rate with which perceptual information can be accumulated (e.g., drift rate), which is affected by the quality or discriminability of the stimuli. As detailed below, both IR and Accumulator models provide relatively detailed specifications of the processes involved in decision-making and how these processes are instantiated in the brain.

To date, individual research groups have largely studied decision-making in a single domain. Therefore, there is little research on the extent to which the neurocognitive processes underlying different judgment types or judgments about different domains are similar. Consequently, there are many unanswered questions about the extent to which the IR and Accumulator models generalize outside of the judgment type or domain for which they were proposed. To address these questions, the present study had participants perform two types of relational judgments (objective, subjective) about material in two different domains (conceptual, perceptual) while their behavioral responses and brain activity were recorded. In addition, given that increases in judgment difficulty are proposed to cause increases in the duration of evaluative processing in both models, difficulty was manipulated for objective judgments so that these processes could be better identified and studied. The relative timing of evaluative processing was assessed by quantifying the onset and duration of the event-related potential (ERP) components elicited during each type of judgment.

As many of the insights into the neural basis of decision-making are based on results from functional neuroimaging studies, the following review begins by providing a brief overview of the ERP and hemodynamic techniques. This is followed by detailed descriptions of the IR and Accumulator models, along with experimental support for each of these conceptualizations.

The review concludes with a comparison of the two models and a presentation of the experimental questions and hypotheses addressed by the current study.

Functional Neuroimaging Techniques. The advent of cognitive neuroscience, which merges cognitive psychology and neurobiology, occurred in part because of advances in functional neuroimaging techniques, which permit researchers to observe the brain correlates of cognitive processes while participants complete various tasks. Although there are a variety of techniques that provide different types of information about brain function, the relevant techniques here are measures of brain electrical activity (e.g., ERPs) and hemodynamic functioning (e.g., functional magnetic resonance imaging; fMRI).

Event-related Potentials (ERPs). ERPs consist of positive and negative voltage changes, called peaks, which are elicited as information is processed in the brain. Thus, these voltage changes reflect passage of information through the nervous system, with each peak representing activity of aggregates of neurons that are positioned so that it can be conducted to the scalp (Johnson, 1992). ERP components have been divided into early (exogenous) and late (endogenous) based on the timing and processing associated with each component. Whereas early components, which occur within approximately 200 ms of stimulus onset, are affected by physical aspects of the stimulus, later components reflect cognitive processing and are affected by such factors as the meaning of the stimulus. Comparing ERPs elicited by different levels of a variable (e.g., type of processing, difficulty) allows one to identify which aspects of the ERP are associated with each experimental variable. In contrast to the blocked designs used in many fMRI studies, ERP studies use event-related designs in which the independent variable is manipulated randomly by trial. This allows the examination of the effects of the manipulation without possible confounds of participants implementing different strategies or amounts of attention in different blocks of trials.

Given how quickly decision-making occurs, the high temporal resolution of ERPs makes them ideal for studying the timing of the cognitive processes involved across both judgment types and domains. ERPs provide a direct measure of post-synaptic activity in the brain and have excellent temporal resolution, on the order of milliseconds, thus providing information on the timing and duration of transitory changes in brain activity. That is, ERPs can provide insights into the temporal characteristics (e.g., onset and duration) of the processes involved in different decisions. It is important to note that just because two ERP peaks occur in succession does not necessarily mean they represent two successive processing stages, as there may be one or more intermediate stages whose neural generators do not have the proper characteristics to be propagated to the scalp.

Given the high temporal resolution of ERPs, the onset and duration of different components can be revealed through ERP averages that are synchronized either to the occurrence of the stimulus or the response. Cognitive processes that occur early in the processing sequence (e.g., sensory processing, rapid memory retrieval) are more time-locked to the stimulus and thus are more clearly revealed in stimulus-synchronized averages. By contrast, processes that occur later in the processing sequence (e.g., slow memory retrieval, stimulus categorization) are more time-locked to the response and thus are more clearly revealed in response-synchronized averages. Further, processes that occur over relatively long durations or have variable durations are more clearly revealed in response-synchronized averages (see Johnson, Simon, Henkell, & Zhu, 2011 for a detailed explication on the utility of stimulus- and response-synchronized ERP averages).

Although ERPs have more limited spatial resolution than fMRI (see below), the spatial resolution of ERPs does increase along with the number of recording sites. When using larger numbers of electrodes (e.g., 32 or more) it is possible to examine the spatiotemporal characteristics of the ERP (i.e., scalp topography) in a sharpened manner that allows for the identification of locations of brain activation via current source density (CSD) analysis. CSD analysis computationally filters out the contribution of brain sources that are more distant from an electrode by representing the second spatial derivative of the potential field recorded at that electrode (Picton et al., 2000). Topographic maps based on CSD analyses can thus reveal local cortical activations, thereby allowing for the localization of cortically-generated activity to a particular lobe of the brain and even sub-regions within the lobes.

One well-characterized ERP component relevant to decision-making studies is the late positive component (LPC; aka P300, P3b). The LPC is a multifaceted component whose latency and amplitude reflect the timing and amount of cognitive processing that occurs in response to a stimulus (see Johnson, 1986, 1988 for reviews). The amplitude of the LPC is affected by a variety of cognitive variables related to the stimulus and task characteristics, which have been grouped into those related to the processing of probability, meaning, and uncertainty (Johnson, 1986). LPC latency is determined by the speed with which this processing occurs and thus provides a sensitive measure of variations in the duration of processing time that occur due to variations in stimulus and task parameters (e.g., Kutas, McCarthy, & Donchin, 1977; Johnson, Pfefferbaum, Kopell, 1985). LPC amplitude decreases to the extent that a person remains uncertain about the correct categorization of a stimulus, regardless of whether the uncertainty results from ambiguous information arising from sensory stimuli (Johnson & Donchin, 1978) or memory retrieval (Johnson et al., 1985). The vast majority of ERP studies, such as those using simple oddball (Kutas et al., 1977) or recognition memory (Johnson, Kreiter, Zhu, & Russo, 1998a; Johnson, Kreiter, Russo, & Zhu, 1998b) paradigms, have been characterized by a single LPC peak reflecting all of the elements of processing discussed above. However, multiple LPC peaks have been reported in paradigms involving more complex judgments (e.g., Johnson & Donchin, 1985).

An additional ERP component, the parietal episodic memory (EM) effect is elicited by retrieval of episodic memories at the same time as the LPC. The parietal EM effect, which has been shown to reflect recollection processes, is typically revealed by subtracting the LPC elicited by items not in episodic memory (i.e., new items or items in semantic memory) from the LPC elicited by items in episodic memory (i.e., old items). Until recently, the LPC and parietal EM effect always occurred simultaneously and immediately prior to the response (see Friedman & Johnson, 2000; Johnson, 1995; and Rugg & Curran, 2007 for reviews). It is important to note that, with one exception (e.g., Johnson et al., 2011 discussed below), all previous data concerning the LPC comes from studies of memory retrieval where once the memories were retrieved task-related processing was complete and a speeded response could be made to indicate the memory status of the item.

Functional Magnetic Resonance Imaging (*fMRI).* The fMRI technique detects the locations of brain activations during task performance by using a strong magnetic field to detect changes in the ratio of oxygenated and de-oxygenated blood (i.e., blood oxygen level dependent method, (BOLD)). This methodology provides excellent spatial information, on the order of millimeters, about the locations of activated brain areas. However, the length of the hemodynamic response (i.e., 10-12 sec) is much longer than the cognitive processes under study and thus fMRI provides little, if any, information about the timing, duration or sequencing of brain activations. Moreover, because the blood flow changes are only 3-4% above or below the baseline activity, the low signal-to-noise ratio means that many fMRI studies employ blocked experimental designs in order to obtain a usable signal. Hence, fMRI cannot provide useful information about the timing of the processes involved in decision-making.

Neurocognitive Models of Decision-Making

Two influential models of decision-making, the IR model (Cunningham & Zelazo, 2007; Cunningham et al., 2007) and Accumulator models (Smith & Ratcliff, 2004; Usher & McClelland, 2001) have been advanced to explain subjective conceptual and objective perceptual judgments, respectively. Their influence has accrued because these models provide the most detailed explication of the processing that occurs during decision-making, with a focus on what occurs during the evaluation stage, coupled with information about how these processes are instantiated in the brain. The IR model was proposed specifically to explain how attitude evaluations, which are subjective conceptual judgments, are computed (Cunningham & Zelazo, 2007; Cunningham et al., 2007). By contrast, the goal of Accumulator models was to explain how objective perceptual judgments were reached (Smith & Ratcliff, 2004; Usher & McClelland, 2001). The details of both these models, along with the data supporting each, are reviewed next.

Iterative-Reprocessing Model.

Cunningham and colleagues proposed the IR model to explain how attitude evaluations are made and instantiated in the brain (Cunningham & Zelazo, 2007; Cunningham et al., 2007).

To begin, these investigators made a distinction between an attitude, which they defined as a relatively stable set of associations stored in memory, and an evaluation, which they defined as a decision arrived at via an iterative process in which activated memory representations are modified to reflect current needs and goals. A central feature of this model is the iterative loop, in which retrieved attitude representations (i.e., “tag”) are evaluated using additional information from the environment and/or memory to modify the representation in an iterative manner until a suitable response (e.g., approach or avoid) is identified (Figure 1A). During each iteration, the current evaluation is compared to a pre-set threshold and, if this threshold has not been met, the representation is reprocessed again through another cycle of the iterative loop. Cunningham and colleagues (2007) proposed that the number of iterative loop cycles required for an evaluation is determined by the interaction of two opposing factors - the need to limit the discrepancy between the situation and one’s evaluation and the need to minimize the amount of cognitive processing required.

As a result of their goal of providing a better explanation of how subjective evaluations of attitudes are reached, the IR model grew out of previous dual process models of attitude evaluations (Cunningham, Johnson, Gateby, Gore, & Banaji, 2003; Smith & DeCoster, 1998). The dual process models divided attitude judgments into implicit and explicit categories. Implicit judgments were posited to be based solely on representations stored in memory and are not available to conscious control or modification. Hence, implicit judgments are automatic, rapid, and invariant across situations. By contrast, explicit evaluations were posited to represent more nuanced judgments, which were conscious. Hence, explicit judgments are more controlled, slow, flexible, require cognitive resources, and can vary across situations. One main purpose of creating the IR model was to combine both implicit and explicit processes into a single model.

Consequently, Cunningham and colleagues proposed that, if an evaluation is reached after only a few cycles through the iterative loop, only the strongest representations are accessed and the evaluation was hypothesized to be equivalent to an implicit evaluation. Conversely, more nuanced, explicit evaluations were hypothesized to be reached through additional cycles through the iterative loop, thereby permitting the contents of stored representations to be progressively modified in a conscious manner so the resulting evaluation better fits with the current situation and goals. Cunningham and colleagues posited that the processing that occurred in the iterative loop was accomplished in the central executive component of Baddeley's (1983, 2003) model of working memory. Based on research suggesting that the cycle time for working memory processes occurs in the theta range (Vertes, Hoover, & DiPrisco, 2004; Raghavachari et al., 2001), they proposed that the iterative loop would function at that frequency (i.e., 5 Hz or 200 ms/cycle). One key advantage of the IR model is that, unlike the separate implicit and explicit evaluation systems in dual process models, the IR model offers a single mechanism that works continuously for shorter or longer durations to reach implicit and explicit attitude evaluations, respectively. Although formulated to model subjective judgments, there is nothing inherent in the model that precludes it from providing an equally valid account of objective judgments.

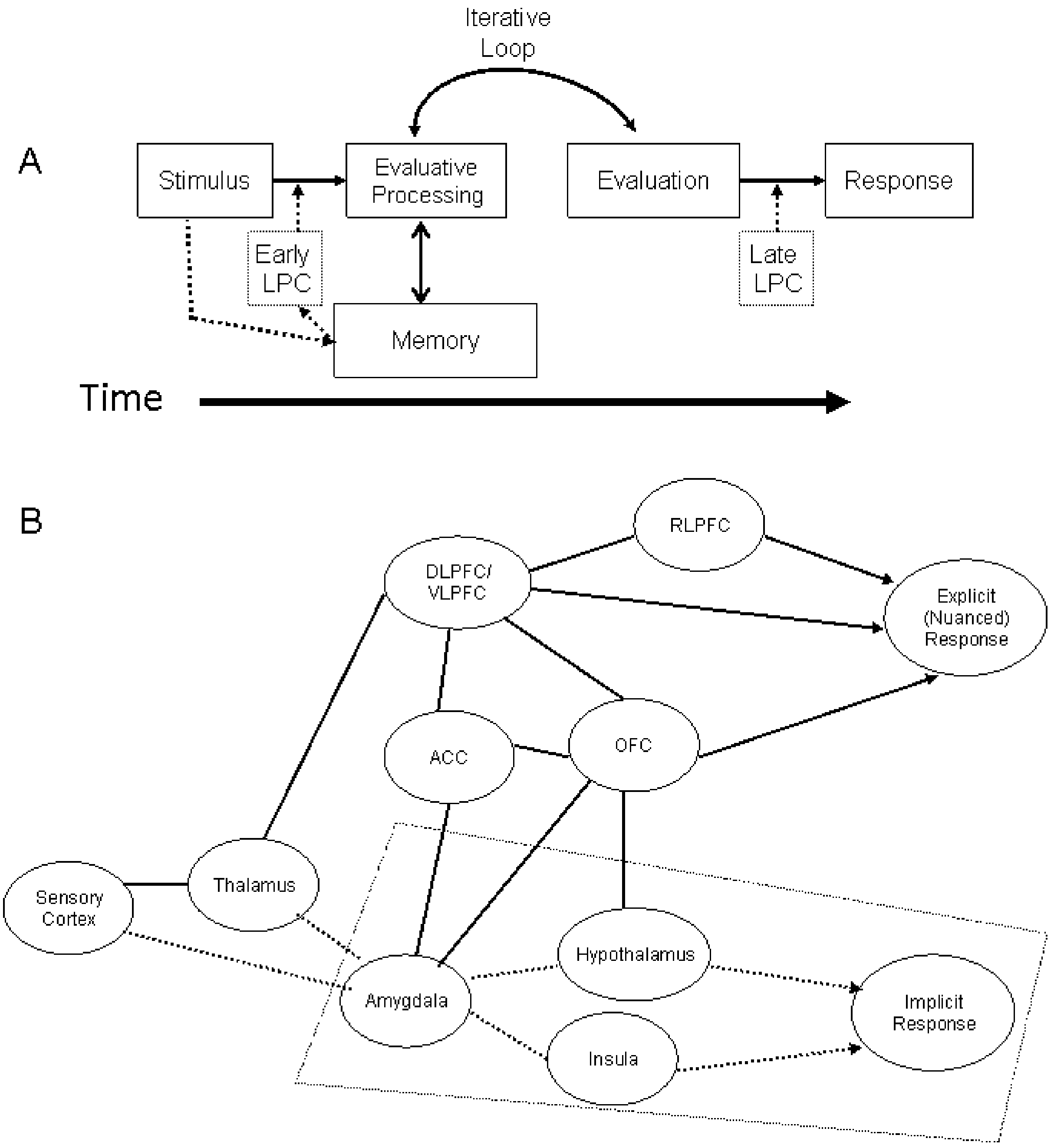


Figure 1. A. Schematic of the Iterative Reprocessing model (solid boxes). Dashed boxes indicate the proposed timing of the Early and Late LPC. B. Proposed neural basis of the IR model. Brain areas within the dashed box have been associated implicit (i.e., not conscious) processing. Adapted from “Attitudes and evaluations: a social cognitive neuroscience perspective” by W. Cunningham and P. Zelazo, 2007, *TRENDS in Cognitive Sciences, 11,* 97-104. Copyright 2013 by Elsevier. Adapted with permission.

Drawing on the extant results of neurocognitive studies of attitude evaluations, Cunningham and colleagues also posited how the processes employed by the IR model are instantiated in the brain (Figure 1B) (Cunningham & Zelazo, 2007; Cunningham et al., 2007; Cunningham, Raye, & Johnson, 2004). After initial sensory processing, information is passed to the thalamus, which in turn sends information to separate neural networks to begin implicit and explicit processing. As the IR model was proposed about attitude evaluations, there are some aspects of the model, such as specifics of the neural processing involved in implicit processing that are not relevant here (within dotted box in Figure 1B). Explicit processing was posited to begin in the anterior cingulate cortex (ACC), which has a role in conflict monitoring and error detection (e.g., Bush, Luu, & Posner, 2000). Once the explicit system is activated, the ACC signals that more reflective processing is necessary (e.g., Ochsner & Lieberman, 2001). The dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC) receive information from the thalamus concerning the stimulus and the signal from ACC that additional processing is needed. As the DLPFC and VLPFC are involved in many higher-order cognitive functions (e.g., working memory, response inhibition, monitoring, top-down attention), they were posited as the sites of reflective (i.e., explicit) processing (e.g., MacDonald, Cohen, Stenger, & Carter, 2000). In addition, the orbital frontal cortex (OFC) was proposed to be involved in reflective processing by combining the current evaluation with information about the current situation (Wallis, 2007).

At the time Cunningham and colleagues proposed the IR model, there was little extant empirical support, with most of it arising from their own studies of attitude evaluations (e.g., Cunningham et al., 2004; Cacioppo & Berntson, 1994). In a study comparing evaluations (good/bad) with abstract/concrete judgments, Cunningham and colleagues (2004) found that activations in ACC, frontal pole, and OFC were correlated with participant ratings of control and ambivalence and concluded that the correlations supported that these brain regions are involved in reflective evaluations. Further evidence supporting the role of the ACC in conflict monitoring and detection came from a study where Pochon and colleagues (Pochon, Riis, Sanfey, Nystrom, & Cohen, 2008) extended the ACC results of studies of objective evaluations of single stimuli to subjective relational judgments requiring the comparison of two faces when asked which one would be considered more attractive. Pochon and colleagues (2008) found that high- compared to low-conflict judgments were associated with greater ACC activation. Additional support for the neural basis underlying the IR model came from studies examining the cognitive functions and development of the prefrontal cortex (Bunge & Zelazo, 2006). Given the lack of direct tests of the IR model, little evidence exists concerning the veracity of the cognitive processes proposed in the model.

Although not the intent of their study, recent research by Johnson and colleagues (2011) using ERPs sheds light on the spatiotemporal characteristics of the brain activity elicited by evaluative judgments and how it differs from that elicited by other types of judgments. Their study was designed to answer questions about how the processing used to make attitude evaluations differs from that used to retrieve autobiographical memories. One result that is key to the present study was the finding that the timing of the LPC and parietal EM effect was different for these two judgments. Replicating the results of previous memory studies, participants' decisions in a cued autobiographical recall task showed the typical pattern of ERPs in which a LPC and superimposed parietal EM effect were elicited simultaneously immediately prior to the response. By contrast, evaluative judgments about attitudes showed a different pattern of results in which an early parietal EM effect, as indicated by an Early LPC, was elicited some hundreds of milliseconds prior to as second LPC, a Late LPC, elicited just prior to the response. The authors interpreted their results as being consistent with the idea that an initial retrieval of the attitude representation (Early LPC) was followed by the processing required to make an evaluation so the attitude object could be categorized (Late LPC) appropriately (i.e., agree/disagree). Additional evidence in support of this interpretation was provided by another condition in their experiment in which the participants had to make objective (i.e., active/inactive) evaluations about the same attitude objects. Given the presence of the same Early-Late LPC results for objective evaluations, the data suggest that this pattern of results is characteristic of evaluative judgments, regardless of whether they are subjective or objective (Johnson et al., 2011). In a subsequent study, Johnson and colleagues replicated and extended their research on evaluations to a second type of subjective judgment (Henkell et al., 2008). That is, the same pattern of results was found as a single LPC was elicited when participants had to decide whether stimuli did or did not relate to facts about their lives, but two temporally separated LPCs were elicited when participants made subjective evaluations about whether specific trait or state adjectives (i.e., happy) applied to them .

Given the similarity of the observed retrieval-response interval for evaluative judgments to the processing posited to occur in Cunningham and Zelazo's IR model (Cunningham & Zelazo, 2007), Johnson and colleagues (in preparation) examined whether the time between the occurrences of the Early and Late LPCs would be affected by judgment difficulty. Using reaction time (RT) as a proxy for judgment difficulty, they used a post-hoc median-split analysis to divide the attitude evaluations and autobiographical retrievals into low- (fast) and high- (slow) complexity categories. The results revealed that, fast attitude evaluations showed little delay between the retrieval of the representation and the response (e.g., 100 to 200 ms) and elicited a single LPC just prior to the response. By contrast, slow attitude evaluations were characterized by the presence of two LPCs separated by 400 ms, consistent with an early retrieval followed by a period of evaluative processing before stimulus categorization. This analysis revealed that, as would be expected, decisions regarding whether or not the stimulus cued an autobiographical memory elicited a single LPC just prior to the response regardless of the length of retrieval processing needed. Thus, these results confirm the special nature of judgments requiring an active evaluation process conducted in real time (attitude evaluations) compared to other types of decision that do not (memory retrievals). The Early LPC occurs prior to the start of evaluative processing, while the Late LPC occurs after the evaluation has been made (see Figure 1A dotted boxes for proposed location of the Early and Late LPCs in the IR model).

In order to begin to elucidate what occurred during the evaluative interval (i.e., iterative loop), Johnson and colleagues (in preparation) examined the ERP activity elicited during the time demarcated by the Early and Late LPCs. ERP activity during this interval was found over frontal brain areas consistent with Cunningham and colleagues (2007) proposal that frontal areas were the site of reprocessing. Specifically, activity was found over left VLPFC (Johnson et al., 2011, in preparation) and DLPFC (Henkell et al., 2008). Johnson and colleagues concluded that activity over left VLPFC reflected selection processes (Badre & Wagner, 2002; Nessler, Johnson, Bersick, & Friedman, 2006), while the activity over DLPFC was similar to ERP activity previously shown to be involved in maintenance of items in working memory (Johnson et al., 1998b). Overall, these ERP studies demonstrated that it is possible to use aspects of the ERP to identify the iterative loop and measure location and duration of brain activity occurring during the evaluative interval.

Cunningham and colleagues (2007) proposed that the DLPFC and VLPFC were involved in the reprocessing of retrieved representations in order to form a more nuanced evaluation, but the specific nature of the cognitive processes involved in the reprocessing were underspecified. As these areas have previously been associated with executive functions (e.g., working memory, selection), it is likely that these processes are involved in the reprocessing. To understand what role these areas may play in reprocessing one can examine other research that supports what cognitive processes are instantiated in these areas.

Cunningham and colleagues (2007) proposed that the DLPFC was involved in working memory in support of reprocessing a retrieved memory into a more nuanced evaluation. Working memory involves the active maintenance and manipulation of information over a short period in order to complete a task (e.g., Baddeley, 2000; see Baddeley, 2012, for a recent review). Working memory allows information from the environment to be combined with information from long-term memory in order to complete a judgment. Working memory has been divided based on the material involved as separate components were proposed for maintaining verbal material (i.e., articulatory loop) and non-verbal material (i.e., visuospatial sketchpad) (Baddeley, 2000). Baddeley’s model of working memory also includes a central executive, which controls the other systems while maintaining and manipulating information relevant to current goals. The main brain area associated with the central executive is the DLPFC (D’Esposito, Postle, Ballard & Lease, 1999; Nee et al., 2012).

Functional hemodynamic studies have revealed mixed results concerning lateralization of activations in frontal cortex elicited by material from different domains (e.g., verbal or visual) (Owen, McMillan, Lairid, & Bullmore, 2005; Wager & Smith, 2003). Some studies found that the left hemisphere was more involved in working memory for verbal material, while the right hemisphere was more involved when visual or spatial material was used (Owen et al., 2005).

However, in a meta-analysis of fMRI studies examining working memory, the trend toward hemispheric lateralization based on the domain of material being examined did not reach statistical significance (Wager & Smith, 2003). Nee and colleagues (2012) argued on the basis of their meta-analysis of functional neuroimaging studies of working memory, that the role of the DLPFC in working memory tasks should be divided on a dorsal/ventral axis, rather than a hemisphere basis. That is, their results indicated that working memory involving spatial material involved dorsal regions of frontal cortex, while working memory tasks involving non-spatial content involved more ventral areas of the frontal cortex (Nee et al., 2012).

A few ERP studies have examined the role of DLPFC in working memory. Ruchkin and colleagues compared ERPs elicited when either visual spatial or verbal information was maintained over a five-second delay (Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992). A negativity that was lateralized over left DLPFC and showed similar timing and scalp topography across domains of material was concluded to reflect the central executive of working memory. As discussed above, Johnson and colleagues found more activity over left DLPFC during the evaluative interval for high- compared to low-complexity attitude evaluations (Henkell et al., 2008; Johnson et al., in preparation). Overall, both functional hemodynamic and ERP studies have revealed that the DLPFC is involved in working memory processes; however, it remains unclear if the type of material involved in the working memory task affects the lateralization of the DLPFC activity.

One notable functional hemodynamic study assessed the neuronal basis of evaluative judgments (e.g., agree/disagree with “I like Berlin”) by comparing the brain activity elicited by retrieval of episodic (e.g., “I have been to Berlin”) and semantic (e.g., “Berlin is the capital of Germany”) memories with that elicited by evaluative judgments (Zysset, Huber, Ferstl, & Von

Cramon, 2002). A key finding of this study that is relevant here is that greater activation was found in VLPFC for evaluative judgments compared to either episodic or semantic memory retrievals. As the VLPFC has previously been associated with semantic selection (e.g., Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997) this finding was concluded to reflect that evaluative judgments likely engender greater selection demands than memory retrievals, due to a greater level of ambiguity concerning whether one is for or against an item, for evaluative judgments. Thus, this finding offers support for the proposition that VLPFC is involved in evaluative processing as proposed in the IR model.

The finding of VLPFC activity during evaluations raises the question of what cognitive process is reflected in this activity. One area where the VLPFC has been extensively studied is semantic memory and two theories about the role of the left VLPFC in this processing have been proposed (Badre & Wagner, 2002; Thompson-Schill et al., 1997; Thompson-Schill, D'Esposito, & Kan, 1999). One theory, the controlled semantic retrieval hypothesis, proposed that the role of the left VLPFC was to provide top-down control of semantic retrieval and thus it was activated when automatic retrieval did not result in sufficient information to complete the current task (Badre & Wagner, 2002). The second theory, the selection hypothesis, proposed that the left VLPFC was involved in selecting from among retrieved semantic memories (Thompson-Schill et al., 1997, 1998, 1999). To examine the role of the left VLPFC, Thompson-Schill and colleagues compared three different semantic tasks (generation, classification, comparison) each with three levels of selection (baseline, low selection, high selection). Increased fMRI activation was found in left VLPFC for the high compared to low selection conditions for all three tasks (Thompson-Schill et al., 1997). To examine if the controlled semantic retrieval hypothesis could explain changes in activity in the left VLPFC, a manipulation of the amount of semantic retrieval necessary was also included. That is, a condition with two possible responses and one with four possible responses, such that the former required less semantic retrieval than the latter, were compared. When these two conditions were directly compared no differences in the activation in left VLPFC was found leading these researchers to reject the controlled semantic retrieval hypothesis. Since the proposal of the selection hypothesis, many studies have found increased activation in the left VLPFC for conditions requiring greater amounts of selection during tasks requiring object naming (Moss et al., 2005) or processing of trigrams (i.e., BXD) (Zhang, Geng, Fox, Gao, & Tan, 2004). Some researchers have argued that the left VLPFC can be subdivided into anterior and posterior regions, which each support a different function related to semantic memory processing. Specifically the anterior left VLPFC was found to be more involved in top-down control of semantic retrieval, while more posterior left VLPFC was found to be more involved in selection from retrieved representations (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005). These findings suggest that both theories about the role of left VLPFC are accurate.

ERP activity reflecting activity in the left VLPFC has now been observed in a number of studies. In one study, Nessler and colleagues (2006) compared two tasks that differed in level of semantic selection required and found a slow wave elicited over left VLPFC, which was negative for high-selection tasks but positive for low-selection tasks. The similarity of the ERPs elicited in the study by Nessler and colleagues and the increased negativity over this area for a semantic compared to orthographic task found by Johnson and colleagues (Johnson, Barnhardt, Grossman, Adler, & Schindler, 2001), resulted in the conclusion that additional negativity elicited over left VLPFC reflected additional neural activity as a result of increased selection demands. Taken together, the research from Zyssett and colleagues (2002) and others (Johnson et al., 2001;

Nessler et al., 2006; Thompson-Schill et al., 1997) suggest the left VLPFC is involved in conceptually-based evaluative judgments because of a role in selecting from among multiple activated memory representations.

Although there have thus far been no direct tests of the IR model, the research reviewed above begins to offer support for both the cognitive processes and neural basis proposed in the model. Johnson and colleagues (2011, in preparation) provided the first experimental support for the iterative loop as posited in the IR model, as a retrieval-response interval, whose duration varied as a function of judgment difficulty was found for attitude evaluations, but not memory retrievals. Additional evidence for the cognitive functions instantiated in the brain areas proposed to serve as the neural basis of the IR model comes from studies revealing the cognitive processes in those areas. Specifically, support has been provided for the role of the ACC in monitoring decision conflict (Pochon et al., 2008; Nakao et al., 2012), while the DLPFC has been implicated in working memory, and the VLPFC has been implicated in selection from among retrieved memory representations.

Accumulator Models.

The models proposed to explain objective perceptual judgments appear substantially different from those proposed to explain conceptual judgments. These models began as computational accounts of RT and accuracy results obtained in two-alternative forced choice tasks (see Smith & Ratcliff, 2004; Usher & McClelland, 2001 for reviews). Subsequently, researchers began to combine information from these computational models with that from neurophysiological studies to create neurocognitive models. At present, there are multiple models of perceptual decision-making that differ on the specifics of the calculations involved (e.g., Ratcliff & Smith, 2004; Usher & McClelland, 2001), although the underlying brain networks appear to be largely the same regardless of which model was being examined. For ease of discussion, the term Accumulator model will be used throughout this thesis to refer to this category of models.

In contrast to the single stimuli typically presented in studies of conceptual evaluations, many experiments testing accumulator models involve relational judgments about pairs of stimuli. In addition, whereas most studies on conceptual judgments have involved human participants, research on perceptual judgments has involved both monkeys and humans. The monkey studies typically involved recording from individual neurons in specific brain areas known or suspected to be involved in the various stages of perceptual decision-making.

The process of making perceptual judgments has been divided into three broad stages (Figure 2A solid boxes) (Philiastides & Sajda, 2007; Shadlen & Newsome, 2001). The first stage, as in all models of decision-making, involves extracting sensory information and forming a representation of the stimulus. Both neurophysiological studies in monkeys (Shadlen & Newsome, 2001) and functional neuroimaging studies in humans (e.g., Heekeren, Bandettini, & Ungerleider, 2004; Kayser, Buchsbaum, Erickson, & D'Esposito, 2010) have revealed increased activity in sensory areas corresponding to extraction of sensory evidence. In tasks that required the processing of motion, V5/MT is activated (Kayser et al., 2010; Shadlen & Newsome, 2001), whereas the fusiform face area and parahippocampal place area is activated in tasks involving discriminations between faces and houses (Heekeren et al., 2004). Thus, this first stage appears to be instantiated in modality-specific sensory areas, with the specific sensory areas determined by the specific stimulus parameters being evaluated. Given that the creation of a stimulus representation for perceptual judgments does not appear to be inherently different from forming a representation of conceptual stimuli, it is reasonable to expect that the conclusion of this first stage of decision-making will also be marked by the appearance of an Early LPC (cf., Johnson et al., 2011) (Figure 2A, dashed box).

According to Accumulator models, the second stage of decision-making involves accumulating and integrating information from the stimulus over time. The speed at which information is accumulated, which has been termed "drift rate" depends on a number of factors that affect stimulus discriminability. Graphically, drift rate is represented as the slope of the line representing accumulation (Figure 2B). The manner in which sensory information is accumulated has been conceptualized as a "random walk" process in which the weight of the evidence being accumulated in favor of a particular outcome can fluctuate. These fluctuations are driven by the level of noise inherent in both the stimuli and the observer, thereby producing variations in the evidence accumulated (i.e., deviations from a straight slope) for or against a specific response. Hence, the accumulation process is studied frequently by experimentally manipulating the amount of noise present in the stimulus to alter the duration of the accumulation process. For example, when stimuli are presented with little noise, information is accumulated rapidly, which is revealed by a steep slope and fast rise to threshold (Figure 2B black line). By contrast, when there is increased noise or decreased differences between the stimuli being judged, useful information is difficult to discriminate, and information is accumulated more slowly. Thus, for difficult (i.e., ambiguous) judgments, a more moderate drift rate ensues, and there is a slower rise to threshold (Figure 2B blue line) (Ho, Brown, & Serences, 2009; Kayser et al., 2010; Roitman & Shadlen, 2002).

Early research on the brain areas involved in information accumulation during sensory judgments involved single-unit recording studies on monkeys (see Gold & Shadlen, 2007 for a review). In these studies, neural activity was recorded while monkeys performed a random-dot motion task employing stimuli consisting of, for example, different color dots with some dots moving coherently and others moving randomly (e.g., Gold & Shadlen, 2007; Heekeren, Marrett, & Ungerleider, 2008). The monkey's task was to decide if more dots were moving toward the right or left. Task difficulty is manipulated by varying the degree of motion coherence (i.e., the percentage of dots moving in one direction). Examining neurons in lateral intraparietal cortex (LIP) revealed a ramp-like increase in neural firing rates corresponding to the degree of motion coherence with faster increases in firing rates for easier judgments. Thus, as predicted by Accumulator models (Figure 2B), measurement of single-units' firing rates within the LIP revealed longer durations of activity prior to reaching a threshold for more difficult trials. Importantly, activity in monkey LIP could be used to predict which response would be chosen when random motion was presented (i.e., 0% coherence) precluding a correct answer. Further, when neural activity was aligned to the onset of the response, roughly the same level of firing rate was found regardless of the judgment difficulty. This finding led some researchers to argue that in addition to a role in accumulation of information, the proposed threshold was also instantiated in the LIP (Philiastides, Biele, & Heekeren, 2010; Roitman & Shadlen, 2002; Sajda, Philiastides, & Parra, 2009; Shadlen & Newsome, 2001). These studies also revealed that performing the random dot motion task also increases activity in sensory cortices (e.g., MT) approximately 100 ms prior to observed changes in LIP neurons further supporting the idea that one of the functions of LIP is to integrate information processed in the sensory areas.

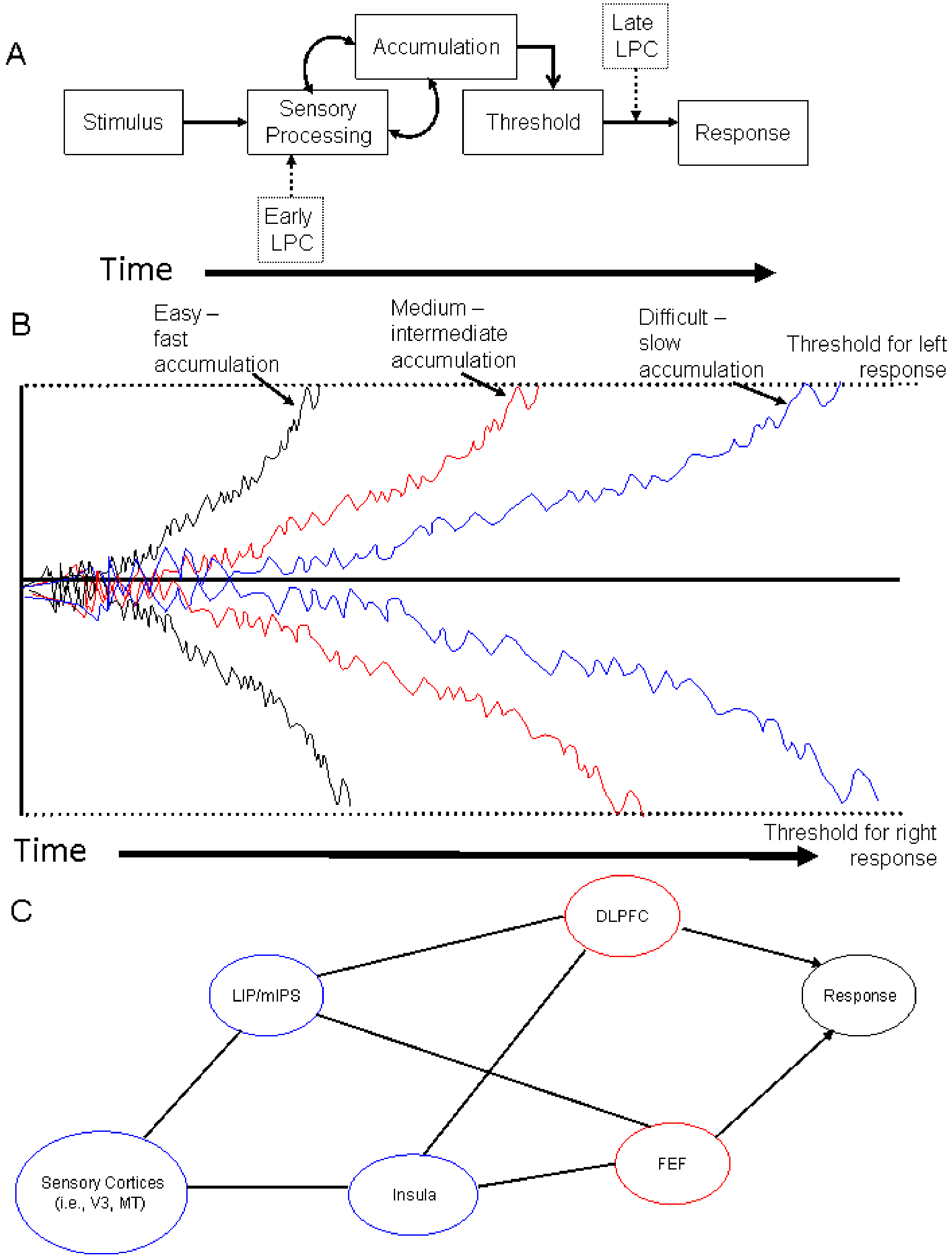


Figure 2. A Schematic of Accumulator models (solid boxes). Dashed boxes indicate the proposed timing of the Early and Late LPC. B. Theoretical data illustrating the differences in drift rate underlying accumulation of sensory information for judgments of three difficulty levels – easy (black line), medium (red line), and difficult (blue line). C. Proposed neural basis of Accumulator models, including areas involved in accumulation (blue ovals) and areas involved in decision variables (red ovals).

Functional neuroimaging studies on humans completing perceptual judgments have found multiple brain areas that appear to be involved in accumulation/integration of information from the stimulus (Ho et al., 2009; Kayser et al., 2010; Ploran, Tremel, Nelson, & Wheeler, 2011). Using a random-dot motion task similar to that used in monkey studies, Heekeren and colleagues (Heekeren, Marrett, Ruff, Bandettini, & Ungerleider, 2006) used fMRI and found increased blood flow in the middle intraparietal sulcus (mIPS). Others have found increased blood flow as a function of increased difficulty of judgments in both occipital and frontal areas (e.g., middle frontal gyrus, frontal eye fields (FEF), ACC, and anterior insula, Kayser et al., 2010). Given that mIPS is the human homologue of the monkey's LIP, the investigators interpreted these activity changes as being related to accumulation. Hence, this finding supports the idea that similar brain networks underlie perceptual decision making in both monkeys and humans. Based on the finding of increases in blood flow for difficult compared to easy judgments, other researchers have concluded that the right insula (Ho et al., 2009), areas of prefrontal cortex (inferior frontal gyrus, middle frontal gyrus, (Ploran et al., 2011) superior frontal sulcus (Heekeren et al., 2006)), middle and superior occipital gyri, and right ACC (Ploran et al., 2011) are also involved in accumulation. Finally, although VLPFC has been found to be activated to a greater extent by difficult compared to easy perceptual judgments in some fMRI studies of perceptual judgments (e.g., Binder, Liebenthal, Possing, Medler, & Ward, 2004; Heekeren et al., 2006), the exact role of this area in these judgments remains unclear. Recalling the research reviewed above, it is possible that VLPFC plays a role in selection among responses or information about the stimuli for perceptual judgments as it has been found to do in the case of semantic memories (Badre & Wagner, 2002; Thompson-Schill et al., 1997). Others have argued that VLPFC is involved in increasing the level of attentional resources allocated to the task (Heekeren et al., 2006).

Some researchers have argued that activity in sensory cortices reflects visual working memory (Hayden & Gallant, 2013). The increased activation in occipital cortex is believed to maintain a representation of the stimulus, sometimes termed visual persistence (Philiastides & Sajda, 2007). Even when the stimulus remains visible until the time of the response, it is still necessary to maintain a mental representation of the stimulus to allow for accumulation of information from the sensory input. Thus, continued activation in sensory cortices, operating in parallel with the brain activity reflecting accumulation of perceptual information, is a hallmark feature of perceptual judgments. Overall, investigations have revealed that sensory cortices and areas termed accumulator areas (e.g., mIPS/LIP and insula) are both involved in the accumulation and integration of information from the stimulus.

The final stage of the decision process is posited to involve a comparison of the level of accumulated information to a pre-set threshold. Once the threshold is reached, the judgment process ends with stimulus categorization. Although underspecified, "decision variable" areas located in frontal brain regions were proposed to provide the basis of this third stage (Heekeren et al., 2006). Evidence supporting this notion includes findings of greater fMRI activation in left DLPFC for easy compared to difficult trials for two perceptual judgments (face/house discrimination, random dot motion task) and two response modalities (button press, saccade) (Heekeren, Marrett, Bandettinin, & Ungerleider, 2004; Heekeren, Marrett, Ruff, Bandettini, & Ungerleider, 2006). Heekeren and colleagues (2004, 2006) concluded that this pattern of left DLPFC activation reflected working memory processes used to compare the signals from sensory and accumulator areas to a decision threshold. Other researchers have demonstrated that repetitive transcortical magnetic stimulation (rTMS) applied to left DLPFC interferes with the efficiency of integration of stimulus information (Philiastides et al., 2011) as indicated by increases in reaction time. Based on these results, these investigators concluded that working memory instantiated in the DLPFC is involved in integration of stimulus information over time. However, as the left DLPFC was the only area assessed in the rTMS study, it is unclear if the DLPFC is involved in the actual integration of the stimulus information or if it only reflects the level of integration that is calculated elsewhere in the brain. Based on research on Accumulator models, researchers have concluded that the DLPFC is one of the main areas involved in computing a response.

Many factors can affect how the decision threshold is set, including instructions, time available, and motivation. For example, one variable commonly used to assess changes in the threshold is instructions regarding whether to stress speed or accuracy. For example, instructions stressing speed over accuracy lower the threshold, which results in faster responses but higher numbers of errors. Regardless of where the threshold is set, the crossing of the decision threshold triggers other processes related to stimulus categorization, which permit a response to be selected and executed. Research on where decision thresholds are maintained in the brain has produced inconsistent results. As mentioned above, some authors argued that the threshold was maintained in the LIP, while others have argued that the threshold is maintained in frontal brain regions (i.e., DLPFC), separate from areas involved in information accumulation (Heekeren, Marrett, & Ungerleider, 2008). As this third stage of decision-making concludes with stimulus categorization, based on the findings of Johnson and colleagues (2011) discussed above, a Late LPC would be expected to demarcate the end of this stage (Figure 2A, dashed box).

As seen above, perceptual decision-making involves the process of choosing from among a set of options based on information gathered from the senses. According to Accumulator models, perceptual decision-making involves accumulating of sensory information, which is then compared to a threshold prior to selection and execution of a response. Studies using single-cell recordings in monkeys and functional neuroimaging techniques in humans have begun to reveal the neural network underlying perceptual decision-making. Although this review has focused on tasks involving visual stimuli, similar results have been found in somatosensory tasks requiring comparisons of vibrotactile frequencies (Pleger et al., 2006) and in auditory tasks requiring phoneme discriminations (Binder et al., 2004). The research reviewed above has revealed that the same mechanisms, both in terms of the computations and neural activations, appear to be engendered regardless of whether stimuli are presented simultaneously (i.e., random-dot motion task), sequentially (i.e., in somatosensory and auditory domains), or if the stimulus is a single item requiring a binary decision (i.e., face/car discrimination). One limitation of the research on Accumulator models is that, with the exception of the 0% motion coherence condition where there was no correct answer, all the tasks involved an objectively correct answer. Thus, it is unknown if Accumulator models can explain the processing used during subjective judgments. In a study that used Accumulator models to explain subjective judgments, Krajbich and colleagues (Krajbich, Armel, & Rangel, 2010) measured behavioral data and eye movements when people made a preference judgment between pictures of two food items (e.g., do you prefer the burger or pizza). This study found that the computational side of the Accumulator models explained the relationship between visual fixation and preference choice. However, because this study did not assess neural activations, it does not address the question of the extent to which the same brain networks are activated for both objective and subjective judgments (Krajbich et al., 2010).

Based on the research reviewed above on Accumulator models, the neural network underlying perceptual decision-making in humans appears to involve sensory cortices, mIPS, insula, and DLPFC (Figure 2C). The sensory cortices, mIPS, and insula have been found to be involved in accumulation of sensory information, while the DLPFC has been proposed to be involved in comparing the accumulated sensory information to a threshold.

Current Study

As reviewed above, decision-making research has over the past several decades resulted in two influential neurocognitive models of decision-making – the IR and Accumulator models. Further, although the IR and Accumulator models were advanced to account for different types of judgments (objective, subjective) in different domains (conceptual, perceptual), it is evident that there are conceptual similarities in the processes contained in these two models. As detailed above, both models can be conceptualized as broadly partitioning decision-making into three similar stages: creating a stimulus representation, evaluative processing, and stimulus categorization so a response can be chosen. Nevertheless, the data indicate that, whereas the processes are generally equivalent, the inherent differences between the domains are evident in how the evaluations are reached and how these processes are represented in the brain. Thus, before describing the design and predictions for the present study, it is necessary to posit an integrated picture of the relevant similarities and differences between these two models' accounts of the decision-making process.

In both models, the judgment process begins with the formation of a stimulus representation. In the Accumulator model, perceptual judgments require that the sensory cortices remain involved throughout the decision-making process in order to provide a representation of the stimulus while stimulus information is accumulated. By contrast, in the IR model, involvement of the sensory cortices in conceptual judgments is brief because once the initial stimulus description has been formed, the evaluation processes required for conceptual judgments depend primarily on interactions between long-term and working memory. In both models, the initial stimulus representation stage marks the end of the first processing stage and beginning of the second. Based on their study of objective and subjective conceptual judgments, Johnson and colleagues (2011) concluded that stimulus representation was marked, at least for memory-based judgments, by the presence of the Early LPC in the ERP.

Evaluative processing is posited to occur in the second stage of both models, although the sub-processes associated with information accumulation and memory retrieval will necessarily differ even as shared processes (e.g., working memory, attention) may not. Although there are domain-related differences in difficulty, a central tenet of both models is that the duration of the evaluative processing increases with judgment difficulty. However, as the type of processing required for perceptual and conceptual stimuli is inherently different, the specific posterior areas involved will be domain specific. For example, whereas perceptual judgments are primarily based on the information provided by the stimuli, the stimuli on which conceptual judgments are based (e.g., words) only provide the conceptual starting point (e.g., the semantic concepts or categories) for all the subsequent memory retrievals required for the evaluation process. Although the lower-level processing (e.g., stimulus processing, semantic memory retrieval) conducted in posterior brain areas is domain specific, the posited higher-level processing (i.e., working memory, decision variables) conducted in anterior (i.e., frontal) brain regions are more similar across models. For example, while working memory processes conducted in DLPFC are a central component of evaluative processing during conceptual judgments (Johnson et al., 2011, in preparation), DLPFC activity is also a frequent finding in studies of perceptual judgments in both monkeys and humans (Heekeren et al., 2006). In addition, selection processes have also been found to play a role in evaluative processing given the need to choose among multiple possible alternatives when deciding which response best fits the current situation. This selection processing has been associated with activity in the VLPFC and VLPFC activity has been seen in studies of various types of judgments (e.g., Binder et al., 2004; Heekeren et al., 2006; Johnson et al., 2011).

The final stage of decision-making involves determining when the evaluation process has reached an endpoint so the stimulus can be categorized, thereby permitting a response to be selected. Thus far, Accumulator models have provided a more detailed account of the processing in this stage, positing that categorization occurs when a pre-set threshold that specifies the required amount of information that must be accumulated is reached. Single-unit studies of monkeys suggest that this threshold is defined by a specific firing rate in the neurons that signal response choice (e.g., LIP) (Gold & Shadlen, 2007). Some researchers argue that information accumulated in the LIP is fed forward to areas in the frontal lobes (i.e., FEF, DLPFC), which can maintain the information until needed to select a response. In monkey studies, evidence supported that the only areas involved in decision-making were those involved in the sensory processing and motor output requirements. By contrast, humans are able to calculate decisions that are more abstract (i.e., arbitrary stimulus-response associations) and thus must have a more abstract decision variable area that is not specific to the sensory stimulus or motor output. Research has suggested that this abstract decision variable area is maintained in the DLPFC, possibly related to working memory so that a response can be chosen. Although the nature of this threshold was left entirely unspecified in the IR model, the research by Johnson and colleagues (2011) suggest that the occurrence of the Late LPC reflects the timing of this final stage of the decision-making process.

Both IR and Accumulator models posit that a fundamental characteristic of the cognitive processes directly involved in perceptual and conceptual evaluations is that their duration will increase as a function of difficulty. Therefore, the evaluation processes involved in various judgments, as well as other variable duration processes (e.g., those maintaining stimulus representations), can be identified readily by relating their duration to such factors as judgment difficulty. Hence, the timing of the various processes involved in decision-making is arguably the most relevant characteristic of the brain activity involved. However, although the fMRI technique, which has been used most frequently to study human decision-making (e.g., Kayser et al., 2010), provides unmatched information about the location where decision-related processes may be occurring, it provides no information regarding the crucial timing of the processes in those brain areas. Consequently, fMRI has been unable to provide any test of the most important aspects of either IR or Accumulator models. By contrast, the excellent temporal resolution inherent in ERPs is the only available technique that allows the examination of the onset, offset, and thus duration of elicited brain activity in humans.

The objective of the current study was twofold. First, to examine whether the timing and location of neural activations of different types of judgments made in different domains is the same or different by including multiple judgments in a single study. A second objective was to assess the effect of difficulty on the duration and extent of evaluative processing during objective perceptual and conceptual judgments. The IR model was proposed about attitude evaluations, which involve memory; however, the exact nature of the type of memory underlying attitudes is unclear as some research indicates episodic memory (Johnson et al., 2011) while others argue semantic memory underlie attitude evaluations. In addition, attitudes are self-referential in nature. Thus, to examine a judgment about a known memory type, specifically semantic memory, for which an objective question could be asked, a judgment about the relative size of animals was used in the current experiment. Therefore, the current study used ERPs to examine the spatio-temporal characteristics of brain activity elicited while participants completed a 2-by-2 factorial design that crossed Judgment Type (Objective, Subjective) and Domain (Semantic, Perceptual). As discussed above, both the IR and Accumulator models partition decision-making into three stages. The specific hypotheses addressed by the current study are presented in accord with the three stages of decision-making.

Effect of Judgment Type and Domain.

As the IR and Accumulator models were proposed to account for subjective conceptual and objective perceptual judgments respectively, a fundamental question is whether any single model of decision-making can explain judgments that vary across domains and types. Thus, the first objective of the present study was to compare and contrast the ERP activity elicited by both objective and subjective judgments in the perceptual and conceptual domains to elucidate the cognitive and brain processes underlying each.

Studies of relational judgments date back to those examining the symbolic distance effect in the 1970's (Loftus & Bell, 1975). In these studies, participants were presented with two animal names and they had to make a relational judgment concerning their relative size. The results revealed a phenomenon referred to as the "symbolic distance effect" in which the time required to determine, for example, which animal is larger, is inversely related to the size difference between the two animals (Moyer, 1973). Two theories have been advanced to explain the symbolic distance effect, which differ based on their explanations of how semantic information is stored and how the comparisons are made. One theory posits that such comparisons are based on mental imagery, in which images for the two animals are retrieved and "visually" compared. Judgment speed is determined by the relative size difference between the two objects being compared. The other theory posits that conceptual information about animals is stored as verbal propositions (e.g., "elephants are large"), with the comparisons being made on the basis of retrieved semantic information about the two animals. According to this conceptualization, the speed with which judgments can be made depends on the timing (i.e., order) with which the information relevant to the dimension being judged is retrieved. For example, if a size judgment is required and size is a defining feature of the animal (e.g., elephants - large, flea - small), then this information will be retrieved from semantic memory sooner than less related information. Thus, if one animal is "tagged" as large and the other "tagged" as small, then this is the only information that needs to be retrieved before a judgment can be made. However, in cases when both animals are tagged in the same way (e.g., both large) or when the animal's tag relates to features irrelevant to the dimension being judged (e.g., ferocious), then semantic information must be retrieved repeatedly until the required information is made available resulting in a slower judgment. Hence, judgment speed (i.e., RT) for objective semantic judgments will increase directly with the number of semantic retrievals required to enable a correct judgment.

To avoid the possible confound of difficulty differences across domains, it was necessary to equate difficulty across all four judgments used in the present study (Objective Semantic, Objective Perceptual, Subjective Semantic, and Subjective Perceptual). This was accomplished with a series of pilot studies during which the nature and selection of the stimuli and stimulus pairs was refined.

Hypothesis 1A: Based on the results of the pilot studies, which indicated the presence of similar difficulty levels across all judgments, it was hypothesized, that there would be neither a significant main effect of Judgment Type or Domain nor an interaction on RT.

Hypothesis 1B: Based on the results of the pilot studies, which indicated the presence of similar difficulty levels between Objective Semantic and Objective Perceptual judgments, it was hypothesized that there would be no significant effect of Domain on accuracy for these judgments. Because accuracy cannot be determined for Subjective judgments, as there is no veridical answer, no prediction is made for these judgments.

Most studies of Accumulator models have examined only objective perceptual judgments (c.f., Paulus & Frank, 2003) and thus it is not known if the same neural network underlies both objective and subjective perceptual judgments. The IR model is an expository model that posited a different view about how attitude evaluations are completed; consequently, there have been no tests of the IR model's ability to account for subjective conceptual judgments, let alone judgments about other domains. Although their experiment was designed for a different purpose, Johnson and colleagues' (2011) findings of a retrieval-response interval for evaluative judgments but not memory retrievals provides the only extant support for the IR model. Further, the finding of the same pattern of ERP activity for both subjective (i.e., attitude) and objective (i.e., semantic) conceptual judgments supports the idea that the IR model may account for different types of judgments in the conceptual domain. Although the study by Johnson and colleagues (2011) offers some support that the IR model is also applicable to objective judgments, how well the IR and Accumulator models explain judgments outside of the domain for which they were proposed remains an open question.

Johnson and colleagues (2011) demonstrated that ERPs could be used to determine the start and end points of the three stages of decision-making by assessing the Early LPC and Late LPC, respectively. When an evaluation was required prior to the selection of the response in a conceptual judgment, an Early LPC interpreted as reflecting stimulus representation, was elicited relatively soon after stimulus onset (Johnson et al., in preparation). In addition, a Late LPC interpreted as reflecting an evaluation-based categorization of the attitude object, was elicited just prior to the response. The interval created by the Early and Late LPCs involved working-with-memory in order to form an evaluation that meets current requirements. As predicted in the IR model, it was found that the duration of the interval between the Early and Late LPCs varied as a function of judgment difficulty (Johnson et al., in preparation). Thus, ERPs can be used to assess the duration of evaluative processing.

> **Hypothesis 2:** Based on the research of Johnson and colleagues (2011, in preparation) and the fact that all judgments in the current experiment required evaluative processing, it was predicted that all judgments would elicit an Early LPC and a Late LPC with an intervening interval during which evaluative processing occurs. The Early LPC was expected to be elicited relatively soon after stimulus onset, hundreds of ms prior to the response, reflecting the creation of an initial internal representation of the stimulus being evaluated. The Late LPC was expected to be elicited after the completion of the

evaluation, just prior to the response, and to reflect processing related to the categorization of the stimulus.

As evident from the review above, the IR and Accumulator models can be seen as proposing similar stages of decision making, although how those stages are instantiated may differ as a function of Judgment Type or Domain. Domain can be expected to create differences during the second stage of decision-making as the different type of stimuli used in perceptual and conceptual judgments results in different amounts of information available in the stimulus. For example, while the stimulus provides the sole source of information for objective perceptual judgments, it provides only the starting point for memory retrieval, which is necessary to complete the judgment for conceptual judgments. These differences between perceptual and conceptual stimuli affect how information is processed in each domain during the evaluation/accumulation stage of decision-making. Information from the perceptual stimuli can be sampled continuously at a rate determined by the individual. In line with this concept, research has shown that the sensory brain areas active during accumulation of perceptual information are specific to the information being evaluated (e.g., V5/MT for motion, fusiform face area for faces) whereas the accumulation of information appears to occur in the mIPS (LIP in monkeys), a more general function brain area. By contrast, processing for conceptual judgments is a discrete process with multiple steps - memory retrieval, evaluative processing, and possibly additional memory retrieval (i.e., the iterative loop) (Cunningham & Zelazo, 2007; Cunningham et al., 2007).

Similar to how the sensory areas involved in accumulation of information discussed above depend on the stimulus parameters, the brain areas related to memory involved in conceptual judgments will depend on where the information relevant to the evaluation is stored. The conceptual judgments in the current experiment were based on semantic memory, which is the long-term memory system for facts, concepts, information about objects, and knowledge of words and word meanings, which is stored without contextual information (Badre & Wagner, 2002; Tulving, 1972). Semantic memory is represented in a distributed network of brain areas, with storage being at least partially based in the temporal lobes and retrieval processes based in the frontal lobes (Jefferies, 2013; Martin, 2007). The organization of semantic memory storage within the temporal lobe has been a topic of extensive research (e.g., Damasio, 1990; Hillis & Caramazza, 1991; Martin, 2007; Rossion et al., 2000), with much of the research indicating that semantic memory is preferentially stored in the left hemisphere. Further, research has shown that the organization of semantic memory storage can be subdivided within the temporal lobe based on sub-categories of semantic memory (e.g., Hillis & Caramazza, 1991; Damasio, 1990; Chao, Haxby, & Martin, 1999). Specifically, naming animals compared to naming tools revealed that the middle portion of the inferior temporal gyrus and medial occipital cortex (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Grabowski, Damasio, & Damasio, 1998) were preferentially activated for animal naming.

Hypothesis 3: Given the fundamental differences inherent in the information available in perceptual and conceptual stimuli, the scalp distributions of ERP activity related to stimulus processing and information accumulation was expected to vary as a function of domain. As the current experiment uses visual perceptual stimuli and requires a judgment of the relative number of black and white squares, participants need to process selectively the available form information. Given that form information is known to be processed in extrastriate occipital cortex (i.e., area V3), greater ERP activity was expected over this area for perceptual compared to semantic judgments. Similarly, as left temporal cortex has been associated with storage of semantic memories about animals, greater ERP activity was expected over left temporal cortex for Semantic compared to Perceptual judgments.

One possible reason for the differences between the hypothesized decision-related processes in The IR and Accumulator models is that they were proposed to account for different types of judgments. That is, while the IR model was proposed about subjective judgments, which are based on an internal scale that vary from one individual to another, Accumulator models were proposed about objective judgments, which are based on the outside world. Evidence concerning the generalizability of the IR and Accumulator models to different Judgment Types is extremely limited. Further, only a few studies have compared the brain activity underlying different types of judgments (e.g., objective, subjective) in a single study (e.g., Johnson, S.C. et al., 2005; Nakao et al., 2012). In one study, Johnson and colleagues (2011) compared objective and subjective judgments about attitude objects and found both similarities and differences between the different judgment types. Specifically, similarities were found in the ERPs elicited over areas involved in executive processing (e.g., left and right VLPFC), while differences were seen in the ERPs elicited over areas related to self-processing (e.g, anterior medial frontal scalp).

Hypothesis 4: For Objective Perceptual judgments, all information necessary to complete the judgment is presented in the stimulus, while this is not the case for

Subjective judgments about similar stimuli. Instead, to answer which of two presented objects one prefers, in addition to observing the objects, one must access positive or negative associations on which to base the preference decision.

Similarly, while only access to semantic memory is necessary to complete Objective Semantic judgments, access to associations about valence in addition to, or instead of, semantic memory is necessary to complete Subjective Semantic judgments.

Thus, an effect of Judgment Type was expected in the domain-specific areas related to information access/accumulation (i.e., occipital and left temporal cortex for Perceptual and Semantic judgments, respectively), with relatively less processing, in terms of either extent or duration, expected for Subjective judgments.

Hypothesis 5: Based on previous research (e.g., Johnson et al., 2011), it was predicted that objective and subjective judgments would elicit similar patterns of ERPs over frontal brain areas involved in executive functions, such as selection (e.g., left VLPFC).

In the second stage of decision-making, both the IR and Accumulator models include a period of evaluative processing. In the IR model, the DLPFC and VLPFC were posited to be the sites of reprocessing during the iterative loop, but the exact nature of the cognitive processes involved were left unspecified. Based on the literature reviewed above, the DLPFC appears to be involved in working memory (Baddeley, 2000; Badre, 2008; Nee et al., 2012), while the VLPFC is involved in selection processes (Nessler et al., 2006; Thompson-Schill et al., 1997). According to Accumulator models, DLPFC is implicated as a site of decision variable activity, and activity in frontal cortex has been found in studies of perceptual judgments in both monkeys

(Heekeren et al., 2006) and humans (Kayser et al., 2010). Research has also suggested the presence of lateralization differences in DLPFC activations based on the type of material being held in working memory (Owen et al., 2005; Wager & Smith, 2003), with greater activity in left DLPFC found for verbal working memory and greater right DLPFC activity associated with visuospatial working memory.

Hypothesis 6A: During the evaluation stage, ERP activity consistent with working memory processing (i.e., over DLPFC) was expected to occur prior to the response for all judgments.

Hypothesis 6B: Consistent with past research showing lateralization of working memory functions for verbal and visuospatial material, ERP activity over DLPFC was expected to be lateralized to over left and right DLPFC scalp for Semantic and Perceptual judgments, respectively.

Effect of Judgment Difficulty on Evaluative Processing.

The 2-by-2 analysis was designed to reveal the network of brain areas involved in decision-making, but that analysis cannot determine definitively if the ERP activity that is elicited is related to evaluative processing. In order to validate the relation between evaluative processing and ERP activity over different areas, a manipulation, such as judgment difficulty, that alters the duration of evaluative processing needs to be examined. Therefore, judgment difficulty was manipulated in a parametric manner for objective perceptual and conceptual judgments. As judgment difficulty could not be manipulated in an a priori manner for subjective judgments, the analysis of judgment difficulty was limited to the objective judgments.

Previous studies have revealed that manipulations of judgment difficulty in the perceptual domain result in increases in RT in both monkeys (Roitman & Shadlen, 2002) and humans (Kayser et al., 2010). In addition, studies have revealed increases in RT as a function of judgment difficulty in the conceptual domain (Zyssett et al., 2006). Despite the fact that an increase in the duration of evaluative processing is a central tenet of the IR mode, the only evidence concerning the duration of the iterative loop, as proposed in the IR model, comes from a study by Johnson and colleagues (in preparation). However, as discussed above, this study did not manipulate difficulty of judgments, but by contrast, specifically chose attitude objects that were important to the individual and then used a median split analysis on RT to examine the effect of difficulty. Significantly, more evidence concerning the relation has been accrued about perceptual judgments from single-unit studies on monkeys, which revealed that increased difficulty was associated with increased duration of activations in sensory areas and LIP (Roitman & Shadlen, 2002) for objective perceptual judgments. However, as much of the human research on perceptual judgments has involved fMRI, there is less extant evidence concerning whether the relation between difficulty and duration of the evaluative processing in humans.

Given the importance of the nature and timing of evaluative processing in both the IR and Accumulator models, the current experiment was designed to directly examine the relation between Judgment Difficulty and duration of evaluative processing. Therefore, relational judgments, which require the comparison of two items on each trial, were used to allow for an a priori manipulation of judgment difficulty by varying parametrically the level of similarity between the two items in each stimulus pair for Objective evaluations. For example, if asked which animal is larger, you know that a horse is larger than a cat and a cat is larger than a mouse, but you cannot know prior to a trial if you will choose cat as the larger animal until you see the context in which it is presented. Thus, by manipulating the context in which the stimulus is presented, it is possible to manipulate the difficulty of the decision. This manipulation allowed us to assess the predicted differential duration of ERP activity as a function of judgment difficulty during evaluative processing.

Johnson and colleagues' (2011, in preparation) studies revealed that ERPs could be used to assess the duration of evaluative processing. The Early LPC appears to demarcate the end of stage one of decision-making as it reflects the formation of a representation of the stimulus. Given the association between stimulus processing and the Early LPC, it is best revealed in stimulus-synchronized ERPs. The Late LPC reflects final categorization of the stimulus and is associated with stage three of decision-making. Given that the Late LPC is more time-locked to the response, it is more clearly seen in response-synchronized ERPs. Therefore, the duration of evaluative processing can be assessed by examining the interval between the Early and Late LPCs, which demarcate the beginning and end of evaluative processing, respectively.

> **Hypothesis 7:** Both the IR and Accumulator models predict that duration of evaluative processing increases directly with judgment difficulty. Therefore, it was predicted that the duration of the Early LPC – Late LPC interval, the evaluative interval, would increase directly with judgment difficulty.

If the brain areas found to be active during the evaluative interval in the 2-by-2 analyses are reflecting processes required to make evaluative judgments, these brain areas should show a direct relation between duration of processing and judgment difficulty.

Hypothesis 8: Both the IR and Accumulator models predict that the duration of evaluative processing relates directly to judgment difficulty. Therefore, it was predicted that the duration of ERP activity identified during the evaluative interval in the 2-by-2 analyses would be found to increase directly with judgment difficulty. Specifically, the tenets of the IR model would be confirmed if the duration of ERP activity over left temporal cortex and DLPFC increased as a function of judgment difficulty for semantic judgments. Similarly, the tenets of Accumulator models would be confirmed if the duration of ERP activity over visual processing areas (i.e. occipital cortex), mIPS, and DLPFC increased as a function of judgment difficulty for perceptual judgments.

It is well established that amplitude of the LPC elicited prior to the response reflects residual equivocation about stimulus categorization (Johnson, 1986, 1988; Johnson & Donchin, 1978, 1985). Correspondingly, Johnson and colleagues (in preparation) found that Late LPC amplitude decreased as complexity of attitude evaluations increased.

Hypothesis 9: Based on the results of Johnson and colleagues (in preparation), it was predicted that Late LPC amplitude would be inversely related to judgment difficulty for both Objective Semantic and Objective Perceptual judgments.

Methods

Participants

Eighteen participants (11 females) with a mean age of 22.8 (SD = 2.3) years were recruited from the Queens College campus and paid $10 per hour for participation in this study. All participants were healthy, right-handed, native English speakers, with normal or corrected-to-normal vision, and had a mean of 15.1 (SD = 0.8) years of education. Participants were pre-screened via a series of questions to exclude those with any history of neurological, psychological, or psychiatric disorders. Participants were also screened for medication and drug use and were not enrolled if currently taking any psychoactive medication. Participants completed a questionnaire verifying that all inclusion/exclusion criteria were met at the time of the study. The Edinburgh Handedness Inventory (Modified) (Oldfield, 1971), where right-handedness is defined as scores between 41 and 50, was used to verify handedness. All participants were classified as right-handed with scores ranging from 42 to 50 (mean = 46.6, SD = 2.8). Informed consent was obtained from each participant in accordance with the Queens College Institutional Review Board.

Stimuli

Objective Semantic. Stimuli in the Objective Semantic condition consisted of pairs of animal names. Eighteen animal names were chosen from the list of animals, ranked in order of size ratings, created by Dean, Dewhurst, Morris, and Whittaker (2005) (Table 1). In their experiment, Dean and colleagues (2005) had participants rate the size of animals on a scale of 1 (smallest) to 9 (largest). Using Dean and colleagues' (2005) scale, three levels of size judgment difficulty were created by generating word pairs that varied in the magnitude of the size difference between the animals in the pair. Animals with mean ratings of 1 to 2, 3 to 5, and 6 to 9 were considered small, medium, and large, respectively and six animals were selected from each of these ranges. Thus, for “Easy” judgments, one animal each was selected from the small and large size groups (Figure 3). For “Medium” judgments, the two animals were selected from adjacent size groups (e.g. small-medium, medium-large). Finally, for “Difficult” judgments, both animals were selected from within a size group (e.g., small-small, large-large). Using this procedure, 100 animal pairs were created and an additional 100 pairs were made by reversing the position of the names in each pair (e.g., Flea-Ant, Ant-Flea) for a total of 64 Easy, 64 Medium, and 72 Difficult pairs. Stimulus pairs were randomly divided between three blocks of trials with the constraints that there were equal numbers of Easy, Medium and Difficult pairs in each block and that each pair appeared only once (i.e., reversals were not permitted in the same block). Final trial counts were 66, 66, and 68 in blocks 1, 2, and 3, respectively.

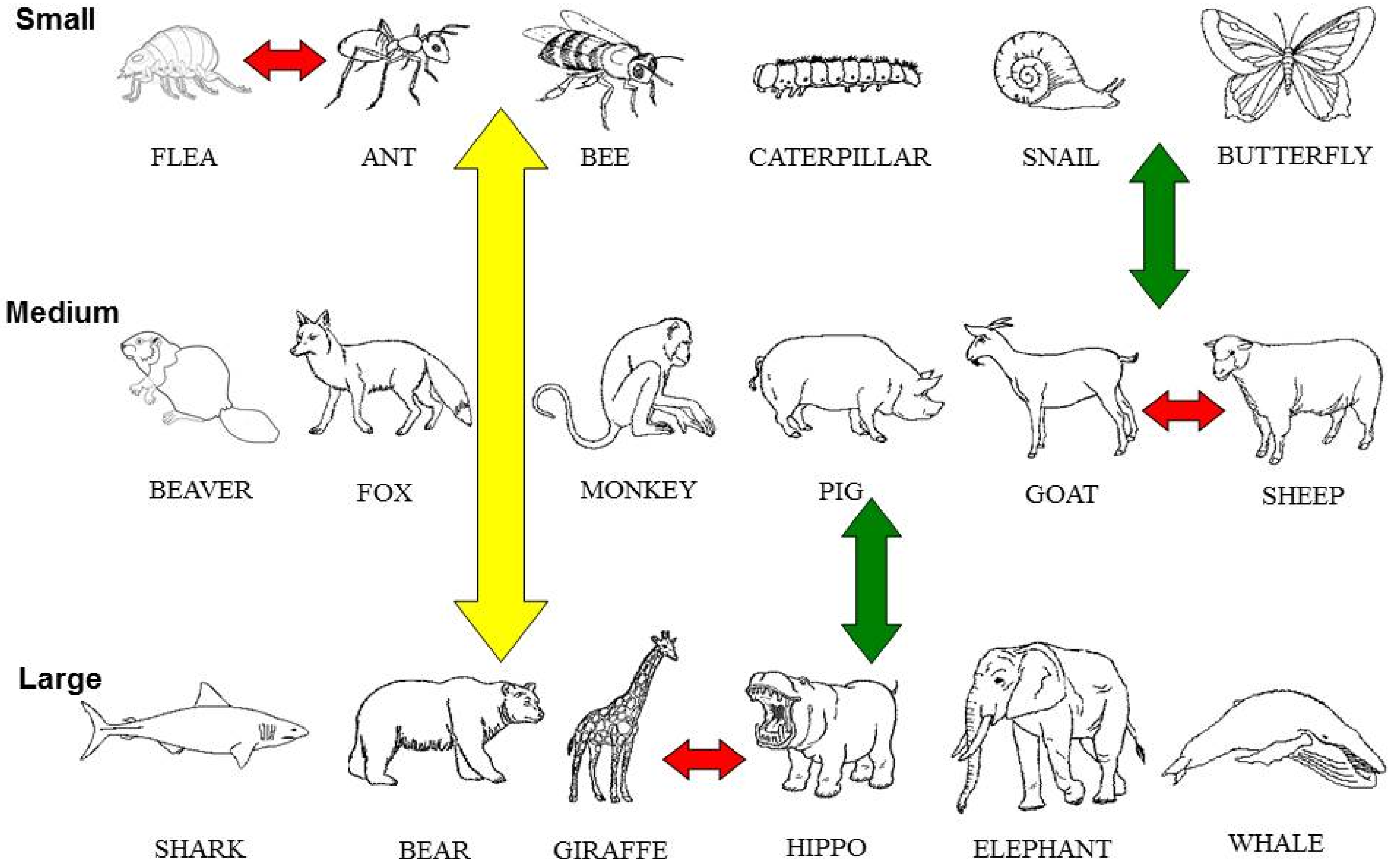


Figure 3. Figure participants were shown prior to the Objective Semantic condition to familiarize them with the animals used in the stimulus pairs. The yellow arrow indicates how Easy pairs were formed using one name each from the categories of small and large animals. Green arrows indicate how Medium pairs were formed using one name each from adjacent size groups (small-medium, medium-large). Red arrows indicate how Difficult pairs were formed using two names from within a size group.

Table 1. Mean size ratings (1 = smallest, 9 = largest) and standard deviations (SD), from Dean, Dewhurst, Morris, & Whittaker (2005), used to order the 18 animal names

	Animal	Mean rating	SD
1	Flea	1.00	0.00
2	Ant	1.26	0.45
3	Bee	1.63	0.61
4	Caterpillar	1.67	0.60
5	Snail	1.69	0.61
6	Butterfly	1.81	0.69
7	Beaver	3.50	0.83
8	Fox	3.91	0.93
9	Monkey	4.29	0.94
10	Pig	4.32	1.03
11	Goat	4.47	0.95
12	Sheep	4.52	1.03
13	Shark	6.59	1.26
14	Bear	6.86	1.08
15	Giraffe	7.38	1.04
16	Hippo	7.59	1.00
17	Elephant	8.41	0.69
18	Whale	8.90	0.43

Subjective Semantic. To create the Subjective Semantic stimuli, a second set of 14 animal pairs was created using Dean and colleagues' (2005) list using none of the animals in the Objective Semantic condition. These pairs were created using animals the participants would be highly familiar with in order to make it easier for them to make preference judgments. The animals used were: Camel, Cat, Dog, Frog, Horse, Lion, Mouse, Panda, Raccoon, Robin, Seal, Snake, Wolf, and Zebra. All possible pairs of animals were created and then reversals (e.g., Robin-Mouse, Mouse-Robin) were removed, resulting in 91 pairs of animal names. Stimulus pairs were then randomly divided into two blocks with final trial counts being 46 and 45 in blocks 1 and 2, respectively.

Objective Perceptual. Stimuli in the Objective Perceptual condition consisted of pairs of adjacent equal-sized squares composed of smaller equal-sized black and white squares that were distributed randomly within their borders (Figure 4A). The appearance of stimulus pairs was manipulated by varying the percentage of small black squares in each large square from 40 to 60 of the total area. Judgment Difficulty was manipulated by varying the difference in percent of small black squares between the two larger squares (range = 2% to 9%). Based on extensive pilot studies, three levels of Judgment Difficulty were created, with differences of 7-9%, 4-6%, and 2-3%, for Easy (mean difference = 8.0%, SD = 0.8%), Medium (mean difference = 5.0%, SD = 0.8%), and Difficult (mean difference = 2.7%, SD = 0.6%), respectively (see Figure 4 for examples of each Judgment Difficulty level). Stimulus pairs were created such that the number of stimuli with the greater percentage of black squares presented on the left and right was equal. Different random patterns were generated for every stimulus so every pair was unique. A total of 216 pairs of squares were created, which were then randomly divided into four blocks with the constraint that there were equal numbers of Easy, Medium and Difficult pairs in each block. The final trial count per block was 54 trials.

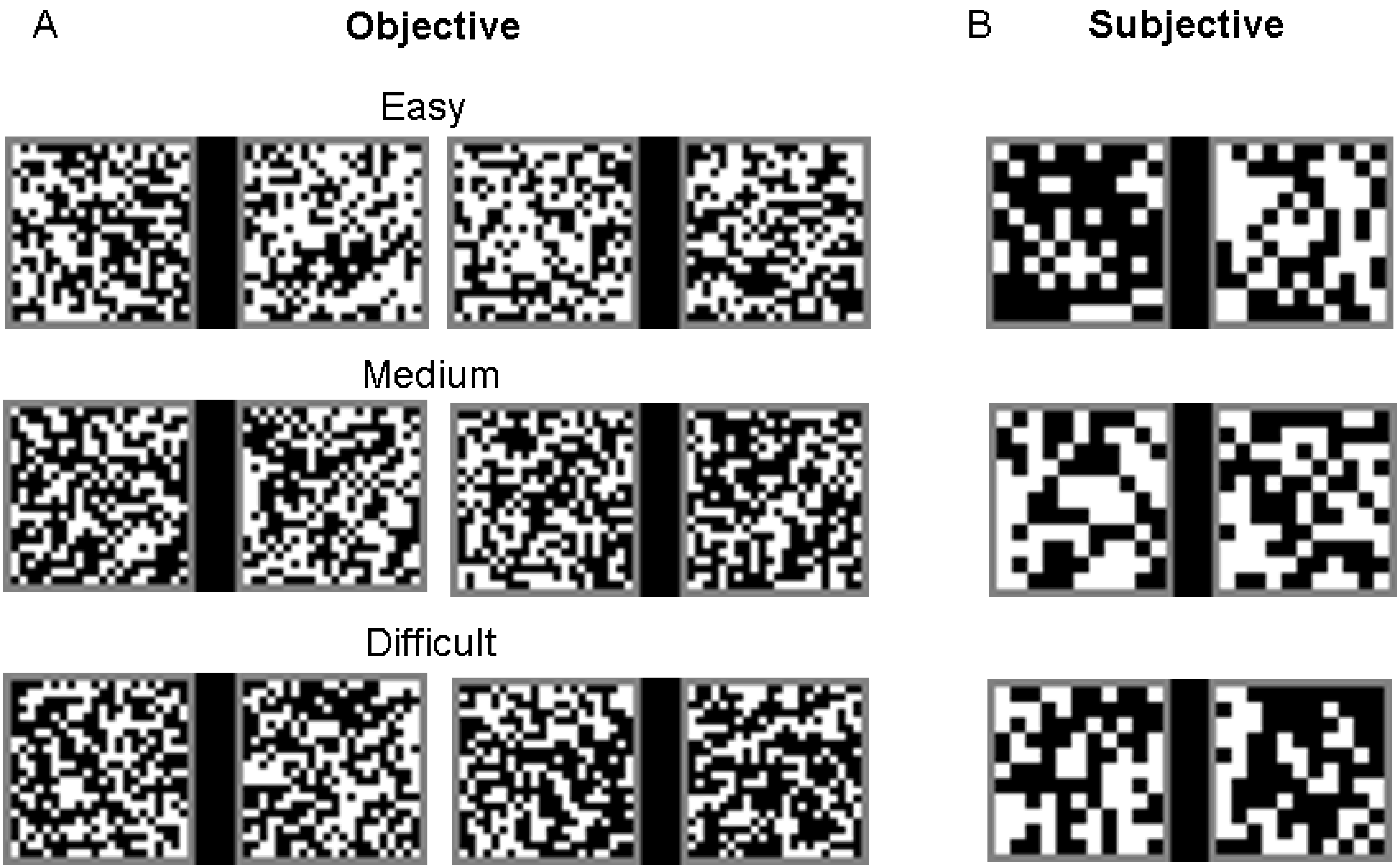


Figure 4. A. Examples of stimuli used in the Objective Perceptual condition at each difficulty level. The task was to judge which square was darker. For illustrative purposes only, the correct answer is the left square for pairs on the left and the right square for pairs on the right. B. Examples of stimuli used in the Subjective Perceptual condition. The blurriness evident in these examples resulted from image transfer to the figure. The features of the stimulus shown to participants were sharp and clear.

Subjective Perceptual. These stimuli also consisted of pairs of the same two large squares as used for the Objective Perceptual stimuli. However, pilot studies revealed that participants had difficulty making reliable subjective judgments with the small black squares and that small square size needed to be increased by a factor of four (see Figure 4B). These studies also revealed that a greater range of percentage differences was needed to get reliable subjective judgments, and thus the range of differences in the percentage of small black squares was increased to 1% to 29% (mean percent difference 10.8, SD = 7.7). As in the Objective Perceptual stimuli, each large square included a randomly-generated pattern of black and white small squares so every square and stimulus pair was unique. Ninety stimulus pairs were created and then randomly divided into two blocks of 45 items each.

Procedure

After obtaining informed consent, participants were asked to complete a form to collect standard demographic information (e.g., age, gender). Participants were then given an introduction to the recording session and electrode placement occurred. They were then seated in front of a computer monitor in a dimly lit room. Participants were given an overview of the experimental conditions, followed by a practice series involving a simple orthographic decision to familiarize them with the stimulus presentation and task structure and to give them practice responding quickly.

Semantic Conditions. Prior to beginning the Objective Semantic condition, participants were shown a sheet of paper with drawings of all 18 animals in order of size, but not to scale, from smallest to largest (see Figure 3) to familiarize them with the animals in the stimulus set.

All pictures, except the Flea, were taken from Snodgrass & Vanderwart (1980). The flea picture was found based on an internet search. A schematic of the trial events in the semantic conditions is shown in Figure 5. For the Objective Semantic condition, participants were instructed to judge, “Which of the two animals is larger?” For the Subjective Semantic condition, participants were instructed to decide which of the animals they preferred.

Perceptual Conditions. In the Objective Perceptual condition, participants were instructed to decide which square was darker then press the appropriate button as quickly as possible. For the Subjective Perceptual condition, participants were instructed to decide which of the two squares they preferred and then press the corresponding button.

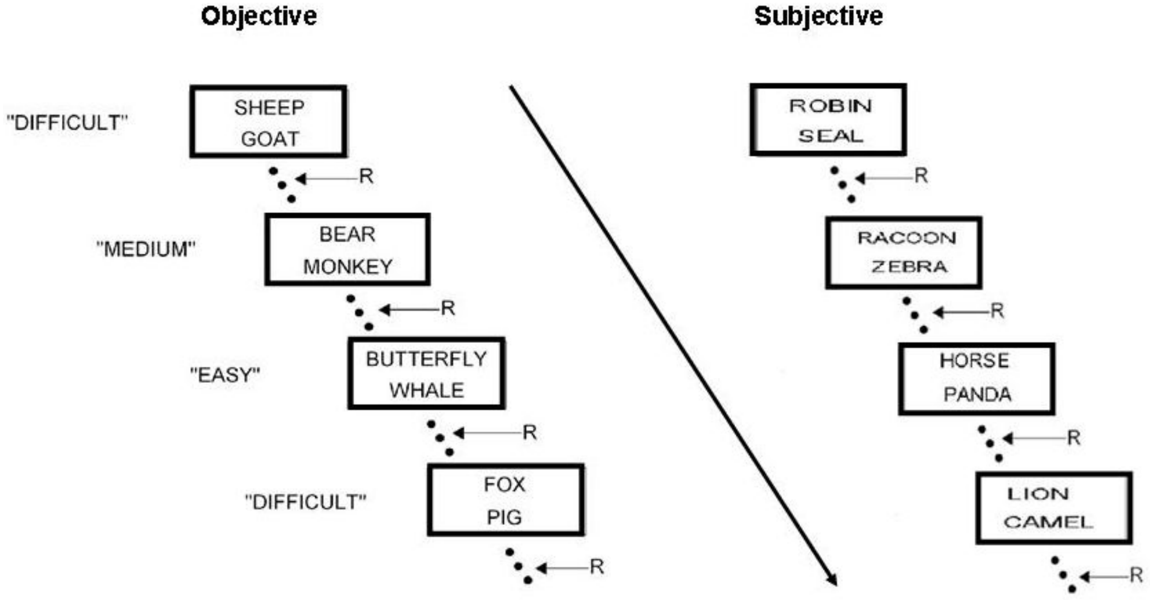


Figure 5. Schematic representation of the event sequence in the Semantic conditions. In the Objective Semantic condition, participants judged which animal was larger. Left labels indicate judgment difficulty level for each stimulus pair. In the Subjective Semantic condition, participants judged which animal they preferred.

All trials lasted 2650 ms beginning with a pre-stimulus 150 ms baseline. Trials were followed by a randomized inter-trial interval ranging from 1100 to 1400 ms. All stimuli were presented in the center of the screen. In the Semantic conditions, the two animal names were presented one above the other in the center of the screen in all uppercase letters in white font on a black background (visual angle: height = 1.5^o; maximum width = 3.5^o). For the Perceptual conditions, the pairs of adjacent squares, which were presented in the center of the screen on a black background (visual angle: height = 1.5^o; maximum width = 2.8^o). The response box had two buttons and participants were instructed to hold the box to correspond with how the stimuli were presented. That is, in Semantic conditions participants held the response box sideways, thereby creating a top/bottom button arrangement and they were instructed to indicate their decisions by pressing the appropriate button (i.e., top/bottom) as quickly as possible. In the Perceptual conditions, participants held the response box so the buttons were oriented in a side-by-side manner and were instructed to indicate their decision by pressing the appropriate button (i.e., left/right) as quickly as possible. In the Objective Semantic condition, the location of the correct response was counterbalanced by including the reversal of each pair so that the larger animal was in the top position once and in the bottom position once. Similarly, in the Objective Perceptual condition, due to including reversals of percentage of black in each small square, the darker square appeared equally on the left and right of the stimulus.

In all experimental conditions, stimulus presentation was terminated by the response or a maximum of 2500 ms. Participants were instructed that RT, as well as, response accuracy in the Objective conditions was being measured. Accuracy was evaluated in the Objective conditions, while as there are no correct answers for the Subjective conditions, proportion of responses allocated to each response button was calculated for these conditions.

During an initial orthographic task, participants were given the opportunity to practice responding until they were comfortable with responding within the allotted time. The experimental conditions were ordered such that Objective conditions occurred first followed by the Subjective conditions. The order in which the Domain judgments were presented within each Judgment Type was randomized between participants. In addition, the order of the blocks within each task was randomized separately for each participant and the trials within each block were presented in a different random order for each participant.

ERP Recording and Quantification

ERPs were recorded from 81 electrode sites, all referred to the left pre-auricular electrode (A1) using tin electrodes embedded in an elasticized custom ElectroCap©. The electrodes were located in four concentric rings, which were spaced at 11.25% of vertex-nasion distance, with an additional ring at the level of the pre-auricular point (see Figure 6). Participants were grounded with a forehead electrode. The EEG was amplified 10,000 times with a bandpass of 0.03-35 Hz and a sampling rate of 100 Hz. Eye movements (EOG) were recorded from above and 2 cm below the outer canthus of the left eye. Trials contaminated with EOG artifacts (signals greater than 50 μV during any six sampling points) were automatically excluded from the averages. During the averaging process, the EEG was digitally re-referenced to an average of the left and right pre-auricular sites (A1+A2).

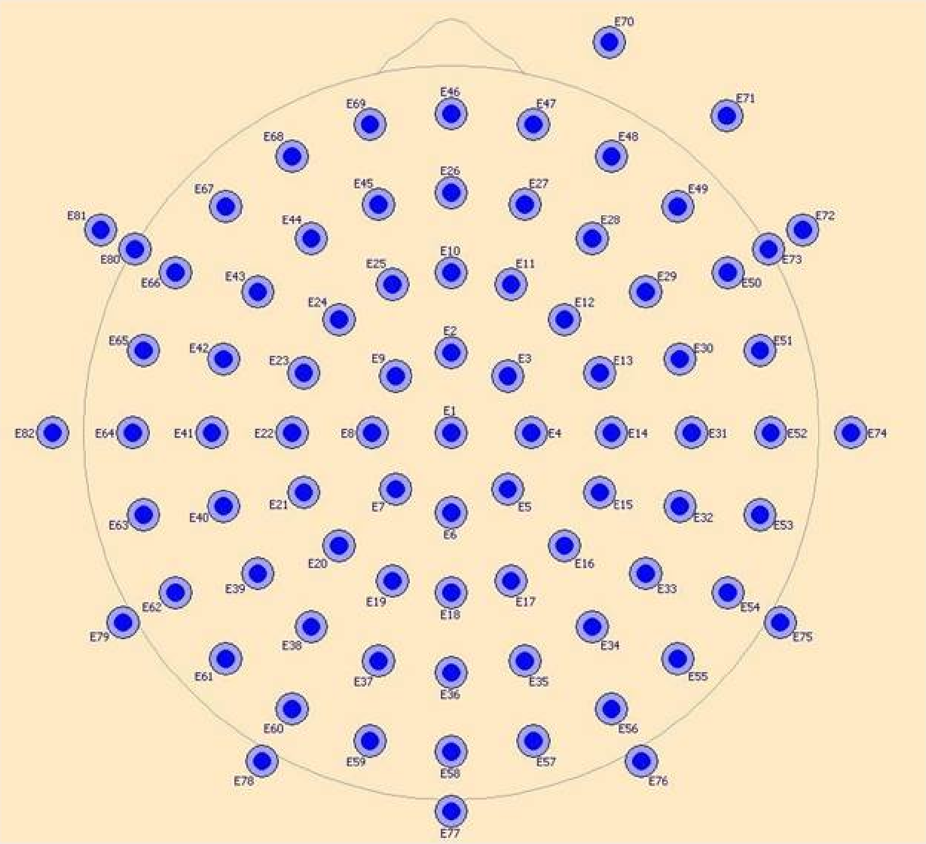


Figure 6. The electrode locations in the custom 81-channel electrode cap used for the ERP recordings.

The ERPs were quantified in two ways - stimulus-synchronized and response-synchronized averages. ERPs in both stimulus- and response-synchronized waveforms were quantified by calculating waveform areas during different temporal epochs after subtracting the activity in the 150 ms baseline. The stimulus-synchronized averages consisted of an interval beginning at time of stimulus onset and continuing for 1400 ms. The response-synchronized averages were synchronized to the time of response for all trials and were calculated for a 1650 ms interval, extending from 1450 ms before the response until 200 ms after the response. An extended pre-response interval was used, as it was approximately equal to the mean RTs of the most difficult items thus ensuring that the baseline interval was approximately equal to time of stimulus onset, where there would be essentially no stimulus-evoked brain activity. Therefore, these response-synchronized averages provided a neutral baseline with which to measure and compare the amplitudes of the ERP components surrounding the response. Stimulus- and response-synchronized averages were calculated based on correct responses in the Objective conditions and all responses in the Subjective conditions, as there was no correct answer.

Potential and current source density (CSD) maps of the data were examined for each ERP component to determine the electrodes and temporal range used in the analysis; therefore, topographical maps are presented along with the waveforms. Two sets of within-subjects analyses were conducted. The first was conducted to examine whether the sub-processes of decision-making are affected by Judgment Type or Domain, a 2-by-2 factorial design with factors of Judgment Type (Objective, Subjective) and Domain (Semantic, Perceptual). The second analysis was conducted to examine the effect of Judgment Difficulty on the amount of time spent in judgment-related processing and the effect of Judgment Difficulty on Objective judgments from both Domains. The second analysis consisted of comparing the three Judgment Difficulty levels (Easy Medium, Difficult) separately for the Objective Semantic and Objective Perceptual conditions. As the experiment was designed to assess the effect of the duration of various decision processes, planned comparisons were completed to assess the differences between each of the levels of Judgment Difficulty during the intervals during which they were active. For the Judgment Difficulty analysis, ERP component amplitudes were analyzed in a series of repeated-measures ANOVAs using the factors Judgment Difficulty (Easy, Medium, Difficult) and Electrode(s), separately for each ERP component (Figure 16).

The results for the Electrode factor will only be discussed if a significant interaction is found between Electrode and another factor, as a significant interaction may indicate topographic differences between conditions. A significant interaction between Electrode and another factor may result from differences in scalp topography, thus indicating the involvement of different neural generators (McCarthy & Wood, 1985), or can result from differences in amplitude between conditions. To assess the cause of the significant interaction, a topographic profile comparison is completed on ERP amplitudes after they have been normalized to remove amplitude differences between conditions (Johnson, 1993). The process of normalization involves scaling the amplitude of the ERP waveforms in each condition so that the root-mean-square (RMS) of the across-participant average waveform amplitudes is the same across conditions. If the interaction between Electrode and condition remains after normalization of amplitude differences between conditions, it indicates topographic differences, suggesting the presence of different neural generators between conditions. As using data from multiple electrode sites may lead to a violation of the sphericity assumption, all ANOVA results were corrected using the Greenhouse-Geisser procedure (Jennings & Wood, 1976). The uncorrected degrees of freedom are presented along with the corrected p values and epsilons (ε). Partial eta-squared (η_ρ^2) is reported as an index of effect size.

Results

Effect of Judgment Type and Domain

Behavioral results. Accuracy could only be determined for Objective judgments due to the lack of veridical answers for Subjective judgments. Thus, accuracy was tested in a one-way ANOVA using the factor Domain (Semantic, Perceptual). As shown in Table 2, as predicted in hypothesis 2, mean percent correct in both Domains was relatively high and did not significantly differ ($p > .05$).

Table 2. Grand Mean (SD) and Range of Percent Correct for Objective Conditions

	Objective Semantic	Objective Perceptual
Mean (SD)	87.1% (3.4)	86.9% (5.7)
Range	81.5–93.9%	70.4–94.0%

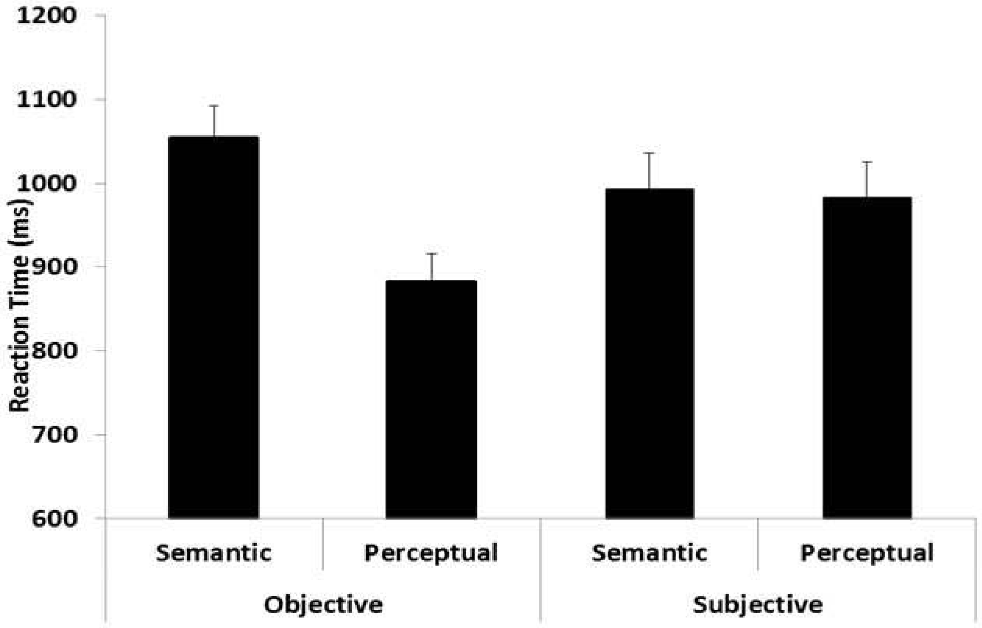


Figure 7. Mean RT in milliseconds (with standard error bars) for all conditions.

Reaction Times were calculated for correct items in the Objective conditions and all items in the Subjective conditions, as there was no veridical answer. It is evident from the data in Figure 7 that RTs were about the same across all conditions, with the exception that Objective Perceptual judgments were somewhat faster than the other conditions. A repeated measures ANOVA with factors Domain (Semantic, Perceptual) and Judgment Type (Objective, Subjective) on RT revealed that although there were no significant main effects (*p*s > .05), there was a significant Domain by Judgment Type interaction $F(1, 17) = 9.65$, $p = .006$, $\eta_\rho^2 = .80$. Confirming the visual impression of the data, RTs for Objective Perceptual judgments were significantly faster, by 172 ms, than RTs for Objective Semantic judgments $F(1, 17) = 14.57$, $p = .001$, $\eta_\rho^2 = .46$, with no RT difference across Subjective judgments ($p > .05$). No significant effect of Judgment Type on RT was seen in either the Semantic or Perceptual domains (*p*s > .05). It is important to note that the RT differences across Domains for Objective judgments are not attributable to differences in the speed-accuracy trade-off, as there were no accuracy differences across Domains. Hence, Perceptual judgments appear to have been somewhat easier than Semantic judgments. This RT difference may reflect that processing could begin sooner after stimulus onset for Perceptual compared to Semantic judgments (see below). A two-way ANOVA on the standard deviations of RT revealed no significant effect of Domain or Judgment Type on RT variability and no interaction between the two factors (*p*s > .05).

Although there is no way to quantify accuracy for Subjective judgments, the finding that RTs did not differ across conditions except for Objective Perceptual suggests that participants made valid preference judgments.

ERP results. As described in the introduction, the 2-by-2 analyses were designed to identify any specific patterns of ERP activity associated with the Domain and Judgment Type variables. In addition, these analyses provided information about which ERP components were affected by these variables, thereby determining which components should be included in the subsequent analyses on the effects of Judgment Difficulty. Therefore, various stimulus- and response-synchronized ERP components were quantified and tested in three-way ANOVAs using the factors Domain (Semantic, Perceptual), Judgment Type (Objective, Subjective), and Electrode, with the specific electrode sites included varying across components examined. The results for the different ERP components are presented according to the temporal sequence in which they occurred.

Early LPC – Stimulus-Synchronized ERPs. As can be seen in Figure 8A, a large positive peak was elicited by all judgments early in the recording interval over posterior-parietal scalp. Given that, this peak was maximal at Pz and peaked between 500 and 600 ms (see CSD maps, Figure 8B), it was identified as a LPC. As hypothesized (Hypothesis 2) and in accord with results of previous studies of evaluative judgments (Johnson et al., 2011, in preparation), this LPC peak occurred early despite mean RTs ranging from 882 to 1054 ms across conditions. As this Early LPC was hypothesized to reflect the beginning of judgment-related processing for all stimulus pairs, peak latencies were quantified as the most positive point at Pz between 400 and 700 ms. As shown in Table 3, Early LPC latencies were highly similar across conditions. An ANOVA on Early LPC latencies revealed no significant effect of Judgment Type ($p > .05$) and a borderline significant effect of Domain $F(1,17) = 3.92$, $p = .064$, $\eta_\rho^2 = .19$ as Early LPC latencies for Perceptual judgments were an average of 43 ms faster than those elicited by Semantic judgments. No significant interaction between Judgment Type and Domain was found ($p > .05$).

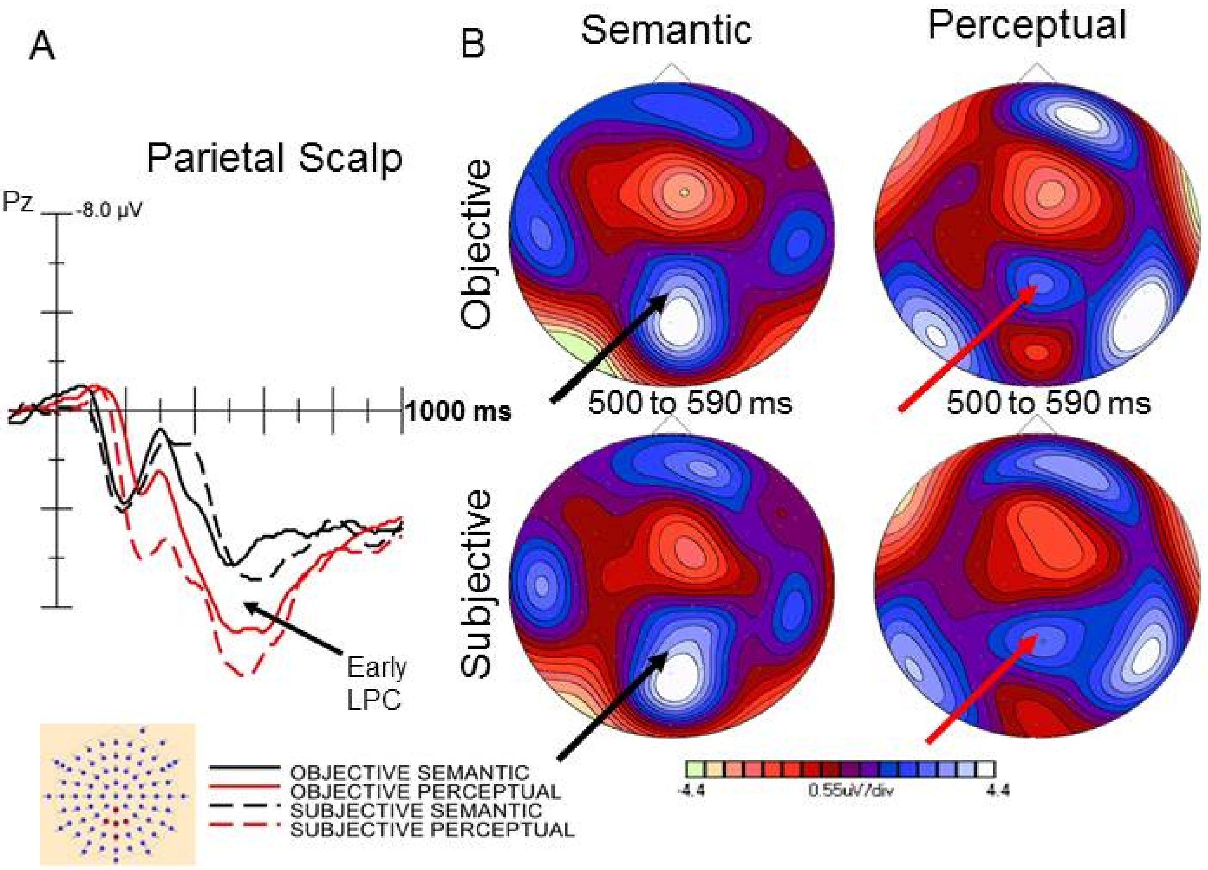


Figure 8. A. Stimulus-synchronized ERPs showing the Early LPCs (arrow) elicited in all four conditions at midline parietal scalp (Electrode: Pz). Activity is shown for an 1150-ms epoch beginning 150 ms prior to stimulus onset, which is indicated by the y-axis (100 ms/tick). In this and all subsequent figures, grand averages ERPs are presented with negative voltages plotted as upward deflections. In this and all subsequent figures, the red circles in the figure of the complete electrode array indicate which electrodes were used to quantify the ERP activity B. CSD maps at the time of peak of the Early LPC (500 to 590 ms) showing the patterns of cortical activation elicited in all four conditions. Arrows point to the midline parietal focus for LPC activity. All maps are presented as 110-degree projections with front of the head at the top. For this and all subsequent CSD map the scale used for each set of maps is shown in microvolts^2/division.

Table 3. Grand Mean Peak Latency in Milliseconds (SD) of Early LPCs for All Conditions

	Judgment Type	
Domain	Objective	Subjective
Semantic	563 (82)	559 (60)
Perceptual	518 (74)	517 (80)

It is also evident from the ERPs in Figure 8A that Perceptual judgments elicited larger Early LPCs than Semantic judgments. Early LPC amplitudes were quantified in a 400 to 700 ms interval at Pz and the four surrounding electrodes where Early LPC amplitudes were maximal (aPz, Pz, 19, 17, aOz). This ANOVA revealed that Perceptual judgments elicited larger Early LPCs than Semantic judgments $F(1, 17) = 6.34$, $p = .022$, $\eta_\rho^2 = .27$, with no effect of Judgment Type or interaction (*p*s > .05).

Medial and Lateral Occipital Scalp – Stimulus-Synchronized ERPs. The stimulus-synchronized ERPs elicited over medial and lateral occipital scalp are shown in Figure 9A. The ERPs in this figure reveal that, despite all stimulus pairs being presented visually, major differences in ERP activity were evident over medial (striate) and right and left lateral (extrastriate) visual areas beginning as early as 100 ms after stimulus onset. Perceptual judgments elicited a series of early sensory components (i.e., P1, N1, P2) that were followed by a large and prolonged positive slow wave that was largest over lateral occipital scalp and bilaterally symmetrical. By contrast, after the early sensory components, Semantic judgments elicited a brief positive-going peak followed by a negative slow wave that was asymmetrical and largest over left lateral occipital scalp. CSD maps of whole head cortical activity for two early intervals (200 to 290 ms, 300 to 390 ms) (Figure 9B) highlight these domain-dependent differences and confirm that Perceptual judgments elicited activity with strong foci over medial (striate) and right and left lateral (extrastriate) cortex.

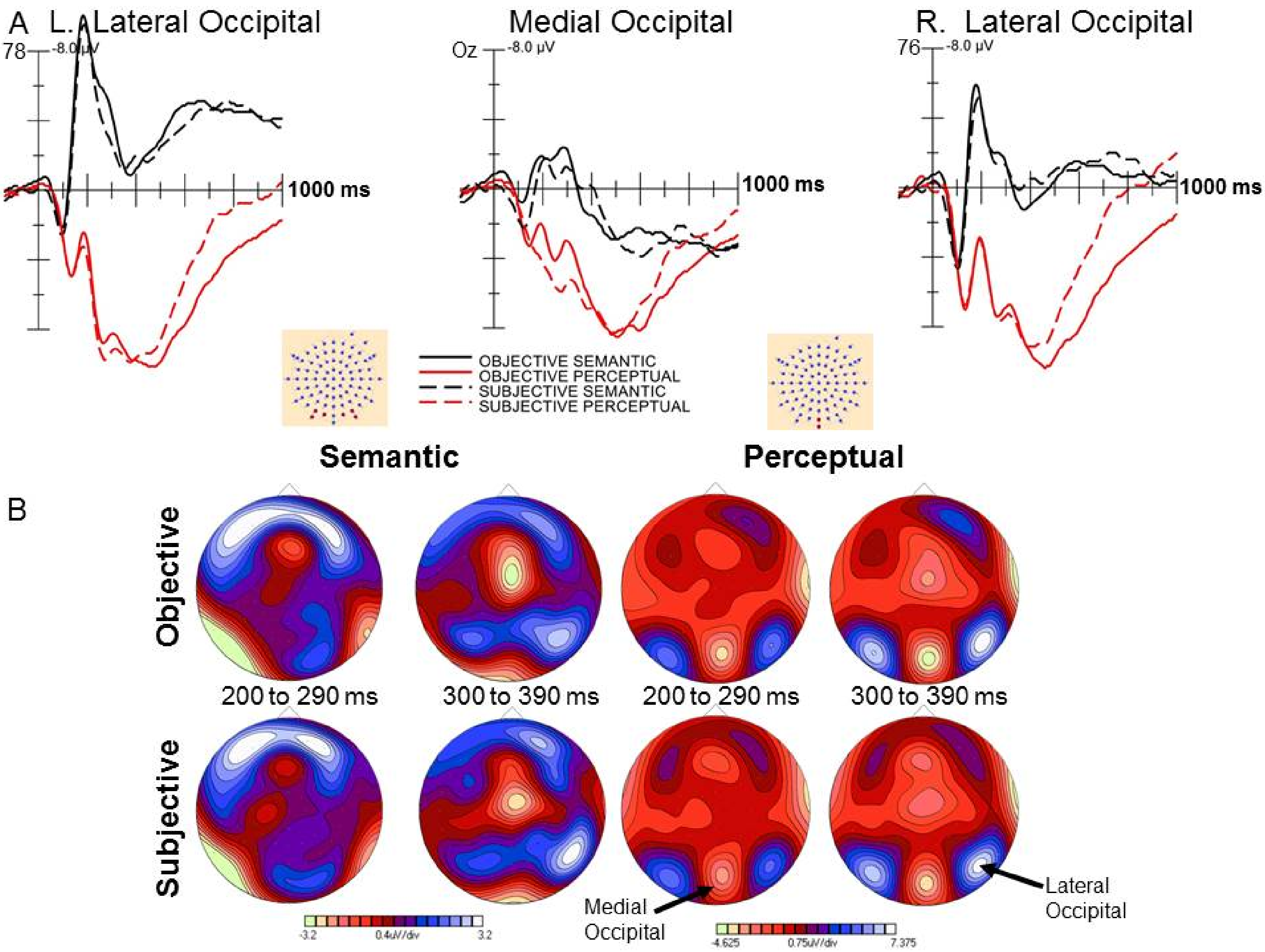


Figure 9. A. Stimulus-synchronized ERPs elicited by all four conditions at medial (Electrode: Oz) and left and right lateral Electrodes: 78, 76) occipital scalp. B. CSD maps of the ERP activity elicited by all four conditions for two intervals (200 to 290 ms, 300 to 390 ms) revealing early occipital activity. Different scales were used for the maps in each Domain because Perceptual stimuli elicited very large positive potentials over occipital scalp during this time interval. Arrows point the foci of the medial and lateral occipital activity.

To quantify medial and lateral occipital ERP activity, separate ANOVAS were calculated on ERP areas in the 300 to 600 ms interval at medial and lateral scalp when the positive potentials were largest (see Figure 9A). The ANOVA on medial occipital activity (Electrodes: Oz, inion) confirmed that Perceptual judgments elicited much larger positivities than Semantic judgments $F(1, 17) = 17.56$, $p < .001$, $\eta_\rho^2 = .51$. There was no effect of Judgment Type or significant Domain by Judgment Type interaction (*p*s > .05). However, a significant Domain by Electrode interaction $F(1, 17) = 27.08$, $p < .001$, $\eta_\rho^2 = .61$ was found as the amplitude differences across Domains were less at Oz compared to at the inion. Similarly, a significant Judgment Type by Electrode interaction $F(1,17) = 4.50$, $p = .049$, $\eta_\rho^2 = .21$ was found because Subjective judgments elicited larger positivities at Oz compared to the inion, resulting in less difference between Objective and Subjective judgments in the Perceptual domain at the inion. Topographic profile analyses revealed that, after normalization, the Domain by Electrode interaction remained significant $F(1, 17) = 21.61$, $p < .001$, $\eta_\rho^2 = .56$ but the Judgment Type by Electrode interaction did not ($p > .05$). This significant Domain by Electrode interaction raises the possibility that there were different patterns of neural generator activity elicited over medial occipital scalp as a function of Domain.

The ANOVA on the positivity elicited at lateral occipital scalp (Electrodes: left – 78, 60, O1; right – 76, 56, O2) revealed that Perceptual judgments elicited larger positivities than Semantic judgments $F(1, 17) = 29.72$, $p < .001$, $\eta_\rho^2 = .64$ regardless of Judgment Type ($p > .05$) and with no interaction ($p > .05$). A significant Domain by Electrode interaction was again found $F(1, 17) = 9.38$, $p < .001$, $\eta_\rho^2 = .36$ because Semantic judgments elicited asymmetrical negative slow waves (i.e., left greater than right) while Perceptual judgments elicited large positivities that were bilaterally symmetrical. After normalization, the profile comparison on the

Domain by Electrode interaction remained significant $F(1, 17) = 6.93$, $p = .017$, $\eta_\rho^2 = .29$, confirming the presence of different patterns of neural generator activity as a function of Domain over lateral occipital scalp.

Medial and Lateral Occipital Scalp – Response-Synchronized ERPs. The ERPs elicited over medial and lateral occipital scalp are shown in Figure 10A, along with CSD maps for intervals spanning -700 to -500 ms and -500 to -200 ms prior to the response (Figure 10B). These ERPs revealed that the small differences in amplitude as a function of Judgment Type early on steadily increased over time. That is, whereas Objective judgments elicited positivities that steadily increased in amplitude in the interval leading up to the response, amplitude increases were much smaller for Subjective judgments. Separate early and late ANOVAs were calculated on the data from medial (Electrodes: Oz, inion) and lateral (Electrodes: left – 78, 60, O1; right – 76, 56, O2) occipital scalp with the factors Judgment Type (Objective, Subjective) and Electrode. These ANOVAs confirmed that although Judgment Type had no effect on the amplitude of the positivity elicited over medial occipital cortex in the early interval ($p > .05$), Objective judgments elicited significantly more positive waveforms than Subjective judgments in the late interval $F(1, 17) = 4.72$, $p = .044$, $\eta_\rho^2 = .22$. Significant Judgment Type by Electrode interactions were also found for both early $F(1, 17) = 7.63$, $p = .013$, $\eta_\rho^2 = .31$ and late intervals $F(1, 17) = 4.73$, $p = .044$, $\eta_\rho^2 = .22$ because Subjective judgments elicited smaller positives at Oz compared than at the inion while Objective judgments elicited more similar waveforms at both sites. Both interactions remained significant after normalization $F(1, 17) = 6.35$, $p = .022$, $\eta_\rho^2 = .27$; $F(1, 17) = 6.67$, $p = .019$, $\eta_\rho^2 = .28$ for early and late intervals, respectively suggesting that different patterns of generator activity were associated with each Judgment Type.

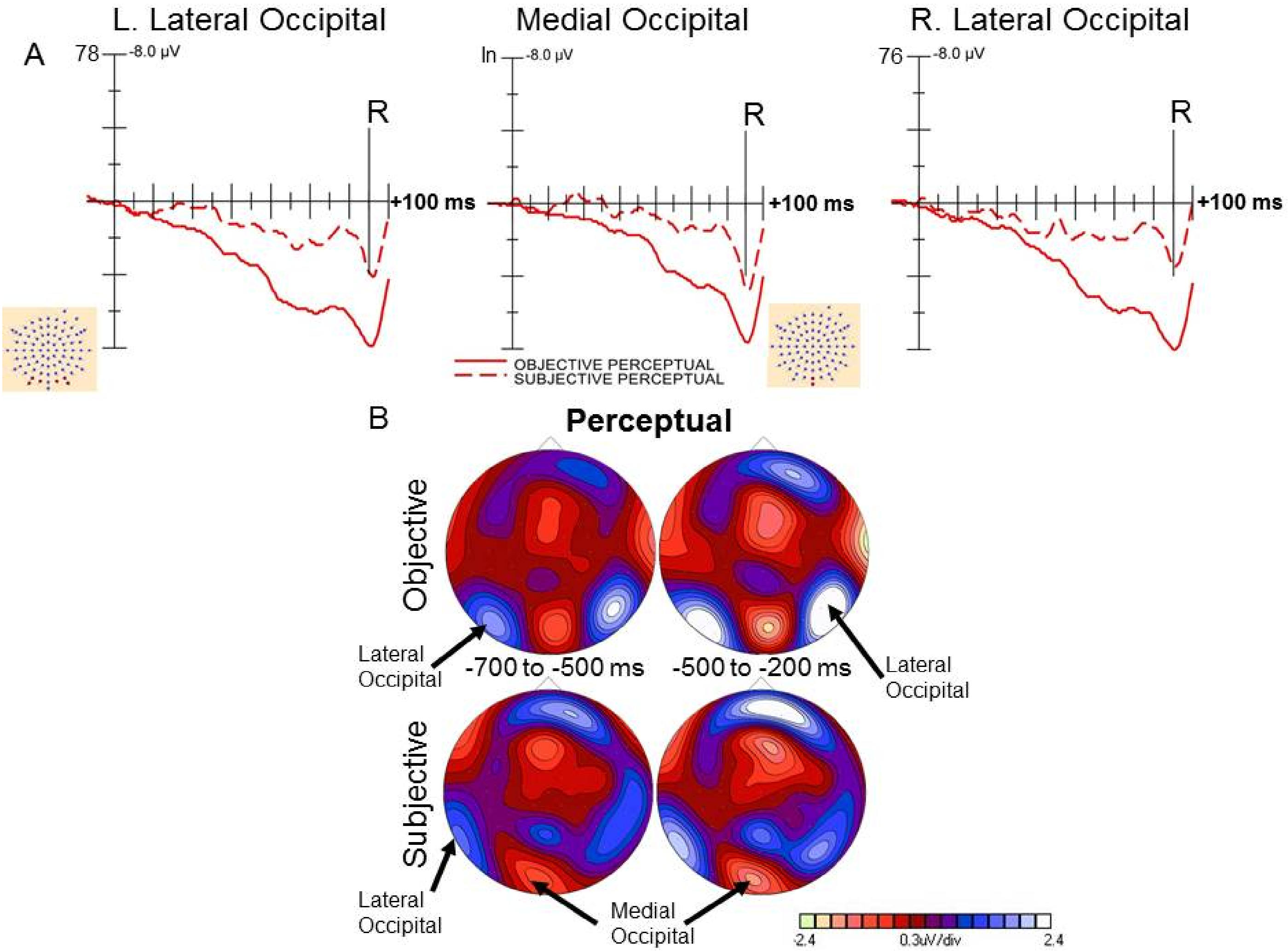


Figure 10. A. Response-synchronized ERP elicited during both Perceptual conditions over medial (Electrode: Oz) and left and right lateral (Electrodes: 78, 76) occipital scalp. In this and subsequent response-synchronized ERP figures, activity is shown for a 1550-ms epoch beginning 1450 ms prior to the response (100 ms/tick). The timing of the response is indicated by the vertical line labeled "R.". B. CSD maps of the ERP activity elicited in both Perceptual conditions during the -700 to -500 ms and -500 to -200 ms intervals prior to the response. Arrows point the foci of the medial and lateral occipital activity.

The ANOVAs on the positivities elicited over lateral occipital scalp revealed a similar pattern of results. Thus, although Judgment Type produced no significant amplitude differences in the early interval ($p > .05$), Objective judgments elicited significantly larger positivities during the late interval $F(1, 17) = 5.74$, $p = .028$, $\eta_\rho^2 = .14$. The Judgment Type by Electrode interaction was significant during the early interval $F(1, 17) = 5.06$, $p = .038$, $\eta_\rho^2 = .23$ but did not remain significant after amplitude normalization ($p > .05$).

In summary, as predicted (Hypothesis 3), significantly greater ERP activity was elicited over medial and lateral visual cortical areas for Perceptual compared to Semantic judgments. An effect of Domain was evident in both the waveforms and CSD maps as activity over medial and lateral visual areas terminated relatively quickly for Semantic judgments (i.e., by 400 ms), but continued for hundreds of milliseconds for Perceptual Judgments. The finding of ERP differences as a function Domain so early in the recording interval (i.e., 200 ms after stimulus onset) was unexpected, as it was predicted that judgment-related processing would commence after the Early LPC in all conditions. This result may have obtained because, unlike the requirement for semantic access in order to comprehend the nature of the two words in each Semantic stimulus pair, processing of the visual characteristics of the Perceptual stimulus pairs could simply continue after sensory processing. In accord with the predicted results, due to the continued requirement for detailed visual analysis of the stimulus pair in Objective judgments, Objective Perceptual judgments elicited significantly greater activity over both medial (striate) and right and left lateral (extrastriate) scalp, with these differences occurring primarily later in the evaluation interval. The finding of significant topographic profile comparisons indicates that significantly different patterns of generator activity were present as a function of Domain over both medial and lateral occipital brain regions.

Posterior Temporal Scalp – Stimulus-Synchronized ERPs. Given that semantic memories are believed to be stored in left temporal cortex, it was predicted that Semantic judgments would preferentially activate the posterior left temporal cortex. Visual inspection of the ERPs confirmed this predication as immediately following the Early LPC, a negative slow wave was elicited over left, but not right, posterior temporal scalp for Semantic judgments (Figure 10). This negativity began at roughly 500 ms, coincident with the Early LPC, and reached a plateau at approximately 700 ms and then continued until the response. By contrast, Perceptual judgments elicited large bilaterally symmetrical positivities over posterior temporal scalp (Electrodes: left – 78, 79, right – 76, 75). The CSD maps for all conditions in the 550 to 750 ms interval (Figure 11) revealed a clear left posterior temporal focus for this negativity for both Semantic judgments. To analyze this negativity, an ANOVA including the factors Domain (Semantic, Perceptual), Judgment Type (Objective, Subjective), Hemisphere (Left, Right), and Electrode was conducted. This analysis confirmed the asymmetrical nature of this negativity with a significant Hemisphere $F(1, 17) = 4.64$, $p = .046$, $\eta_\rho^2 = .21$ and Hemisphere by Domain interaction $F(1, 17) = 6.96$, $p = .017$, $\eta_\rho^2 = .29$.

A significant effect of Domain was also found as Semantic judgments elicited larger negativities than Perceptual judgments $F(1, 17) = 32.26$, $p < .001$, $\eta_\rho^2 = .65$. Although there was no main effect of Judgment Type found ($p > .05$), the Domain by Judgment Type interaction was significant $F(1, 17) = 7.10$, $p = .016$, $\eta_\rho^2 = .29$. To deconstruct this interaction, post-hoc analyses were completed to examine the effect of Domain separately for Objective and Subjective judgments and the effect of Judgment Type separately for Semantic and Perceptual judgments. The effect of Domain was significant for both Objective and Subjective judgments $F(1, 17) = 38.72$, $p < .001$, $\eta_\rho^2 = .69$; $F(1, 17) = 22.05$, $p < .001$, $\eta_\rho^2 = .56$, respectively as Semantic

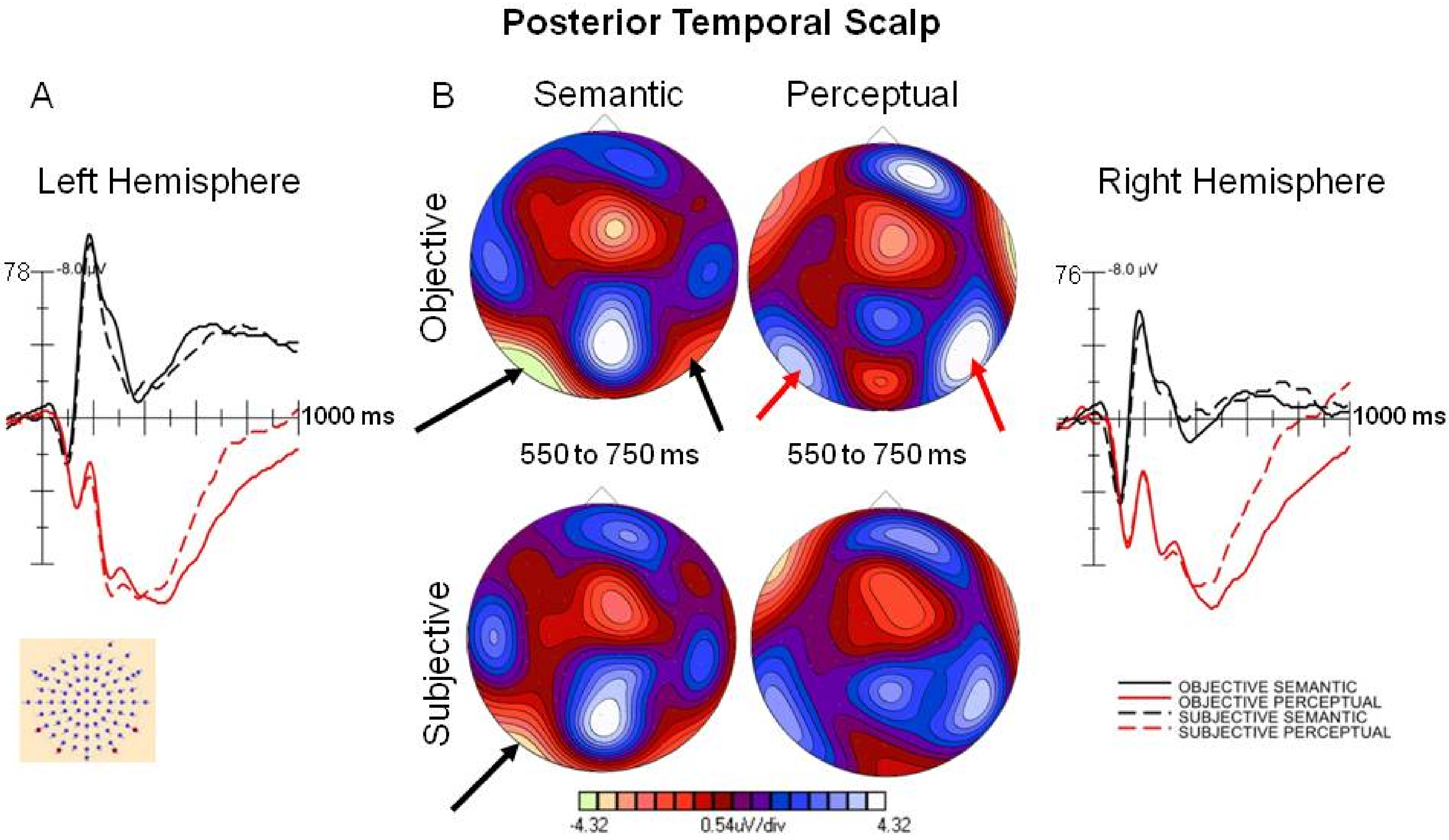


Figure 11. A. Stimulus-synchronized ERPs elicited in all four conditions over left (Electrode: 78) and right (Electrode: 76) posterior temporal scalp. B. CSD maps showing the activity for all conditions during the 550 to 750 ms interval when activity began over left posterior temporal scalp. Black arrows point to posterior temporal foci on Semantic maps, while red arrows indicate the same areas on a Perceptual map.

judgments elicited significantly larger negativities than Perceptual judgments for both Judgment Types. Supporting the observation that Semantic judgments elicited asymmetrical ERP activity, the Hemisphere by Domain interaction approached significance when Objective judgments were examined alone $F(1, 17) = 3.6$, $p = .075$ $\eta_\rho^2 = .17$ and was significant when Subjective judgments were examined alone $F(1, 17) = 8.77$, $p = .009$, $\eta_\rho^2 = .34$. In addition, Objective judgments alone produced a significant effect of Hemisphere $F(1, 17) = 6.36$, $p = .022$, $\eta_\rho^2 = .27$ and the Hemisphere by Domain by Electrode interaction was significant $F(1, 17) = 4.99$, $p = .039$, $\eta_\rho^2 = .23$. This pattern of interactions reflects that Semantic judgments elicited asymmetrical ERP activity. When each Domain was analyzed alone, an effect of Judgment Type was found for Perceptual $F(1, 17) = 7.17$, $p = .016$, $\eta_\rho^2 = .30$ but not Semantic judgments ($p > .05$), as Subjective judgments elicited smaller potentials than Objective judgments in the Perceptual but not Semantic domain. The lateralization differences for Semantic judgments was confirmed as a significant Hemisphere effect was found when Semantic judgments were examined alone $F(1, 17) = 8.73$, $p = .009$, $\eta_\rho^2 = .34$. The Domain by Electrode interaction was significant when Objective judgments were examined alone $F(1, 17) = 7.94$, $p < .001$, $\eta_\rho^2 = .32$ but did not remain significant after amplitude normalization across Domains ($p > .05$). In addition, a Judgment Type by Electrode interaction was found when Perceptual judgments were examined alone $F(1, 17) = 14.89$, $p = .001$, $\eta_\rho^2 =.47$, which remained significant after normalization $F(1, 17) = 8.82$, $p = .009$, $\eta_\rho^2 =.34$. This result suggests that different patterns of neural generator activity underlie the ERPs elicited by Objective and Subjective Perceptual judgments over posterior temporal scalp.

Posterior Temporal Scalp-Response – Synchronized ERPs. To examine whether Judgment Type had an effect on the amount or duration of access to semantic memory, response-synchronized ERP activity was analyzed in a two-way ANOVA with factors Judgment Type (Objective, Subjective) and Electrode. As evident from the waveforms and CSD maps (Figure 12), the left posterior temporal negativity elicited by both Semantic judgments slowly increased in amplitude until about 100 ms prior to the response. ANOVAs on the ERP activity elicited at

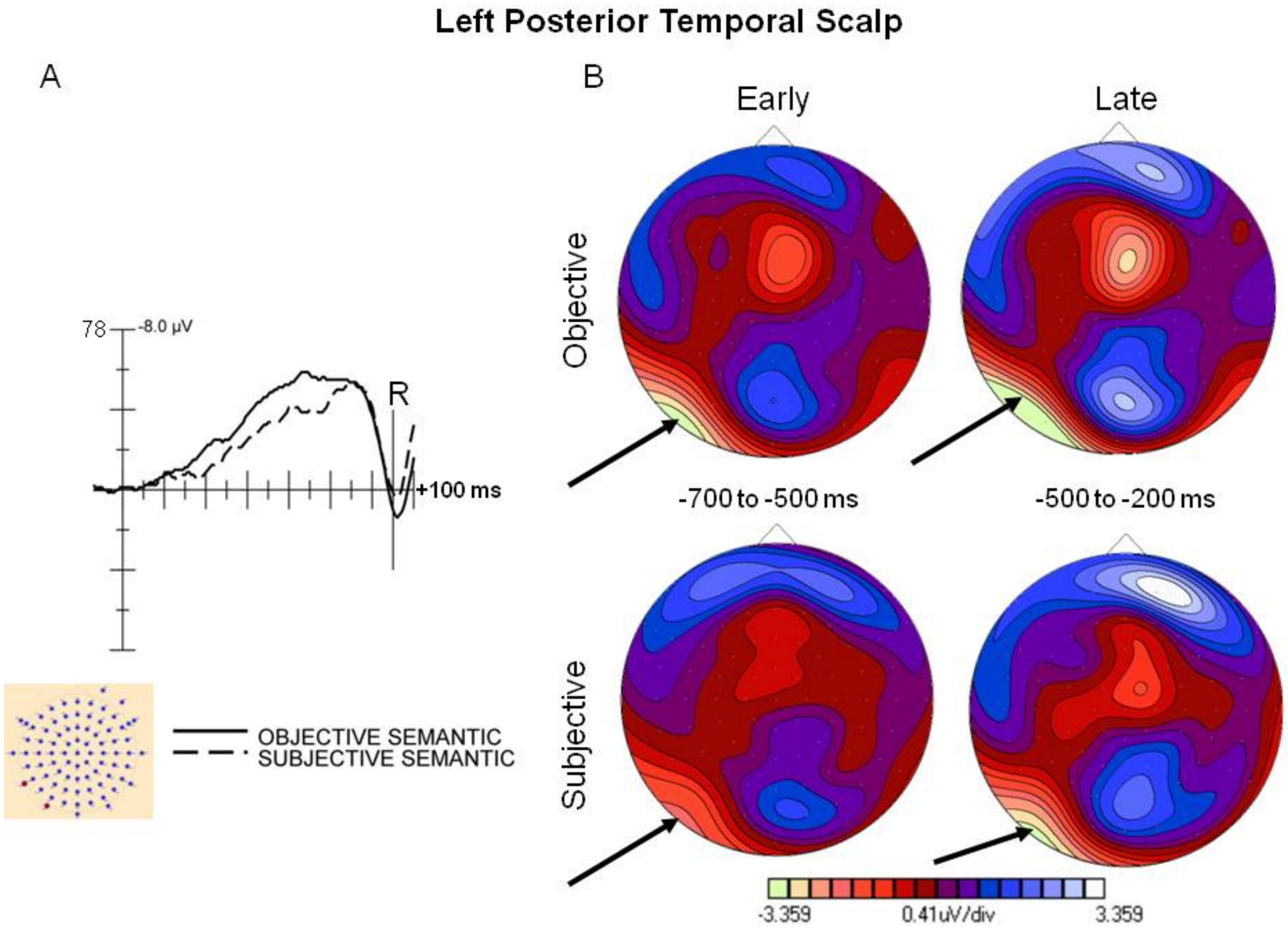


Figure 12. A. Response-synchronized ERPs elicited by both Semantic conditions over left posterior temporal scalp (Electrode: 78). B. CSD maps showing cortical activity for these conditions for two successive intervals (-700 to -500 ms and -500 to -200 ms) prior to the response.

the two left temporal sites (Electrodes: 78, 79) during early (-700 to -500 ms) and late (-500 to -200 ms) intervals revealed no significant amplitude differences in either interval (*p*s > .05). In contrast to predictions, these results suggest that this brain activity was equally involved in Objective and Subjective Semantic judgments throughout the evaluation interval.

In sum, consistent with access to semantic memory, Semantic judgments elicited a long-duration negativity over posterior temporal scalp that began early and steadily increased in amplitude until just prior to the response. By contrast, Perceptual judgments elicited bilaterally symmetrical positivities at the same locations that seemed to be volume conducted from more posterior, extrastriate areas.

Frontal Scalp – Response-synchronized ERPs. The possible contribution of late-onset processes such as working memory and executive processes was assessed by quantifying response-synchronized ERP activity elicited over frontal cortical areas. As can be seen in Figure 13, while Objective Semantic judgments elicited negative slow potentials over frontal scalp, the other three conditions were characterized by waveforms that were at baseline or positive. The CSD maps (Figure 13) show two foci at this time for Objective Semantic judgments, with one over left DLPFC and one over medial frontal scalp. The other three conditions were characterized by a single focus over medial frontal scalp.

Dorsolateral Prefrontal Scalp. As predicted in Hypothesis 6B as verbal and visuo-spatial working memory have been shown to be left and right lateralized, respectively (e.g., Owen et al., 2005), the ANOVA on ERP amplitudes elicited over DLPFC included a Hemisphere factor, in addition to the factors Domain (Semantic, Perceptual), Judgment Type (Objective, Subjective), and Electrode. The ANOVA was performed on ERP activity elicited at three electrodes over left (Electrodes: F3, F5, aF5) and right (Electrodes: F4, F6, aF6) DLPFC in an interval spanning -350 to -150 ms prior to the response. In contrast to predictions, the Hemisphere factor failed to achieve significance ($p > .05$), possibly due to the lateral frontal activity being predominantly present only in the Objective Semantic condition. Nevertheless, Semantic judgments elicited larger negativities than Perceptual judgments $F(1, 17) = 6.29$, $p = .023$, $\eta_\rho^2 = .27$ and Objective judgments elicited larger negativities than Subjective judgments $F(1, 17) = 9.89$, $p = .006$, $\eta_\rho^2 = .37$. No significant Domain by Judgment Type interaction was found ($p > .05$). The Judgment Type by Electrode interaction was significant $F(1, 17) = 4.55$, $p = .048$, $\eta_\rho^2 = .21$ and remained significant after normalization $F(1, 17) = 6.27$, $p = .022$, $\eta_\rho^2 = .79$. This interaction suggests the presence of different patterns of neural generator activity underlying the waveforms elicited by Objective and Subjective judgments because Subjective judgments elicited somewhat larger waveforms over right compared to left DLPFC. Although no significant effect of Hemisphere was found, the CSD maps (Figure 13) reveal a left DLPFC focus for Objective Semantic judgments. Thus, in contrast to the prediction that all judgments would engender working memory processes, based on the fact that only the Objective Semantic judgments elicited negative waveforms, suggests that these judgments required greater amounts of working memory than the other three judgments.

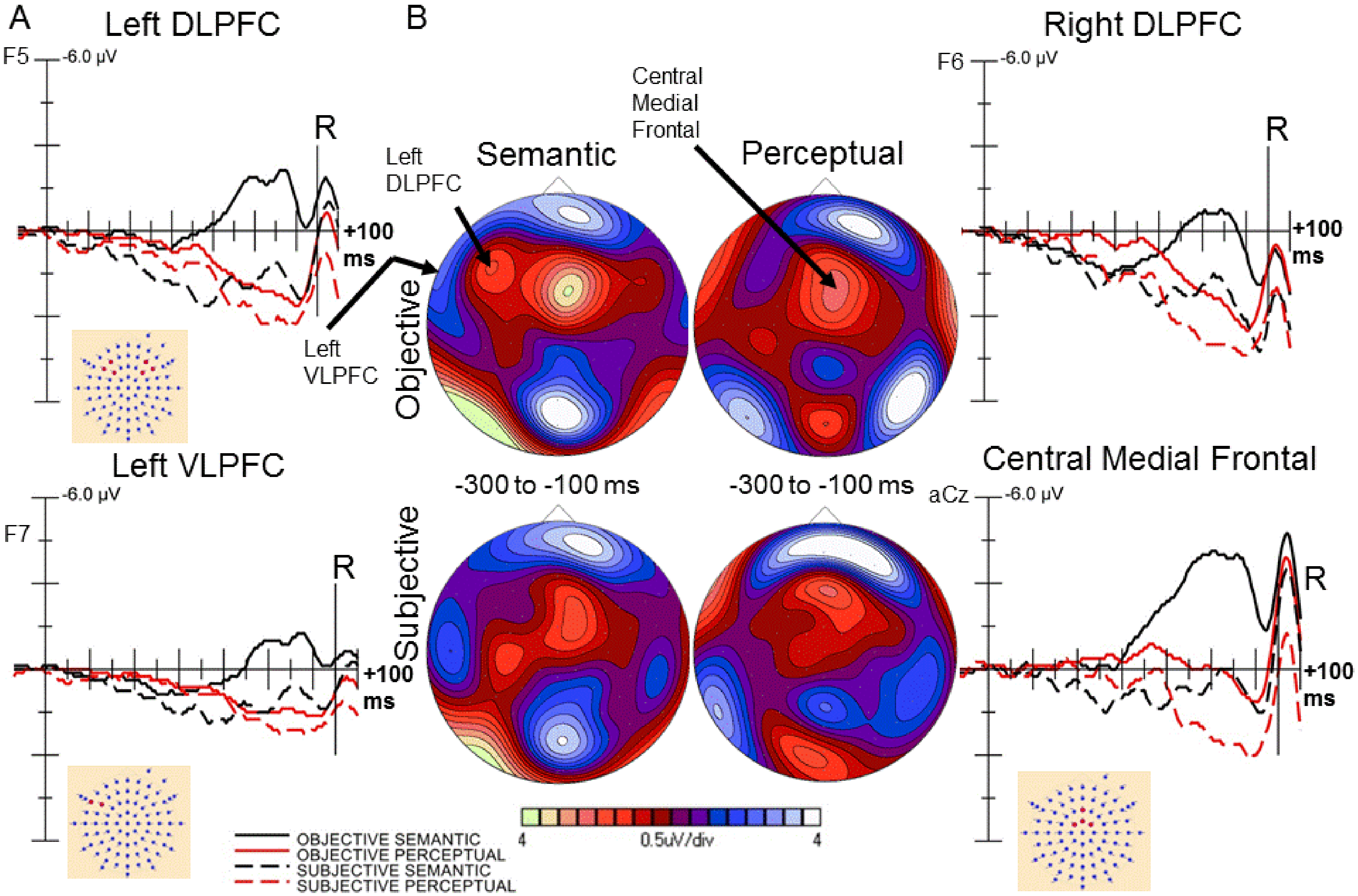


Figure 13. Response-synchronized ERPs elicited by all four conditions over central medial frontal (Electrode: aCz) and left (Electrode: F5) and right (Electrode: F6) DLPFC. CSD maps showing cortical activity elicited during all four conditions in the -300 to -100 ms interval prior to the response.

Central Medial Frontal Scalp. Consistent with the finding of a second, medial focus in the CSD maps of pre-response activity (Figure 13), a negative slow potential, beginning about 700 ms prior to the response, was elicited over central medial frontal scalp by Objective Semantic judgments. This focus, centered at aCz, was similar across Domains for Objective judgments with a slightly different, nearby focus for Subjective judgments. This activity was assessed during the -400 to -200 ms interval prior to the response at four central-frontal sites (Electrodes: aCz, Fz, 9, 3). A significant effect of Domain was found $F(1, 17) = 5.74$, $p = .029$, $\eta_\rho^2 = .25$, as a negativity was elicited by Objective Semantic judgments but positivities were elicited in the other conditions. This pattern of activity also resulted in a significant effect of Judgment Type $F(1, 17) = 11.8$, $p = .003$, $\eta_\rho^2 = .41$ but a non-significant Domain by Judgment Type interaction ($p > .05$). There was, however, a significant Judgment Type by Electrode interaction $F(1, 17) = 7.07$, $p = .017$, $\eta_\rho^2 = .29$ as Subjective judgments elicited more positive ERPs at medial (aCz, Fz) compared to lateral (3,9) sites. This interaction remained significant after normalization $F(1, 17) = 6.4$, $p = .022$, $\eta_\rho^2 = .27$, suggesting that different patterns of medial frontal generator activity were associated with Objective and Subjective judgments.

Left Ventrolateral Prefrontal Scalp. A third focus of activity over frontal scalp was evident in the CSD maps over left VLPFC, centered at electrode F7 (Figure 13). This activity appeared as a negative-going waveform beginning approximately 500 ms prior to the response for Objective Semantic judgments. The amplitude of the ERP component was quantified during the -400 to -100 interval at two electrodes over left VLPFC (F7, aF7). The effect of Domain was borderline significant $F(1, 17) = 4.32$, $p = .053$, $\eta_\rho^2 = .20$, as a negativity was elicited by Objective Semantic judgments but positivities were elicited by all other judgments. This pattern of activity also resulted in a significant effect of Judgment Type $F(1, 17) = 5.41$, $p = .033$, $\eta_\rho^2 = .24$, but a non-significant Domain by Judgment Type interaction ($p > .05$).

Late LPC – Response-synchronized ERPs. As can be seen in Figure 14A, a second LPC peaking just before the response was apparent in all conditions in the response-synchronized ERPs. The scalp distribution (see potential maps in Figure 14B) of this positivity was the same as that of both the Early LPC here and the Late LPCs found previously for evaluative judgments (Johnson et al., 2011). Further, the timing of this positivity was the same as that of Late LPCs found previously for evaluative judgments. The amplitude of the Late LPC was assessed at the same electrodes as used for the Early LPC (aPz, Pz, 19, 17, aOz) using the interval from -100 ms before to 100 ms after the response and no significant effects of Domain or Judgment Type, or their interaction, (*p*s > .05) were found. This lack of differences is consistent with the idea that, regardless of Domain or Judgment Type, all judgments end with processing associated with stimulus categorization, which is reflected in the Late LPC.

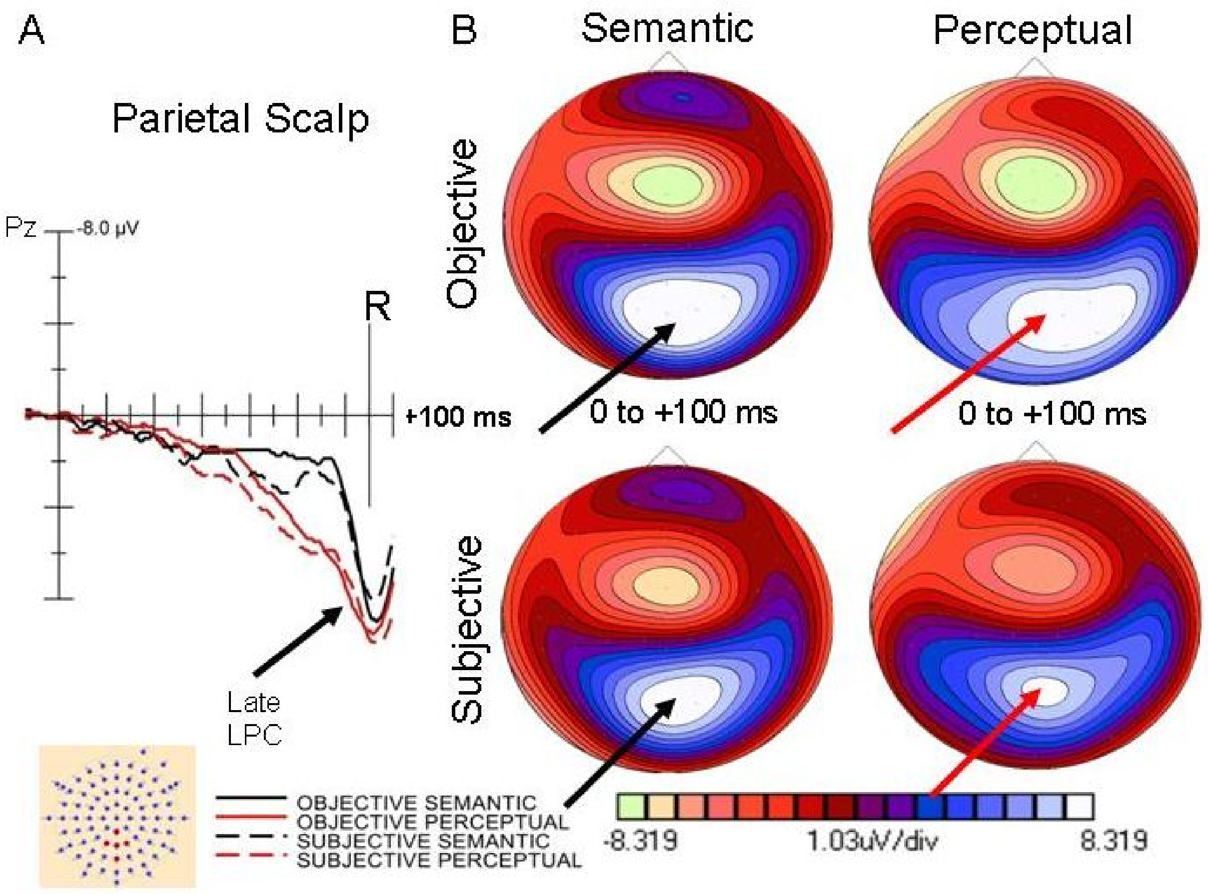


Figure 14. A. Response-synchronized ERPs showing the Late LPCs (arrow) elicited in all four conditions at the midline parietal electrode (Electrode: Pz). B. Potential maps showing whole brain activity elicited in all four conditions at the time of the Late LPC peak (0 to +100 ms).

In the interval leading up to the Late LPC, Semantic and Perceptual judgments elicited different patterns of ERP activity (Figure 14). The ERPs elicited by Perceptual judgments were characterized by a slowly increasing parietal positivity that began between -800 and -700 ms and ended around -100 ms, just prior to the onset of the Late LPC. By contrast, the parietal ERPs elicited by Objective Semantic judgments remained near baseline until approximately 100 ms prior to the response when the Late LPC was elicited. Finally, the ERPs elicited by Subjective Semantic judgments fell in between these two patterns. To assess these amplitude differences across conditions, an ANOVA was completed on the ERP amplitudes at the three centroparietal electrodes (17, Pz, 19) in the -500 to -300 ms interval. This ANOVA revealed a borderline significant effect of Domain $F(1, 17) = 4.11$, $p = .058$, $\eta_\rho^2 = .19$, as Semantic judgments elicited less positive ERPs than Perceptual judgments. No significant effect of Judgment Type or their interaction was found (*ps* >.05). The finding of differences in amplitude leading up to the Late LPC, despite the absence of differences in Late LPC amplitude across conditions, indicates that different processing underlies Semantic and Perceptual judgments in the pre-Late LPC interval, which nevertheless results in a similar final categorization of the stimulus.

Summary – Effect of Judgment Type and Domain. The 2-by-2 analyses revealed that both Domain and Judgment Type affected evaluative processing during relational judgments in the interval between the Early LPC and Late LPC. In accord with predictions, this interval was characterized by greater activity over primary and secondary visual areas for Perceptual judgments and greater activity over left temporal areas associated with semantic memory storage for Semantic judgments. Moreover, these different patterns of activity were obtained regardless of Judgment Type. A pattern over three frontal regions (central medial frontal, DLPFC, left VLPFC) emerged where Objective Semantic judgments elicited a negative going slow wave while the ERPs elicited by the three other types of judgments were at baseline or positive. An unexpected finding was that processing for Perceptual judgments began about 200 ms earlier than processing for Semantic judgments. This finding likely reflects that Semantic judgments require an additional step of retrieving information from memory prior to the beginning of evaluative processing, whereas this processing can begin almost immediately for Perceptual judgments.

Effect of Judgment Difficulty.

Both the IR and Accumulator models predict that the duration of judgment-related processing should increase as a function of judgment difficulty. Hence, the following analyses were conducted to determine which aspects of ERP activity described above showed differential durations as a function of Judgment Difficulty.

Although difficulty of Objective judgments was manipulated experimentally, it did not produce three non-overlapping RT distributions due to large within-individual differences in perceived difficulty. To eliminate overlapping RTs across difficulty levels, each individual's trials were divided into tertiles based on their RTs, and ERP averages were created on this basis (i.e., trials with fast, medium, and slow RTs were averaged into Easy, Medium, and Difficult categories). This procedure resulted in the loss of one participant's data because excessive eye movements resulted in too few trials in some tertile averages. Therefore, the Judgment Difficulty analyses were conducted on the remaining 17 participants. As can be seen from the data in Table 4 which shows mean RT both as a function of a priori difficulty and the tertile split, a clearer separation as a function of difficulty obtained from the tertile split than from the a priori difficulty levels. Therefore, the following analysis was conducted based on the Judgment Difficulty divisions based on the tertile split on RT.

Table 4. Mean RT (SD) in Milliseconds for the Three Levels of Difficulty Determined by a Priori and Tertile RT Splits for Objective Judgments

	Semantic			Perceptual		
	Easy	Medium	Difficult	Easy	Medium	Difficult
A priori	884 (150)	1041 (157)	1263 (204)	812 (143)	906 (146)	976 (162)
Tertiles	755 (97)	1001 (140)	1381 (196)	646 (106)	853 (152)	1210 (201)
Differences	Easy to Medium	Medium to Difficult		Easy to Medium	Medium to Difficult	
A priori	157	222		94	70	
Tertiles	246	380		207	357	

Behavioral results. The behavioral results were analyzed in a series of repeated-measures ANOVAs with factors of Domain (Semantic, Perceptual) and Judgment Difficulty (Easy, Medium, Difficult).

Accuracy. As seen in Table 5, accuracy varied as a function of Judgment Difficulty $F(2, 16) = 28.87$, $p < .001$, $\eta_\rho^2 = .60$ but did not vary as a function of Domain ($p > .05$). Planned comparisons revealed that for Objective Semantic judgments, accuracy was significantly lower for Difficult compared to Medium $F(1, 16) = 33.75$, $p < .001$, $\eta_\rho^2 = .68$ and Easy $F(1, 16) = 32.33$, $p < .001$, $\eta_\rho^2 = .67$ judgments, although the latter categories did not differ ($p > .05$). Similar results were obtained for Objective Perceptual judgments, as accuracy was significantly lower for Difficult compared to Medium judgments $F(1, 16) = 16.65$, $p < .001$, $\eta_\rho^2 = .50$ and Easy $F(1, 16) = 6.93$, $p = .018$, $\eta_\rho^2 = .30$, which did not differ from each other ($p > .05$). The Domain by Judgment Difficulty interaction also was not significant ($p > .05$) indicating that the effect of Judgment Difficulty was not different across Domains.

Table 5. Mean Accuracy (SD) and Range for All Three Judgment Difficulty Levels for Each Objective Condition

	Semantic			Perceptual		
	Easy	Medium	Difficult	Easy	Medium	Difficult
Mean (SD)	91.3% (4.8)	90.5% (3.7)	82.1% (5.7)	89.6% (8.7)	89.4% (5.8)	83.8% (6.9)
Range	82.4 to 98.3%	85.7 to 96.7%	71.4 to 90.7%	64.6 to 98.5%	74.6 to 97.1%	70.7 to 97.0%

Reaction Time. In order to confirm that the division of trials into Easy, Medium, and Difficult based on a tertile split of RT resulted in groupings with significantly different RTs, the RTs across groupings were compared. As can be seen from the data in Figure 15A, RT for Objective judgments increased with Difficulty in both Domains $F(2, 16) = 523.55$, $p < .001$, $\eta_\rho^2 = .97$ and as discussed above (Figure 7), RTs for Semantic judgments were longer than RTs for Perceptual judgments $F(1, 16) = 10.34$, $p = .005$, $\eta_\rho^2 = .39$. Planned comparisons revealed that RTs for Easy Semantic judgments were 246 ms faster than RTs for Medium judgments $F(1, 16) = 305.93$, $p < .001$, $\eta_\rho^2 = .95$, which in turn were 380 ms faster than RTs for Difficult judgments $F(1, 16) = 391.56$, $p < .001$, $\eta_\rho^2 = .96$. Similar results were obtained for Perceptual judgments, with RTs for Easy judgments being 207 ms faster than RTs for Medium judgments $F(1, 16) = 187.76$, $p < .001$, $\eta_\rho^2 = .92$, which in turn were 357 ms faster than RTs for Difficult judgments $F(1, 16) = 261.38$, $p < .001$, $\eta_\rho^2 = .94$. The Domain by Judgment Difficulty interaction was not significant ($p > .05$), indicating that Domain and Judgment Difficulty had independent effects on RT.

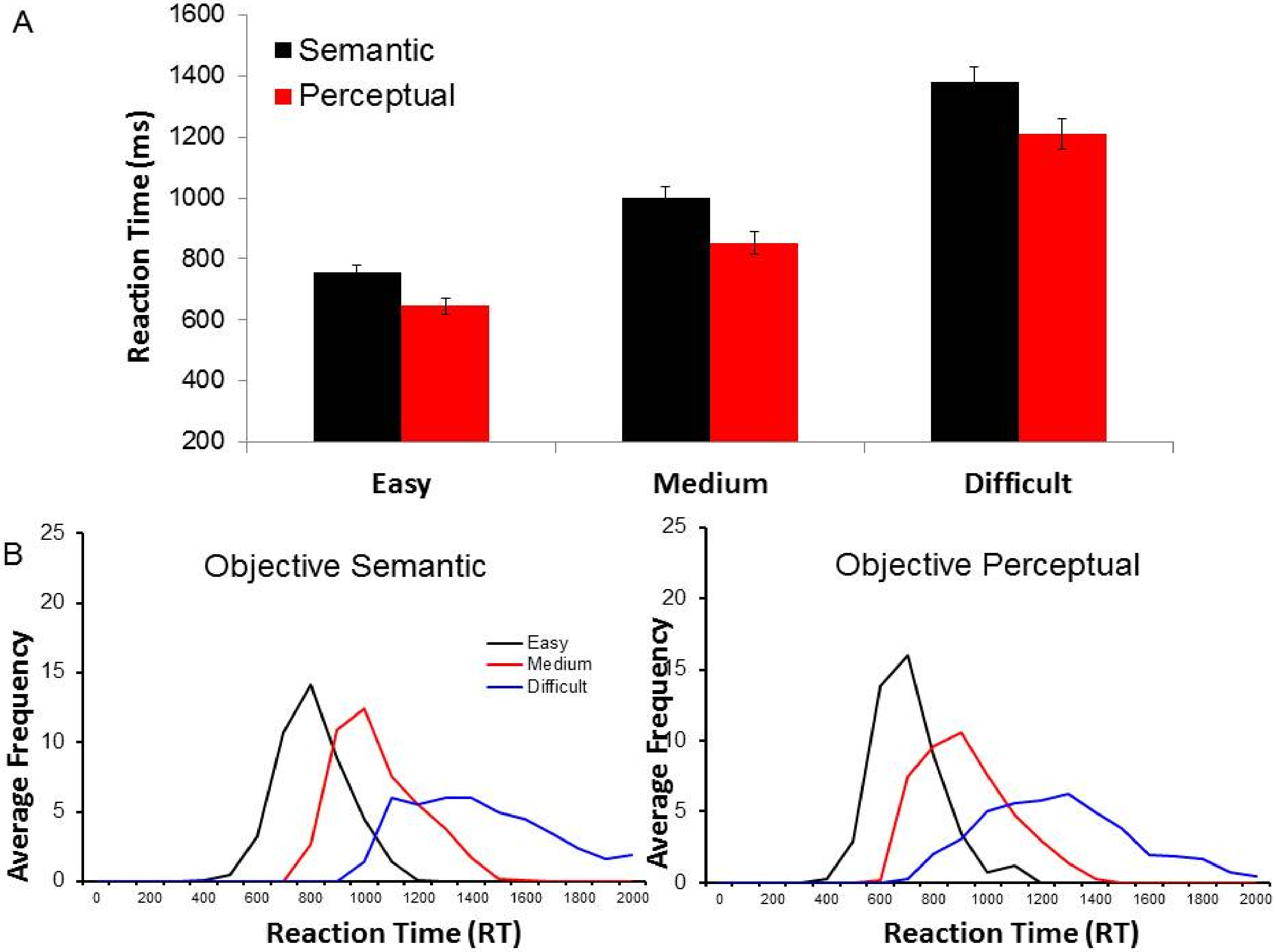


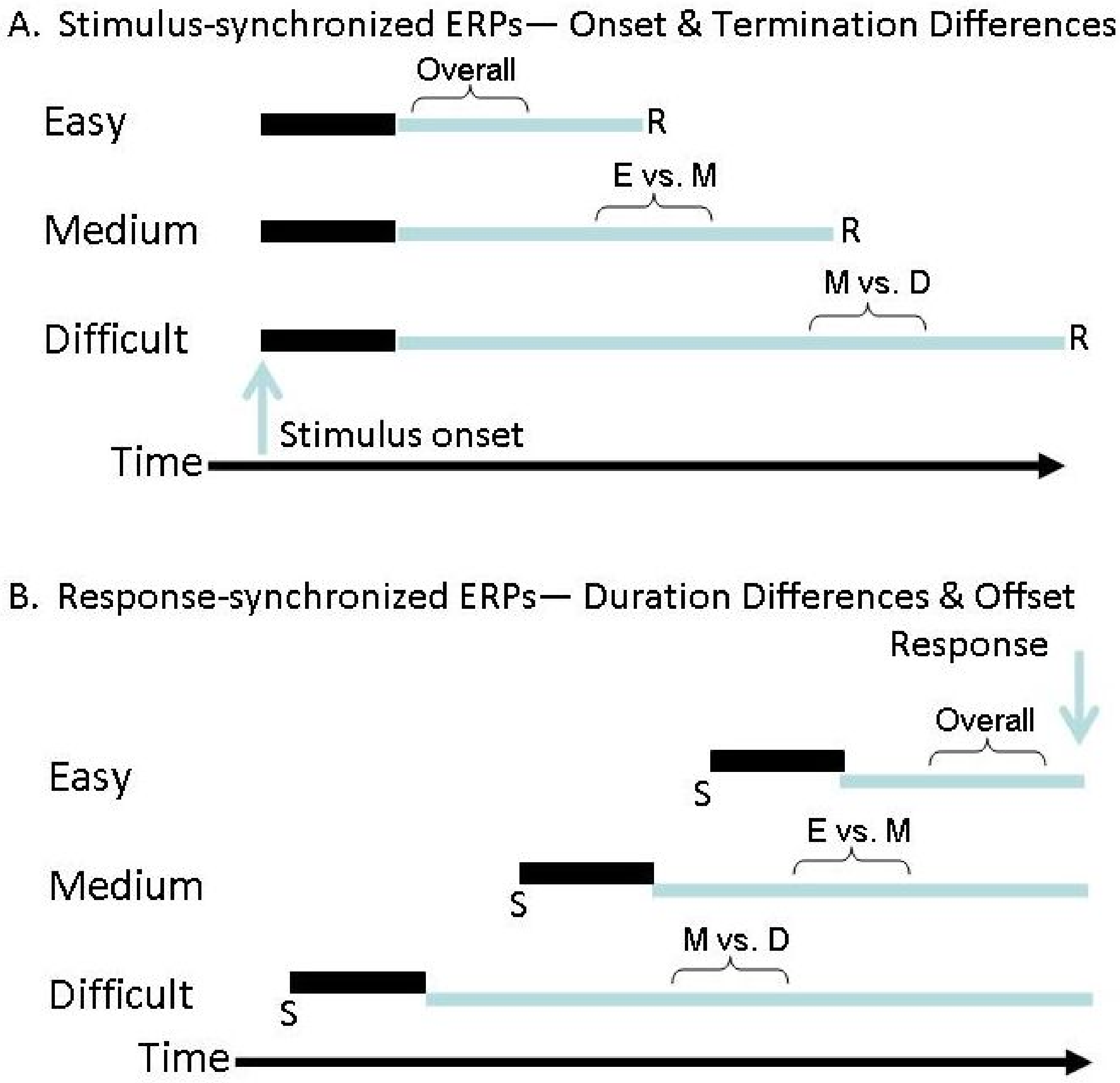
Figure 15. A. RT in milliseconds (with standard error bars) as a function of Judgment Difficulty for the Objective Semantic (Black) and Perceptual (Red) conditions. B. Relative frequency graphs showing the mean number of responses as a function of RT (100 ms bins) for Objective Semantic (Left) and Perceptual (Right) conditions for Easy (Black), Medium (Red) and Difficult (Blue) judgments.

Overall, the divisions based on the tertile split on RT created a high degree of variability in the time required to complete the relational judgments in both Domains. This can be seen in the grand mean RT frequency histograms for the Objective Semantic and Perceptual judgments at each difficulty level (Figure 15B). As expected, RT variability increased with Judgment Difficulty, as evidenced by the decreasing height and increasing breadth of the RT distributions. An ANOVA on the RT standard deviations revealed that RT variability was significantly affected by Judgment Difficulty $F(2, 16) = 213.42$, $\varepsilon = .69$, $p < .001$, $\eta_\rho^2 = .93$, with no effect of Domain or interaction (*p*s > .05). Planned comparisons revealed that RTs for Semantic judgments were significantly more variable for Difficult judgments compared to either Medium $F(1, 16) = 186.55$, $p <.001$, $\eta_\rho^2 = .92$ or Easy $F(1, 16) = 128.32$, $p < .001$, $\eta_\rho^2 = .89$ judgments, with no significant difference between Medium and Easy judgments ($p > .05$). Similarly, RTs for Perceptual judgments were significantly more variable for Difficult judgments compared to either Medium $F(1, 16) = 118.0$, $p < .001$, $\eta_\rho^2 = .88$ or Easy $F(1, 16) = 79.79$, $p < .001$, $\eta_\rho^2 = .83$ judgments, with no difference between Medium and Easy judgments ($p > .05$).

Overall, RT and RT variability increased directly along with Judgment Difficulty. Further, accuracy was inversely related to Judgment Difficulty, with significantly lower accuracy for Difficult compared to easier judgments.

ERP results. As indicated above, the duration of any ERP slow potentials associated with relational judgment processing should vary as a function of Judgment Difficulty. To assess the predicted differences in duration of ERP activity as a function of difficulty, three intervals of activity were analyzed. High levels of RT variability were built into the current experiments in order to create three Judgment Difficulty levels. This high level of variability affected the way the examination of the differences in duration of processing between the Judgment Difficulty levels could occur. Thus, it was necessary to adopt an analysis strategy that is somewhat different than is usually employed to quantify ERP activity (see Figure 16).

In stimulus-synchronized averages (Figure 16A), ERP components reflecting judgment-related processing were expected to have the same onset regardless of Judgment Difficulty but variable offsets, with activity for Easy judgments ending first and Difficult judgments ending last. To capture the differences in overlap created by differences in offset time, three intervals, each with a different pattern of overlapping processing, were analyzed. In the earliest interval at the outset of processing, related ERP activity should occur for all levels of difficulty, which was assessed with an overall ANOVA, followed by post-hoc comparisons as needed. In an intermediate interval, processing for Easy judgments should be complete, while continuing for Medium and Difficult judgments. To determine if this pattern of results was obtained, ERP activity elicited by Easy and Medium judgments was compared, with greater activity expected for Medium judgments. Finally, in the last interval, processing for Medium judgments should be complete while continuing for Difficult judgments. To confirm whether this pattern of results was obtained, ERP activity elicited by Medium and Difficult judgments was compared, with greater activity expected for Difficult judgments.



A. Stimulus-synchronized ERPs— Onset & Termination Differences

B. Response-synchronized ERPs— Duration Differences & Offset

Figure 16. Schematic of the analysis strategy used to test for the presence of duration differences in the ERP activity elicited by different levels of judgment difficulty. A. Stimulus-synchronized ERPs allow for the examination of the onset of evaluative processing and termination differences. In this figure, 'R' represents time of average RT. B. Response-synchronized ERPs allow for the examination of differences in the duration of evaluative processing, as well as the offset of the processing. In this figure, 'S' represents time of average stimulus onset. Black horizontal bars represent the duration of sensory processing. In Panel B, it is clear that the sensory processing for easier judgments overlaps with the evaluative processing of more difficult judgments. In both panels, the blue horizontal bars represent evaluative processing, black horizontal bars represent sensory processing, and horizontal braces (⏞) provide approximations of the intervals used in the statistical analysis.

Differences in the duration of judgment-related ERP activity should appear in the opposite order in response-synchronized averages (Figure 16B). In this case, judgment-related ERP activity should be present, regardless of difficulty level, late in the ERP waveform near the timing of the response, while processing of more difficult judgments should begin earlier relative to the response compared to easier judgments. Hence, a late interval immediately prior to the response was examined with an overall ANOVA, followed by post-hoc tests as necessary. In the intermediate interval, processing for Medium judgments was expected to begin prior to the start of processing for Easy judgments and thus ERP activity for these two judgments was compared, with greater amplitude expected for Medium judgments. Finally, processing for Difficult judgments was expected to have the longest duration and thus begin before the Medium judgments. This was tested by comparing ERP activity across Medium and Difficult judgments in an early interval, with greater amplitude expected for Difficult judgments. Although the timing of the analyses' intervals is relatively straightforward for stimulus-synchronized ERPs due to there being little impact of response processing, this is not the case for the pre-response intervals in response-synchronized ERPs. The main difficulty with choosing the analysis intervals in response-synchronized ERPs was that, as can be seen in Figure 5B, the large early sensory ERPs (e.g., P1, N1, P2) elicited for easier judgments temporally overlapped judgment-related processing intervals for more difficult judgments. This differential overlap of sensory and judgment-related ERP activity across difficulty levels meant that the quantification intervals used at each scalp area had to be tailored to avoid including the early sensory ERPs in the comparison interval.

The following analyses involved repeated measures ANOVAs with the factors Judgment Difficulty and Electrode. The levels of Judgment Difficulty included in each test depended on the interval being examined, as described above. The Electrodes included in each test depended on which aspect of ERP activity was being examined.

Objective Semantic Judgments.

Early LPC – Stimulus-Synchronized ERPs. As evident from the stimulus-synchronized ERPs in Figure 17A, the latency of the Early LPC (i.e., approximately 524 ms, 504 ms, 518 ms, for Easy, Medium, and Difficult judgments respectively) was unaffected by Judgment Difficulty in the Semantic domain. This was confirmed as an ANOVA on Early LPC peak latency (i.e., the most positive peak at Pz between 450 and 600 ms) revealed no significant differences ($p > .05$). As evident from the CSD maps in Figure 17B, Early LPCs had the same PZ focus regardless of Judgment Difficulty. The amplitude of the Early LPCs elicited by Easy and Difficult judgments were about the same, while Medium judgments elicited a somewhat smaller potential. However, an ANOVA on Early LPC area in the 450 to 600 ms interval (Electrodes: aPz, Pz, 19, 17, aOz) failed to reveal significant amplitude differences ($p > .05$). These results indicate that, as expected, the initial processing of animal names was completed at the same time and in substantially the same manner regardless of Judgment Difficulty. Based on the timing of the Early LPC, onset of judgment-related processing for all judgments began, on average, at 500 ms.

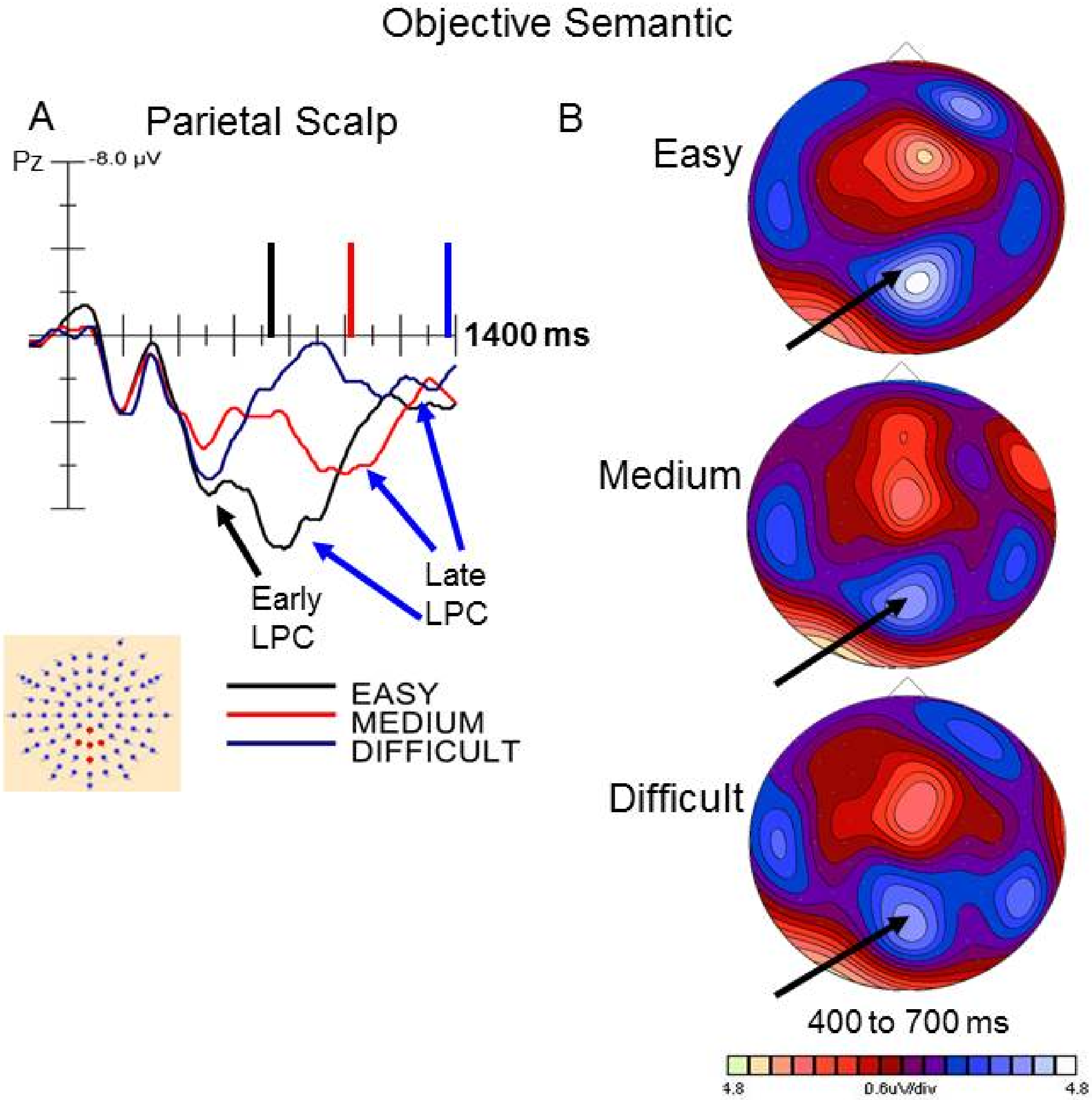


Figure 17. A. Stimulus-synchronized ERPs showing the Early (black arrow) and Late LPCs (blue arrows) elicited at midline parietal scalp (Electrode: Pz) in the Objective Semantic condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the occurrence of mean RT for the Easy, Medium, and Difficult judgments, respectively. For this and subsequent figures on Judgment Difficulty, the epoch for the stimulus-synchronized ERPs was extended to 1400 ms post-stimulus. B. CSD maps for the interval when the Early LPC peaked (400 to 700 ms) are shown for all three Judgment Difficulty levels. Arrows point to the midline parietal foci of Early LPC.

Left Posterior Temporal Scalp– Stimulus-Synchronized ERPs. As revealed in the 2-by-2 analyses, Semantic judgments were characterized by a prolonged negativity over left posterior temporal cortical areas beginning around 400 ms. As evident from the ERPs in Figure 16A, this negativity began at the same time for all Semantic judgments, although its amplitude and duration increased directly with Judgment Difficulty. As evident from the maps in Figure 18B, the activity was focused over left posterior temporal scalp (Electrodes: 78, 79). An overall ANOVA on the ERP activity in an early interval (550 to 750 ms) revealed a significant effect of Judgment Difficulty $F(2, 16) = 5.75$, $\varepsilon = 833$, $p = .024$, $\eta_\rho^2 = .26$, with Easy judgments eliciting significantly less negativity than either Medium $F(1, 16) = 6.97$, $p = .018$, $\eta_\rho^2 = .30$ or Difficult $F(1, 16) = 7.31$, $p = .016$, $\eta_\rho^2 = .31$ judgments, whose amplitudes did not differ ($p > .05$). In accord with Easy judgments being completed, on average, by 755 ms, the negativity elicited by Easy judgments peaked and began decreasing around 600 ms. An ANOVA on the intermediate interval (700 to 900 ms) revealed that significantly more negativity was elicited for Medium compared to Easy judgments $F(1, 16) = 4.97$, $p = .041$, $\eta_\rho^2 = .24$. Following this interval, whereas the negativity continued for Difficult judgments, it ended between 900 and 950 ms, just prior to the 1001 ms mean RT for Medium judgments. An ANOVA on the late interval (900 to 1000 ms) confirmed that the negativity remained for Difficult but not Medium judgments $F(1, 16) = 25.68$, $p = .0001$, $\eta_\rho^2 = .96$. Thus, whereas the onset of this left posterior temporal negativity was the same regardless of Judgment Difficulty, its duration was directly related to the time required to make the different judgments.

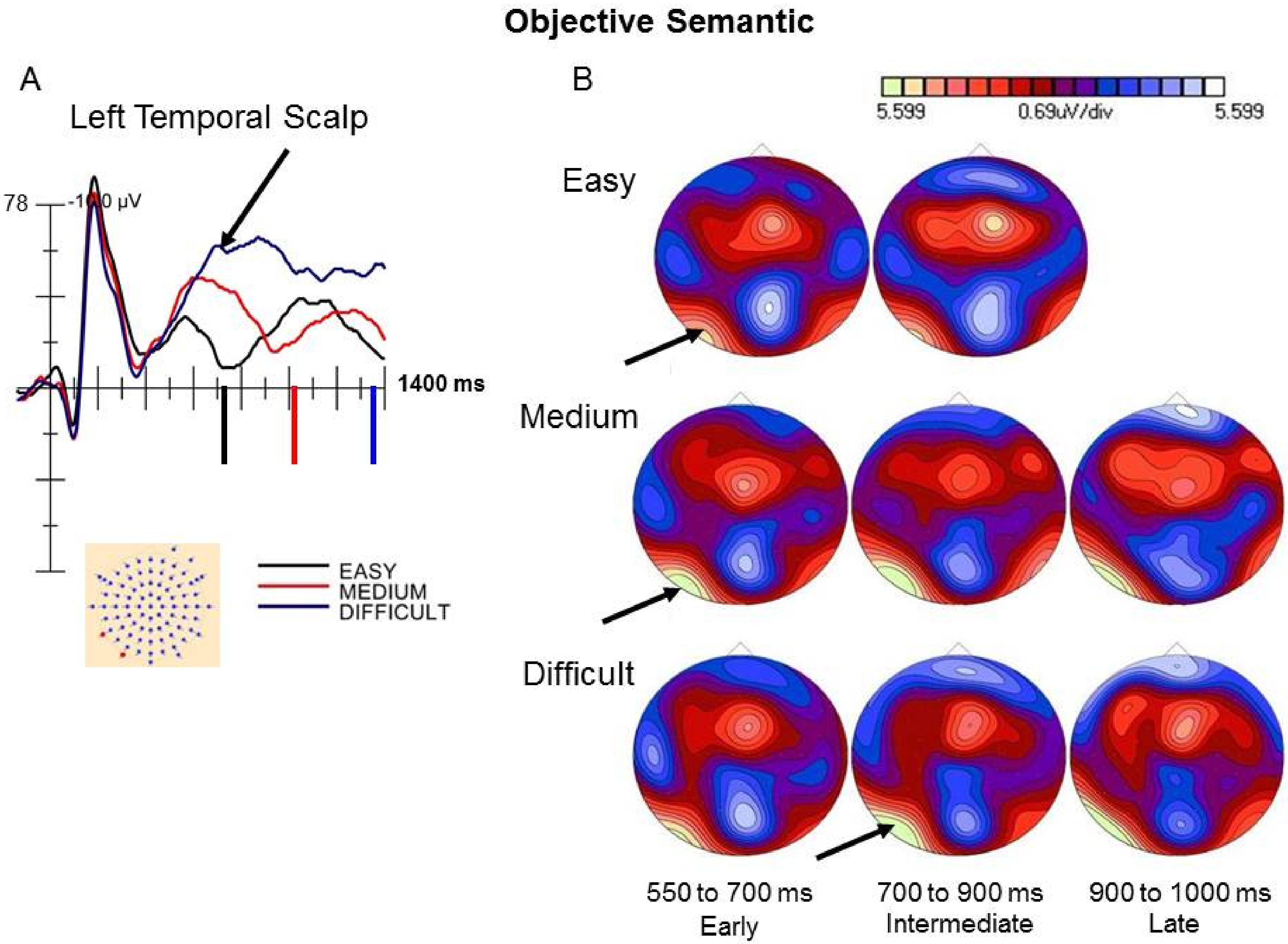


Figure 18. A. Stimulus-synchronized ERPs elicited over left temporal scalp (Electrode: 78) in the Objective Semantic condition at all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the occurrence of mean RT for Easy, Medium, and Difficult judgments, respectively. B. CSD maps of the ERP activity elicited during the early (550 to 700 ms), intermediate (700 to 900 ms), and late (900 to 1000 ms) quantification intervals for all three Judgment Difficulty levels.

Left Posterior Temporal Scalp – Response-Synchronized ERPs. Response-synchronized ERPs (Figure 19A) revealed that both the duration and amplitude of the left posterior temporal negativity increased as a function of Judgment Difficulty. These ERPs show that, in keeping with the long decision time for Difficult judgments, the amplitude of this negativity steadily increased beginning at least 1000 ms prior to the response, with progressively shorter durations and smaller amplitudes elicited by Medium and Easy judgments. For all judgments, this negativity began a rapid decline 150 to 200 ms prior to the response. The maps in Figure 19B reveal a left posterior temporal focus (Electrodes: 78, 79) that was greater for Difficult compared to Easy judgments. In the late interval (-250 to -150 ms), an overall ANOVA revealed a borderline significant effect of Judgment Difficulty $F(2, 16) = 3.65$, $\varepsilon = 797$, $p = .068$, $\eta_\rho^2 = .19$. Post-hoc tests revealed that Easy judgments elicited significantly less negativity than Medium $F(1, 16) = 6.92$, $p = .018$, $\eta_\rho^2 = .3$ judgments and borderline significantly less negativity than Difficult $F(1, 16) = 4.36$, $p =.053$, $\eta_\rho^2 = .21$ judgments. The negativities elicited by Medium and Difficult judgments in the late interval did not differ ($p > .05$). Given the overlap of sensory processing for Easy judgments with semantic retrieval for more difficult judgments, no intermediate interval comparing Medium and Easy judgments could be created. A comparison of the negativity elicited by Difficult and Medium judgments in an early interval (-550 to -400 ms) confirmed that Difficult judgments elicited significantly larger negativities $F(1, 16) = 3.71$, $p =.07$, $\eta_\rho^2 = .19$. These results are consistent with Hypothesis 8, that the interval over which semantic memory retrieval was required increased directly as a function of Judgment Difficulty.

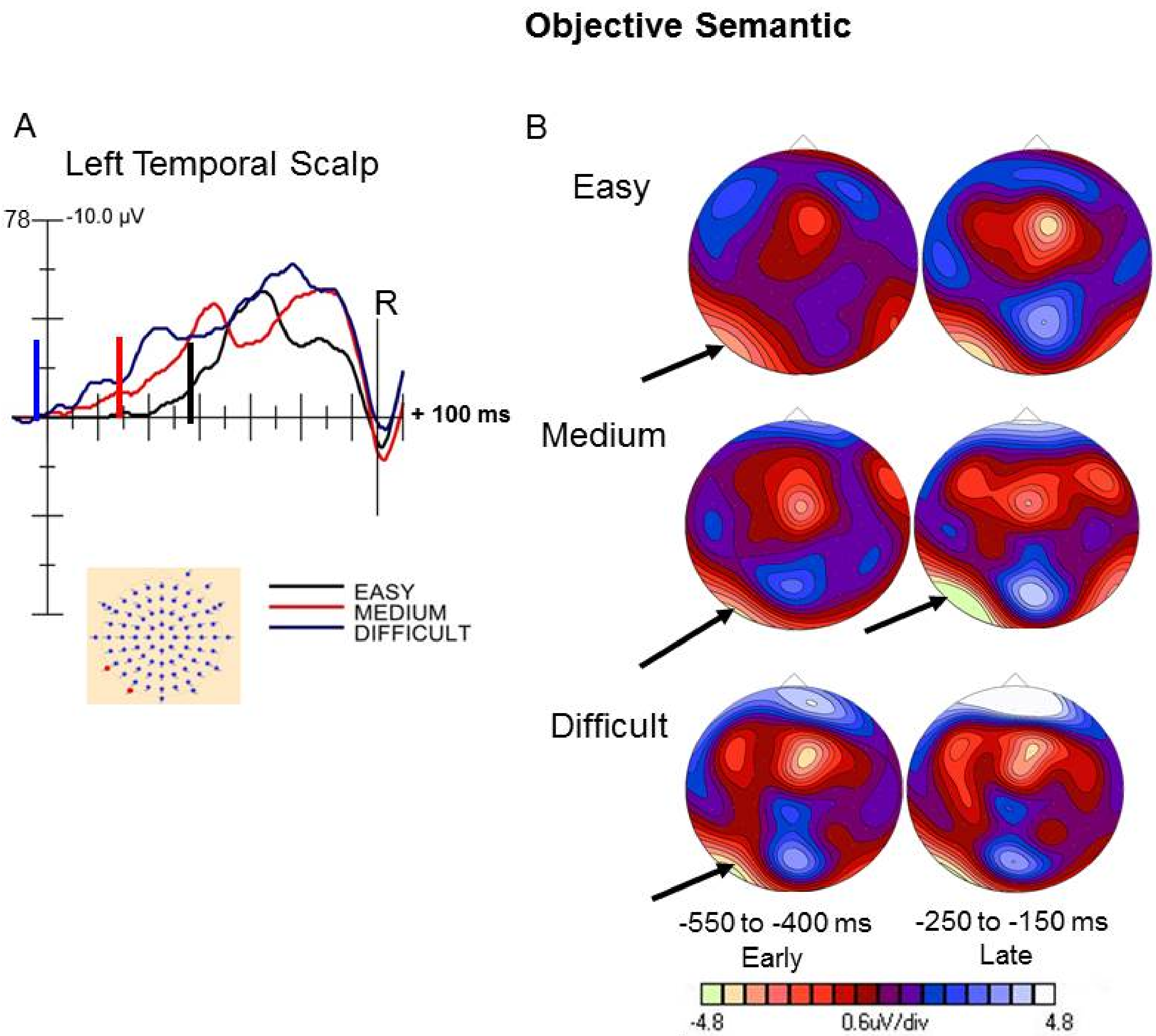


Figure 19. A. Response-synchronized ERPs elicited over left temporal scalp (Electrode: 78) in the Objective Semantic condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark mean stimulus onset time for Easy, Medium, and Difficult judgments, respectively. B. CSD maps of the ERP activity elicited during the early (-550 to -400 ms), and late (-250 to -150 ms) quantification intervals for all three Judgment Difficulty levels.

Frontal scalp – Response-Synchronized ERPs. The CSD maps in Figure 20B reveal foci of activity over multiple frontal scalp areas including medial frontal scalp, DLPFC, and left VLPFC, each of which is discussed in turn. In all these frontal brain regions, judgment-related ERP activity began later relative to activity elicited over more posterior brain regions and thus is most clearly seen in response-synchronized waveforms (Figure 20A). As evident in Figure 20A, the negativity over central medial frontal and DLPFC began at approximately the same time for all Judgment Difficulty levels. By contrast, a negativity appeared only for Difficult items over left VLPFC, with an onset approximately 100 ms later than onset over the other areas. Despite differences of 381 ms between the RTs for Difficult and Medium judgments and 246 ms between Medium and Easy judgments, the onset of the frontal negativities in response-synchronized ERPs occurred with 200 ms lags across all Judgment Difficulty levels. For all judgments, the amplitudes of these negativities increased steadily until -150 to -200 ms prior to the response.

Central Medial Frontal Scalp. As evident from the ERPs in Figure 20A, both the duration and amplitude of the medial frontal negativity increased as a function of Judgment Difficulty. As evident from the CSD maps (Figure 20B), this negativity had an aCz focus with a slight right lateralization so it was quantified at aCz and the adjacent right medial frontal scalp sites (Electrodes: aCz, 3, 11). In the late interval (-350 to -150 ms), despite some apparent amplitude differences, an overall ANOVA revealed no significant effect of Judgment difficulty ($p > .05$). In the intermediate interval (-550 to -350 ms), the ANOVA revealed that Medium judgments elicited significantly larger negativities than Easy judgments $F(1,16) = 5.33$, $p = .035$, $\eta_p^2 = .25$. Finally, in the early interval (-800 to -600 ms), Difficult judgments elicited larger negativities than Medium judgments $F(1, 16) = 6.55$, $p = .024$, $\eta_p^2 = .29$.

Left Dorsolateral Prefrontal Scalp. The maps in Figure 20B show a focus over left DLPFC that was centered at three sites (Electrodes: F3,aF5,F5), which were used in the analyses. In the late interval (-350 to -150 ms), the overall ANOVA revealed no significant effect of Judgment Difficulty on the amplitude of this negativity (p >.05). In the intermediate interval (-500 to -350 ms), the ANOVA confirmed that Medium judgments elicited significantly more negativity than Easy judgments $F(1, 16) = 3.06$, $p = .026$, $\eta_\rho^2 = .27$. Similarly, in the early interval (-700 to -600 ms) the ANOVA revealed that Difficult judgments elicited significantly more negativity than Medium judgments $F(1, 16) = 5.79$, $p = .029$, $\eta_\rho^2 = .27$.

Left Ventrolateral Prefrontal Scalp. Unlike the other two frontal areas, the negativity recorded over left VLPFC, a brain area associated with semantic selection processes, was only clearly present for Difficult judgments (Figure 20A). The CSD maps (Figure 20B) indicate that this negativity was focused at two sites (Electrodes: F7, aF7) and, because it was only clearly seen for the Difficult judgments, it was examined with an overall ANOVA over a single interval (-700 to -100 ms). A significant effect of Judgment Difficulty was found $F(2, 16) = 4.46$, $p = .043$, $\eta_\rho^2 = .22$ as Difficult judgments elicited more negative waveforms than either Medium $F(1, 16) = 3.82$, $p = .068$, $\eta_\rho^2 = .19$ or Easy $F(1, 16) = 7.29$, $p = .016$, $\eta_\rho^2 = .31$ judgments, which did not significantly differ (p >.05).

Overall, the duration of both the central medial frontal and left DLPFC activity increased along with Judgment Difficulty in roughly 200 ms “steps” between all Judgment Difficulty levels. By contrast, activity over left VLPFC was mainly seen for Difficulty judgments indicating that these judgments engendered more semantic selection than easier judgments.

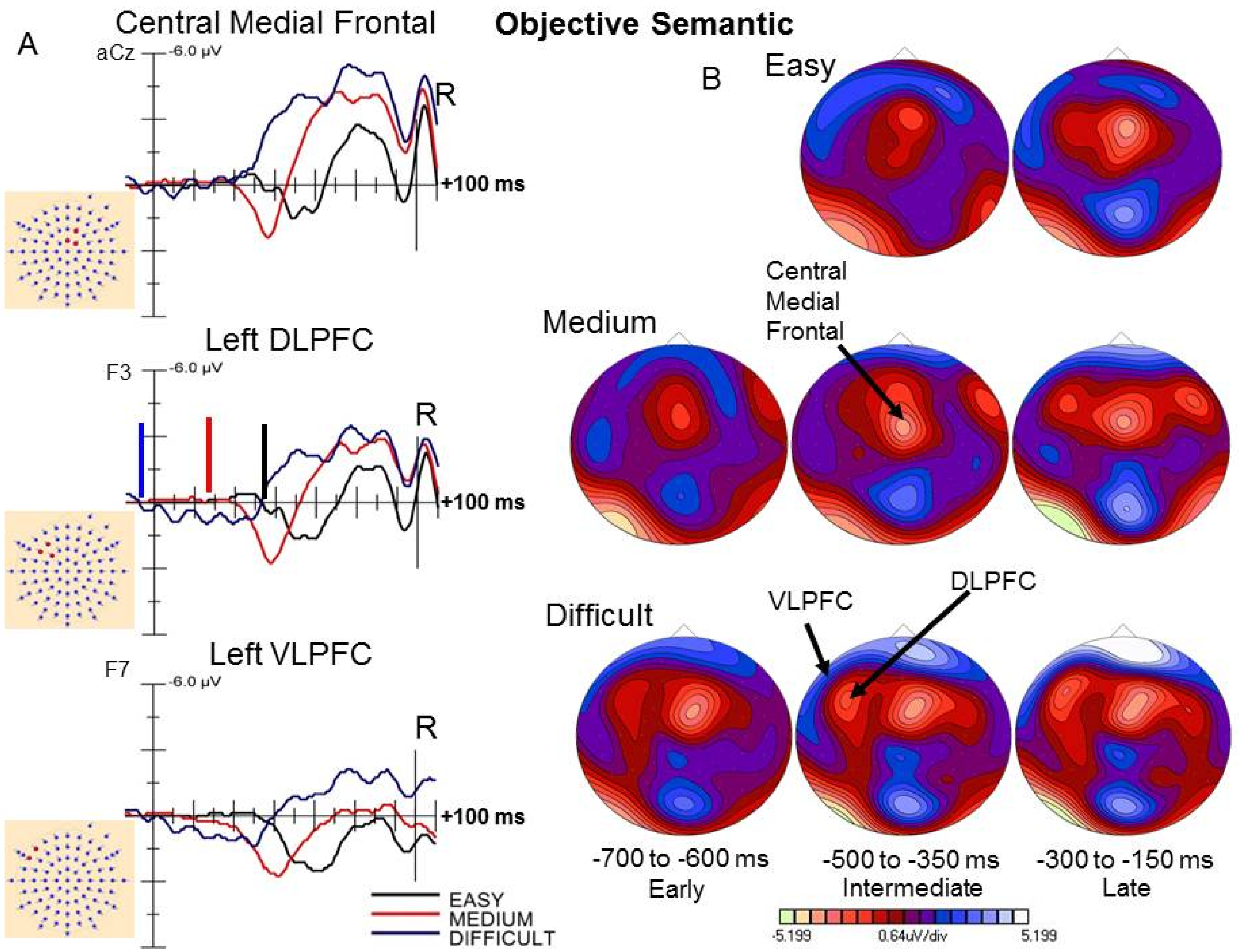


Figure 20. A. Response-synchronized ERPs elicited over central medial frontal (Electrode: aCz), left DLPFC (Electrode: F3), and left VLPFC (Electrode: F7) in the Semantic Objective condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark mean stimulus onset time for Easy, Medium, and Difficult judgments, respectively. B. CSD maps of the ERP activity elicited during the early (-700 to -600 ms), intermediate (-500 to -350 ms), and late (-300 to -150 ms) quantification intervals for all Judgment Difficulty levels. Arrows point to the central medial frontal, left DLPFC, and left VLPFC foci in the CSD maps.

Late LPC – Response-Synchronized ERPs. A Late LPC with the same scalp distribution as the Early LPC, was apparent in both the stimulus- and response-synchronized waveforms (Figures 17 and 21, respectively). As would be expected from their faster and less variable RTs, the stimulus-synchronized Late LPC was clearest in the ERPs elicited by the Easy judgments. This second LPC can be seen at approximately the same time as mean RT for Easy judgments (e.g., 755 ms, blue arrow in Figure 17). Although later and somewhat broader, in accord with their later and more variable RTs, the second LPC for the Medium judgments again occurred 100 to 200 ms prior to the mean RT. This Late LPC was even less distinct in the stimulus-synchronized waveforms for Difficult judgments, as would be expected from their much longer and more variable RTs.

The fact that the Late LPC reflects categorization for all judgments, regardless of Judgment Difficulty, is readily apparent in the response-synchronized ERPs. As evident from the waveforms and maps in Figure 21, the Late LPC elicited at the time of the response had all the spatiotemporal and amplitude characteristics of a typical LPC. The Late LPC was quantified at the same sites as used for the Early LPC (Electrodes: aPz, Pz, 19, 17, aOz) over the interval from -50 to 150 ms after the response. The overall ANOVA revealed a significant effect of Judgment Difficulty $F(2, 16) = 6.97$, $\varepsilon = .45$, $p = .014$, $\eta_\rho^2 = .30$ on amplitude. Post-hoc analyses revealed that, although the amplitudes of the Late LPCs elicited by Easy and Medium judgments did not significantly differ ($p > .05$), both these judgments elicited significantly larger Late LPCs than those elicited by Difficult judgments $F(1, 16) = 9.32$, $p = .008$, $\eta_\rho^2 = .39$; $F(1, 16) = 14.22$, $p < .001$, $\eta_\rho^2 = .9$, for Easy and Medium judgments, respectively.

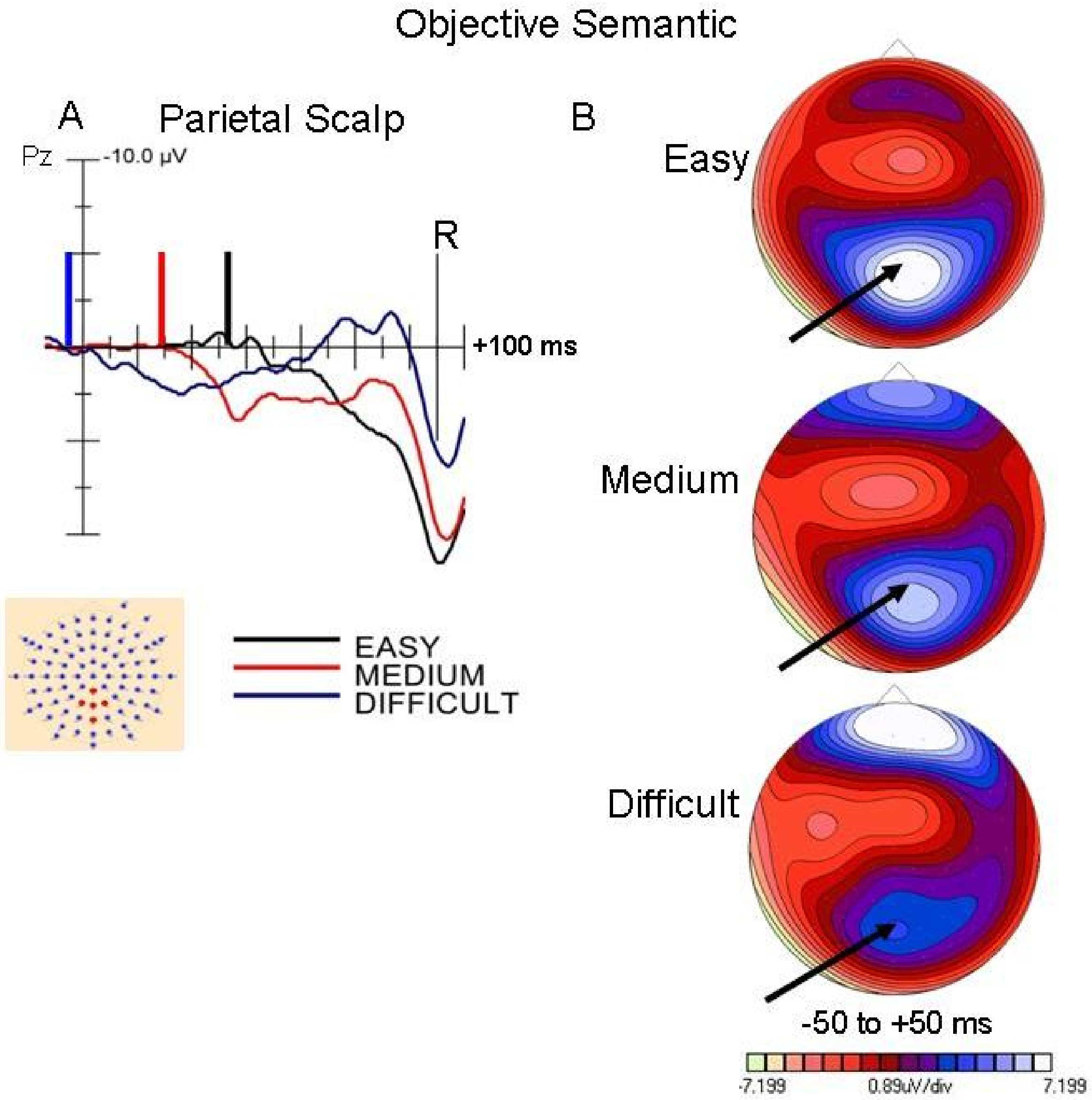


Figure 21. A. Response-synchronized ERPs showing the Late LPCs (arrow) elicited at midline parietal scalp (Electrode: Pz) in the Objective Semantic condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark mean stimulus onset time for Easy, Medium, and Difficult judgments, respectively. B. Potential maps for the interval when the Late LPC peaked (-50 to +50 ms) are shown for all three Judgment Difficulty levels.

Objective Perceptual Judgments.

Early LPC – Stimulus-Synchronized ERPs. The ERPs in Figure 22A reveal that an Early LPC, maximal at Pz, was elicited for all Perceptual judgments. The latency of these Early LPCs, at approximately 519 ms, 512 ms, 491ms, for Easy, Medium, and Difficult trials, respectively, was quantified as the most positive peak elicited at Pz in a 400 to 650 ms interval. An overall ANOVA revealed no significant difference in latency ($p > .05$). Figure 22A, also reveals that, although Early LPC amplitude appeared to be the same initially regardless of Judgment Difficulty, the Early LPC for Easy judgments became larger, eliciting a peak about 100 ms after the initial LPC peaks. An overall ANOVA was calculated on ERP area for an interval spanning 450 to 700 ms after stimulus onset, which includes the later peak for Easy judgments, at the three electrodes over posterior parietal scalp (Electrodes: Pz, 17, 19). This test revealed a significant effect of Difficulty $F(2, 16) = 6.76$, $\varepsilon = .95$, $p = .014$, $\eta_\rho^2 = .30$. Post-hoc tests confirmed that Easy judgments elicited significantly larger Early LPCs than either Medium $F(1, 16) = 12.77$, $p = .003$, $\eta_\rho^2 = .44$ or Difficult $F(1, 16) = 8.47$, $p = .01$, $\eta_\rho^2 = .35$ judgments, whose amplitudes did not differ ($p > .05$).

Given the initial similarity in shape of the waveforms elicited by judgments at all levels of difficulty, the altered appearance of the Early LPC for Easy judgments is likely to be an artifact of the very fast RTs for these judgments. That is, the largest peak for the Early LPCs elicited by Easy judgments at 519 ms is, on average, 67 ms prior to the mean RT for these judgments. Thus, the increased breadth and amplitude of the Early LPC for Easy judgments suggests that this LPC represents the combined activity related to both the start and completion of evaluative processing (i.e., a temporal summation of the Early and Late LPCs). Hence, the timing of the LPC latencies for Medium and Difficulty judgments (approximately 500 ms) will be used as the onset of evaluative processing for Objective judgments.

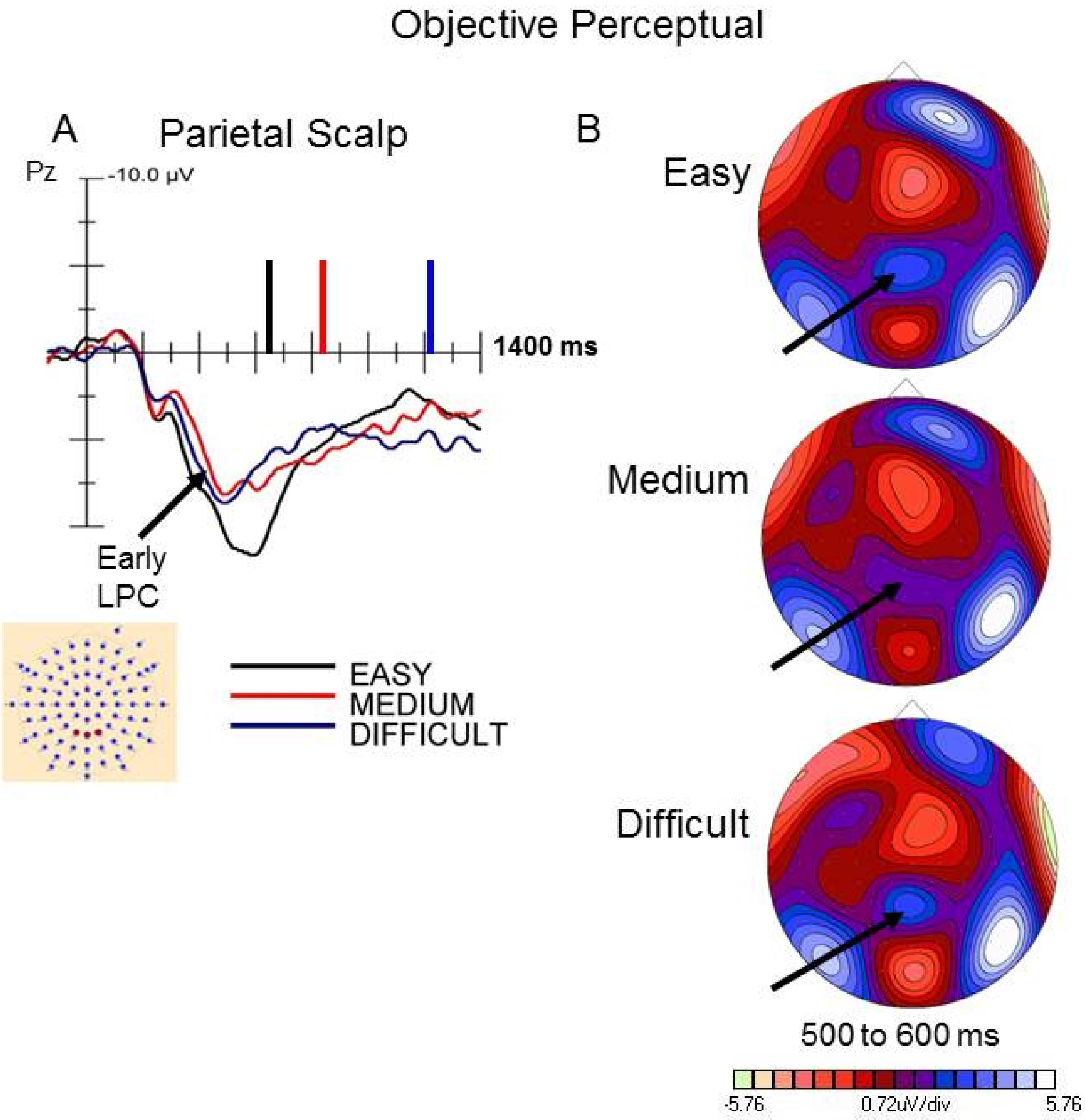


Figure 22. A. Stimulus-synchronized ERPs showing the Early LPCs elicited at midline parietal scalp (Electrode: Pz) in the Objective Perceptual condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the occurrence of mean RT for the Easy, Medium, and Difficult judgments, respectively. B. CSD maps for the interval when the Early LPC peaked (500 to 600 ms) are shown for all three Judgment Difficulty levels. Arrows point to the LPC peak in panel A and the midline parietal foci in panel B.

Medial and Lateral Occipital Scalp – Stimulus-Synchronized ERPs. The separate foci seen over medial and lateral occipital scalp in the 2-by-2 analyses, separate foci were present for all Objective Perceptual judgments regardless of difficulty (Figure 23A). The ERPs in Figure 23A reveal that a large positive potential, beginning about 300 ms post-stimulus, was elicited by all judgments over both medial and lateral occipital scalp. To examine the effect of Judgment Difficulty on the beginning of this positivity, separate ANOVAs were calculated on the ERP areas in the interval between 300 to 450 ms over medial primary occipital cortex (Electrodes: Oz, inion) and bilaterally over lateral extrastriate visual areas (Electrodes: left – 78 60, O1; right – 76, 56, O2). As would be expected from the ERPs in Figure 21B, neither ANOVA revealed any significant effect of Judgment Difficulty (*ps* > .05*)* during this early interval. The duration of this positivity varied as a function of Judgment Difficulty, continuing until approximately the time of mean RT for Easy Judgments (i.e., 646 ms) and longer for the Medium and Difficult judgments at both scalp locations. Thus, Objective Perceptual judgments were characterized by prolonged positive potentials whose duration varied with Judgment Difficulty that began over both medial and lateral occipital scalp immediately after the obligatory early sensory components.

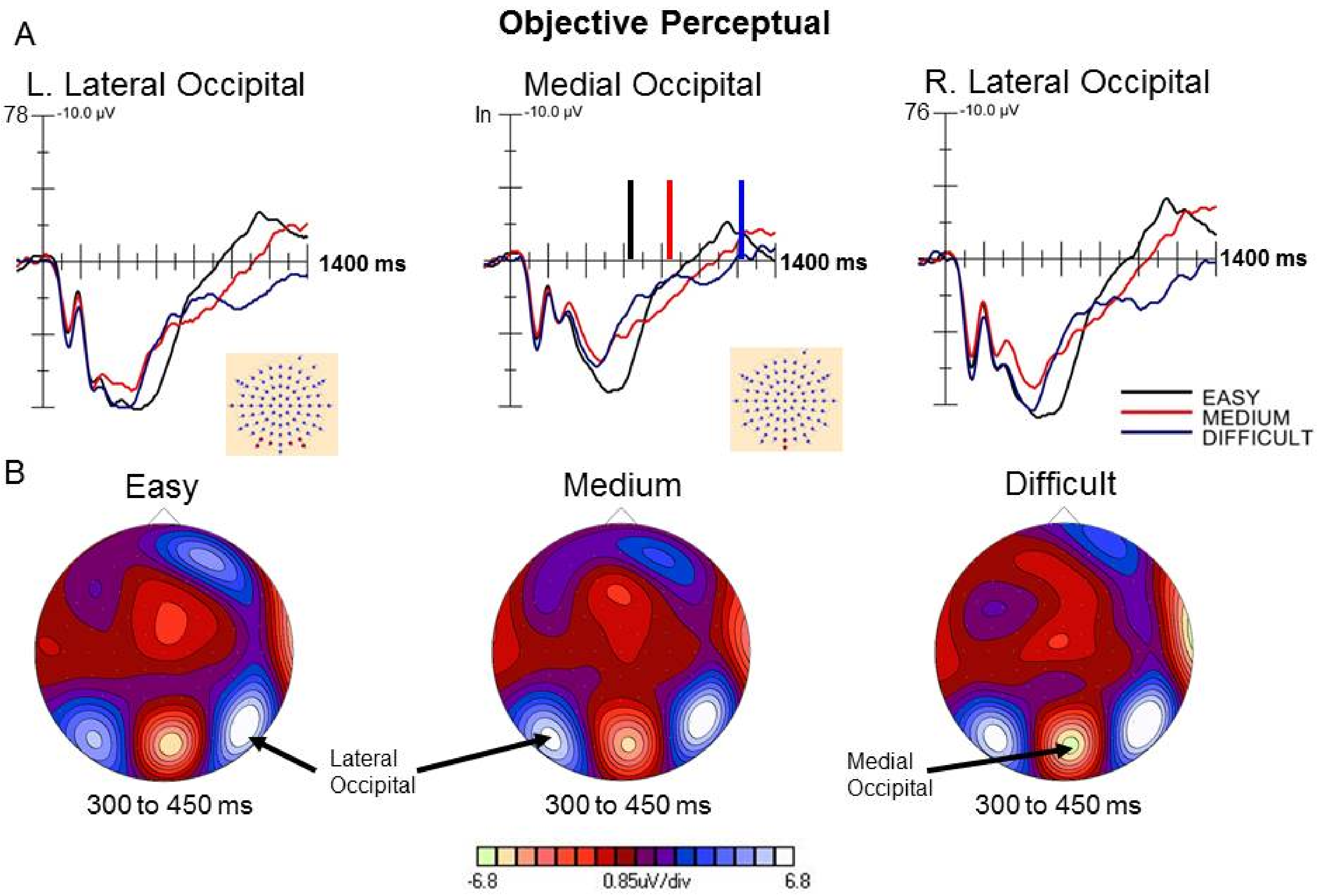


Figure 23. A. Stimulus-synchronized ERPs elicited over medial (Electrode: inion) and lateral (Electrodes: 78, 76) occipital scalp in the Objective Perceptual condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the average RT for the Easy, Medium, and Difficult trials, respectively. B. CSD maps for the interval when early occipital activity began (300 to 450 ms) are shown for all three Judgment Difficulty levels. Arrows point to the medial and lateral occipital foci in panel B.

Medial and Lateral Occipital Scalp – Response-Synchronized ERPs. The positive potential apparent in stimulus-synchronized ERPs appeared in response-synchronized ERPs as more of a positive slow wave for Medium and Difficult judgments than for Easy judgments (Figure 24). These ERPs also reveal that the duration of this positivity increased with Judgment Difficulty and that larger, and perhaps earlier, potentials were apparent over lateral compared to medial occipital sites. The positivity elicited over medial occipital scalp began soon after stimulus onset, at around -1100 ms, -800 ms, and -500 ms prior to the response, for Difficult, Medium and Easy judgments, respectively. Unlike the positivity elicited by Easy and Medium judgments, which increased steadily from onset until just prior to the response, the positivity elicited by Difficult judgments appeared to reach a maximum around 500 ms before the response and then slowly decrease. An overall ANOVA on waveform areas in a late interval (-250 to -150 ms) revealed a significant effect of Judgment Difficulty $F(2, 16) = 4.62$, $\varepsilon = .92$, $p = .04$, $\eta_\rho^2 = .22$. Post-hoc tests confirmed that Easy judgments elicited significantly larger positivities than Difficult judgments $F(1, 16) = 8.00$, $p = .012$, $\eta_\rho^2 = .33$ and that amplitudes were not different between Easy and Medium judgments ($p > .05$). An ANOVA comparing the positivities elicited by Easy and Medium judgments in an intermediate interval (-500 to -350 ms) revealed no effect of Judgment Difficulty ($p > .05$). The ANOVA on an early interval (-1000 to -800 ms) confirmed that Difficult judgments elicited significantly larger positivities than Medium judgments $F(1, 16) = 5.30$, $p = .035$, $\eta_\rho^2 = .25$ over medial occipital cortex.

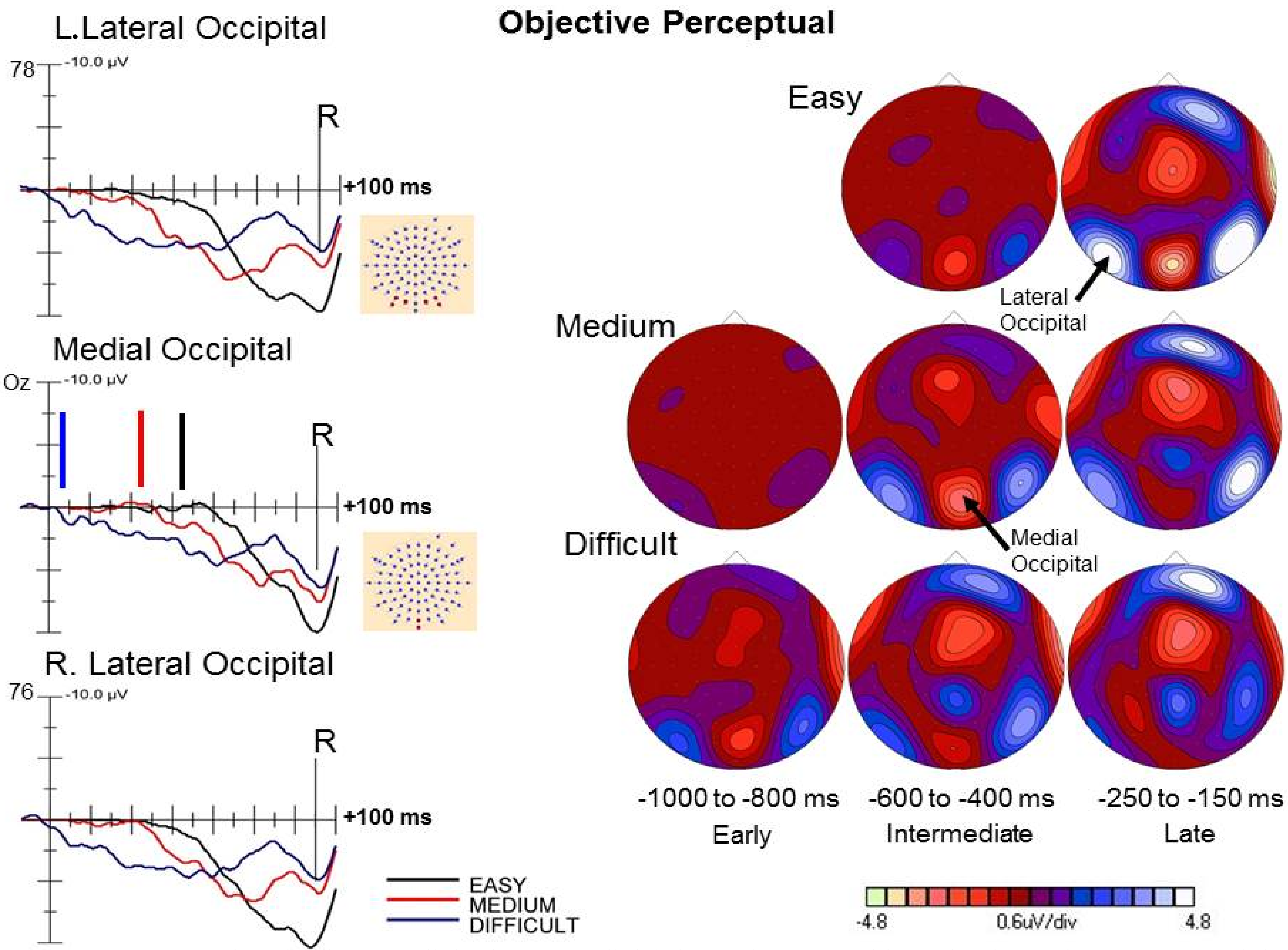


Figure 24. A. Response-synchronized ERPs elicited over medial (Electrode: Oz) and lateral (Electrodes: 78, 76) occipital scalp in the Objective Perceptual condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the average stimulus onset for the Easy, Medium, and Difficult trials, respectively. B. CSD maps of the ERP activity elicited during the early (-1000 to -800 ms), intermediate (-600 to -400 ms), and late (-250 to -150 ms) quantification intervals for all three Judgment Difficulty levels.

The positivity over lateral occipital scalp began concurrently with average stimulus onset, at around -1200 ms, -900 ms and -700 ms for Difficult, Medium and Easy judgments, respectively (Figure 24). Unlike the positivity elicited by Easy judgments, which increased steadily from onset until just prior to the response, the positivities elicited by Medium and Difficult judgments appeared to plateau at around -500 ms. Moreover, the amplitude of this positivity was inversely related to Judgment Difficulty, although the overall area appeared equal across difficulty levels. An ANOVA on a late interval (-250 to -150 ms) revealed a significant effect of Judgment Difficulty $F(2, 16) = 9.7$, $\varepsilon = .73$, $p = .005$, $\eta_\rho^2 = .38$. Post-hoc tests confirmed that Easy judgments elicited significantly larger positivities than either Medium $F(1, 16) = 8.39$, $p = .01$, $\eta_\rho^2 = .34$ or Difficult $F(1, 16) = 20.73$, $p = .0003$, $\eta_\rho^2 = .56$ judgments, while no amplitude differences were found between Medium and Difficult judgments ($p > .05$). In an intermediate interval (-650 to -500 ms), an ANOVA revealed that Medium judgments elicited significantly larger positivities than Easy judgments $F(1, 16) = 5.29$, $p = .035$, $\eta_\rho^2 = .25$. Finally, in an early interval (-1000 to -800 ms), an ANOVA revealed that Difficult judgments elicited significantly larger positivities than Medium judgments $F(1, 16) = 11.0$, $p = .004$, $\eta_\rho^2 = .41$.

Frontal Scalp – Response-Synchronized ERPs.

Central Medial Frontal Scalp. As can be seen in the CSD maps in Figure 25, following the activity over occipital scalp, a focus appeared centered over central medial frontal scalp (i.e., at aCz) regardless of Judgment Difficulty. The timing of this focus varied such that its onset was earlier relative to the response for Difficult compared to Medium and Easy judgments. However, this differential duration was not apparent in the response-synchronized ERPs elicited over medial frontal scalp (Figure 25). Rather, medial frontal ERPs showed positive-going waveforms beginning at approximately -350 ms for Easy items and about -200 ms for Medium and Difficult items. Thus, this activity was analyzed only in a single late interval. An ANOVA on a late interval (-300 to -150 ms) revealed no effect of Judgment Difficulty ($p > .05$).

Dorsolateral Frontal Scalp. Although a clear focus of activity was not seen over DLPFC in the CSD maps (Figure 25), evidence of the differential duration as a function of Judgment Difficulty was seen in the waveforms (Electrodes: Left – FC3, Right – FC4) as it began around -1100 ms, -700 ms, and -500 ms for Difficult, Medium and Easy judgments, respectively. An ANOVA on a late interval (-300 to -100 ms) revealed no effect of Judgment Difficulty ($p > .05$). In an intermediate interval (-550 to -450 ms), an ANOVA revealed no significant effect of Judgment Difficulty between Medium and Easy judgments ($p > .05$), possibly due to Easy judgments beginning earlier over right than left DLPFC. Finally, in an early interval (-900 to -700 ms), an ANOVA revealed that Difficult judgments elicited significantly larger positivities than Medium judgments $F(1, 16) = 9.29$, $p = .008$, $\eta_p^2 = .37$.

Left Ventrolateral Prefrontal Scalp. An additional focus of activity was apparent in the CSD maps (Figure 25) over left VLPFC, (Electrodes: F7, F5). As reflected in the ERPs (Figure 23), this focus also had a differential onset relative to the response as a function of Judgment Difficulty as it began around -1050, -700, and -450 ms for Difficult, Medium and Easy judgments, respectively. An ANOVA on a late interval (-300 to -100 ms) revealed no effect of Judgment Difficulty ($p > .05$). In an intermediate interval (-650 to -450 ms), an ANOVA revealed that Medium judgments elicited significantly larger positivities than Easy judgments $F(1, 16) = 6.21$, $p = .024$, $\eta_p^2 = .28$. Finally, in an early interval (-850 to -750 ms), an ANOVA revealed that Difficult judgments elicited significantly larger positivities than Medium judgments $F(1, 16) = 4.75$, $p = .045$, $\eta_\rho^2 = .22$.

Differential duration of activity was found over bilateral DLPFC and left VLPFC, but not central medial frontal scalp (Figure 25). These findings suggest different cognitive functions are instantiated in each area that respond differently to experimental manipulations. The differential duration of activity found over DLPFC and left VLPFC is consistent with the idea that information processed and/or accumulated in posterior brain areas (e.g., sensory cortex) is passed frontally prior to categorization.

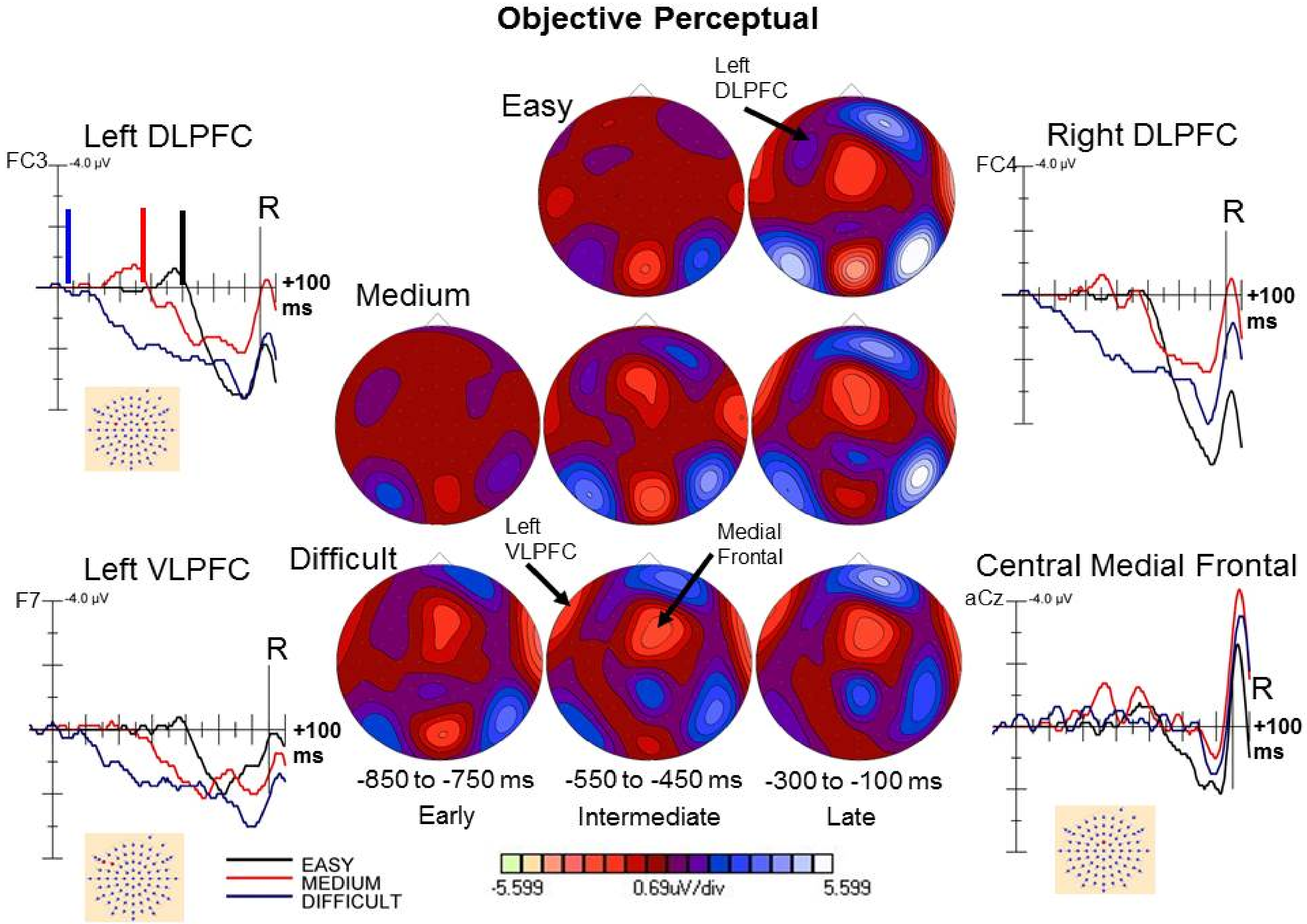


Figure 25. A. Response-synchronized ERPs elicited over central medial frontal (Electrode: aCz), left DLPFC (Electrode: FC3), right DLPFC (Electrode: FC4), and left VLPFC (Electrode: F7) in the Objective Perceptual condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the occurrence of average stimulus onset for the Easy, Medium, and Difficult trials, respectively. B. CSD maps of the ERP activity elicited during the early (-850 to -750 ms), intermediate (-550 to -450 ms), and late (-300 to -100 ms) quantification intervals for all three Judgment Difficulty levels.

Late LPC – Response-Synchronized ERPs. As evident in the response-synchronized ERPs (Figure 26A), all judgments elicited a Late LPC around the time of the response, with larger potentials for Easy judgments compared to those for Medium and Difficult judgments The CSD maps in Figure 26B show that the scalp distribution of the Late LPC is the same as that found for the Early LPC. An overall ANOVA on Late LPC amplitudes (-100 to +50 ms) using the same electrodes used to quantify the Early LPC (Electrodes: 17, Pz, 19) revealed a borderline significant effect of Difficulty $F(2, 16) = 4.16$, $\varepsilon = .85$, $p = .051$, $\eta_\rho^2 =.21$. Post-hoc tests confirmed that Easy judgments elicited larger Late LPCs those elicited by either Medium $F(1, 16) = 11.03$, $p = .004$, $\eta_\rho^2 = .41$ or Difficult $F(1, 16) = 4.79$, $p = .044$, $\eta_\rho^2 = .23$ judgments, with no amplitude differences between these latter two categories ($p > .05$).

An effect of Judgment Difficulty was also apparent in the interval leading up to the Late LPC as the ERPs elicited by Difficult judgments elicited a longer duration positive slow wave than those elicited by either Medium or Easy judgments (Figure 26A). This ERP activity was maximal over centroparietal scalp (Electrodes, 17, Pz, 19) and its amplitude was assessed for early and intermediate intervals. The late interval was not assessed because it corresponds to that used in the Late LPC analysis. In an early interval (-950 to -700 ms) an ANOVA revealed that Difficult judgments elicited significantly more positive ERPs than those elicited by Medium judgments $F(1, 16) = 13.82$, $p = .002$, $\eta_\rho^2 = .46$. Similarly, in the intermediate interval (-550 to -450 ms) an ANOVA revealed that Medium judgments elicited significantly more positive ERPs than Easy judgments $F(1, 16) = 4.59$, $p = .048$, $\eta_\rho^2 = .22$.

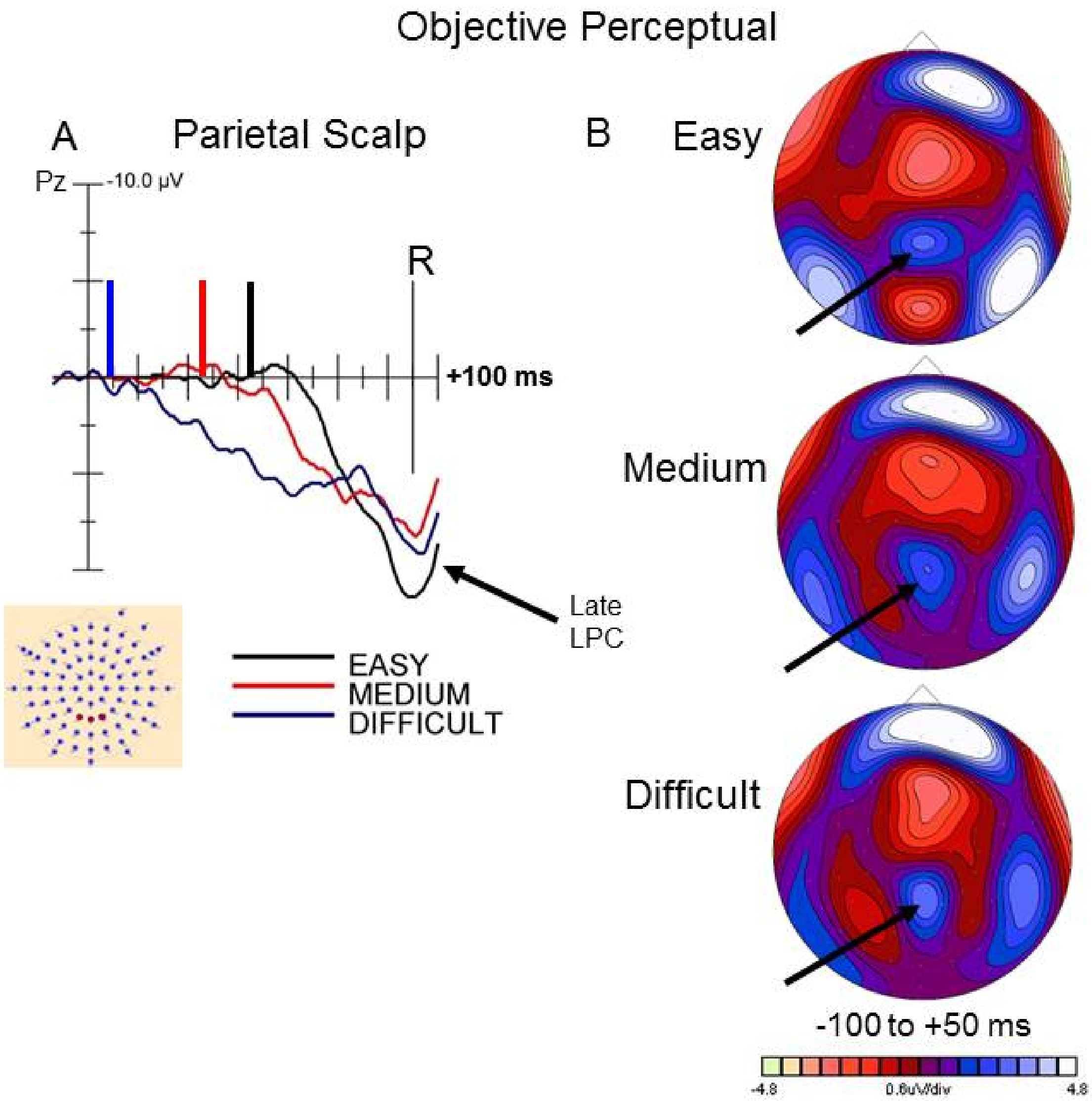


Figure 26. A. Response-synchronized ERPs showing the Late LPCs (arrows) elicited at midline parietal scalp (Electrode: Pz) in the Objective Perceptual condition for all three Judgment Difficulty levels. The black, red, and blue vertical lines mark the occurrence of mean stimulus onset for the Easy, Medium, and Difficult judgments, respectively. B. CSD maps for the interval when the Late LPC peaked (-100 to +50 ms) are shown for by all three Judgment Difficulty levels. The arrows point to the LPC peak in panel A and the midline parietal foci in panel B.

Discussion

Summary of Results

The purpose of the current study was twofold. The first objective was to examine whether the spatiotemporal characteristics of ERP activity elicited by relational judgments differed as a function of Judgment Type (Objective, Subjective) or Domain (Semantic, Perceptual). The second objective was to study the effect of Judgment Difficulty during Objective Semantic and Objective Perceptual judgments to better link specific patterns of ERP activity to different aspects of evaluative processing.

Overall, the behavioral results (i.e., accuracy, RT) confirmed a general absence of differences in task difficulty across Domains and Judgment Types and that the difficulty manipulations were successful in creating different levels of judgment difficulty for the Objective judgments in both Domains (Hypotheses 1 and 2). It is important to note that task performance was not different across Domains for Objective judgments, and the Subjective judgments were equally distributed between response choices. Dividing trials into tertiles based on RT successfully created easy, medium, and difficulty groupings with significantly different RTs.

In accord with the results of Johnson and colleagues (2011), all judgments elicited both an Early LPC and a Late LPC (Hypothesis 2), with the interval between them increasing as a function of Judgment Difficulty (Hypothesis 7). The results here extend this pattern of ERP results to Perceptual judgments and offer additional support for the idea that this pattern occurs independently of Judgment Type. The analysis of Judgment Difficulty revealed that the duration of ERP activity elicited over both posterior and multiple frontal brain regions proposed to be involved in evaluative processing varied directly with Judgment Difficulty. As expected, Domain affected which posterior brain areas were involved in providing information relevant to the judgment, with activity elicited over occipital for Perceptual judgments compared to over posterior temporal scalp for Semantic judgments (Hypothesis 3). By contrast, the pattern of ERP activity elicited over frontal scalp (left DLPFC, left VLPFC, central medial frontal) varied as a function of both Domain and Judgment Type, with Objective Semantic judgments eliciting activity that was different both spatially and temporally from that elicited by the other three types of judgments (Objective Perceptual, Subjective Perceptual, and Subjective Semantic). In addition, the timing of the activity over frontal scalp divided along the same lines as it began soon after stimulus onset for three of the judgments, while it did not begin until after semantic memory retrieval began for Objective Semantic judgments. While the three judgments showed slowly increasing positivities over frontal scalp, Objective Semantic judgments elicited ERPs that showed a faster rise and then plateau of activity, which ended approximately 100 ms prior to the categorization of the stimulus as evidenced by the Late LPC. Finally, no differences in processing were seen post-evaluation when the stimuli were categorized, as evidenced by equivalent Late LPCs elicited by all four judgments, although Late LPC amplitude decreased as a function of Judgment Difficulty.

While behavioral results did not distinguish between the four judgments used here, the brain activity revealed two networks with Objective semantic differing from the other three judgments (Objective Perceptual, Subjective Perceptual, and Subjective Semantic). These two networks differ in terms of the pattern of activity elicited over mIPS prior to the Late LPC and in the polarity, time course, and scalp topography of activity elicited over frontal areas. The two networks do not divide based on Judgment Type (Objective, Subjective) or Domain (Semantic, Perceptual), but instead differ on another dimension. The Objective Semantic judgments are fact-based and depend on the retrieval of a specific fact, or set of facts, to complete the judgments. That is, these judgments can be completed based on the details, parts, or facts retrieved; thus, the network underlying these judgments will be referred to as the local network. On the other hand, Objective Perceptual, Subjective Perceptual, and Subjective Semantic judgments required a greater processing of the whole of the object (i.e., global); thus, the network underlying these judgments will be referred to as the global network. The timing and appearance of the slow waves elicited over frontal areas by global judgments were generally similar to the drift rate curves (e.g., Figure 2C), which represent the speed (i.e., slope) of accumulation and time over which information is being accumulated as proposed in Accumulator models. Thus, suggesting that these waveforms represent accumulation of information. By contrast, local judgments elicited waveforms over left posterior temporal scalp reflecting memory access prior to waveforms elicited over frontal areas related to working memory. This pattern suggests that the frontal activity represents evaluative processing or working with the retrieved memories as proposed by the IR model.

Behavioral Findings

Overall, as predicted in Hypothesis 1A, RTs were similar for all judgments, although a significant interaction between Judgment Type and Domain was found as Objective Perceptual judgments were significantly faster by 172 ms than Objective Semantic judgments. Given that Judgment Difficulty was manipulated to create a range of difficulty levels, it is not surprising that a relatively large range of accuracies was obtained for Objective judgments. However, as predicted, accuracy did not significantly differ between Objective Semantic and Objective Perceptual judgments (Hypothesis 1B). The lack of difference in accuracy indicates that there was no speed-accuracy trade-off on Objective Perceptual judgments.

Although the number of studies using relational judgments is limited and the Perceptual task used in the current experiment was novel, a comparison of the RTs obtained here to previous studies is still informative. The RTs here were comparable to those found previously for self-referential and semantic evaluations about attitude objects by Johnson and colleagues (2011). The RTs obtained in the current study, ranging from 655 ms for Easy Objective Perceptual judgments to 1381 ms for Difficult Objective Semantic judgments tend to fall in between the extremes of RTs reported in studies of objective perceptual judgments. For example, Kayser and colleagues (2010) reported RTs from a single person on a random dot motion task ranged from 500 ms to 2400 ms for motion coherences from 64 (easy trials) to 0 (difficult trials) percent. Thus, the levels of difficulty included in the current experiment fall within the ranges of difficulty used in previous studies.

One objective of the current study was to examine the duration of evaluative processing as a function of Judgment Difficulty. Therefore, Judgment Difficulty was parametrically manipulated and, using RT as a proxy for difficulty, a tertile split was used to create three non-overlapping RT groupings within each individual. This creation of non-overlapping RTs may be why this methodology of dividing trials based on RT has been used before to study the effect of difficulty in both monkeys (Roitman & Shadlen, 2002) and humans (Johnson et al., in preparation). RTs significantly differed between each grouping and, although RTs for Objective Perceptual judgments remained significantly faster than Objective Semantic judgments, the lack of significant interaction meant that the effects of Domain and Judgment Difficulty were independent of each other. A comparison of RT variability across different Judgment Difficulty levels revealed that the RTs for Difficult judgments were significantly more variable than either Medium or Easy judgments. Previously, Johnson and colleagues (Johnson, Henkell, Simon, &

Zhu, 2008) found an increase in the variability of the RT distribution for both truthful and deceptive responses when the participant had to decide on each trial how to respond in order to make their responses conform to a pre-set criterion about the proportion of truthful and deceptive responses. In that case, the authors concluded that the increased RT variability (i.e., rectangular distribution) was associated with the need to select an intention-driven deceptive response instead of a stimulus-based truthful response. However, this type of RT distribution has since also been found in tasks requiring evaluations, as in the case of attitude (Johnson et al., 2011) and trait (Henkell et al., 2008) judgments. Combining the current and previous results suggests that the increased variability in RT distributions may be indicative of the need for evaluative processing.

ERP Results.

Early LPC – Late LPC Interval. As predicted, based on the results of Johnson and colleagues (2011) all judgments elicited both an Early LPC and a Late LPC (Hypothesis 2), with the duration of the interval between them increasing directly as a function of Judgment Difficulty (Hypothesis 7). This latter finding adds considerable strength to the argument that the duration of the Early LPC – Late LPC interval can provide a useful metric for determining the timing and duration of evaluative processing during decision-making. Johnson and colleagues (2011) had found this pattern of a prolonged Early LPC – Late LPC interval for attitude and semantic evaluations, which are both conceptual evaluations. However, the attitude and semantic evaluations differed in that they required different types of memory retrieval, episodic and semantic, respectively. Further, while the attitude evaluations were subjective, the semantic evaluations, which required an active/inactive judgment, were intended to be an objective judgment. Nevertheless, given the attitude objects used in the study of Johnson and colleagues (2011) (e.g., work for welfare, interracial marriage, death penalty), the semantic evaluation was also somewhat subjective as there was no clear correct answer. Thus, the fact that the conceptual (i.e., Semantic) judgments used here elicited an Early LPC and a Late LPC, replicated the pattern of findings of Johnson and colleagues (2011, in preparation) and extended these results to Subjective judgments based on semantic memory. In addition, this pattern of ERPs was extended to Perceptual judgments as the same pattern of Early LPC – Late LPC was elicited by both Objective and Subjective Perceptual judgments. The finding of both an Early LPC and a Late LPC for all judgments is consistent with the fact that this pattern is indicative of a period of evaluative processing. This processing is necessary when the stimulus alone does not provide sufficient information to categorize the stimulus. In these cases, identification of the stimulus representation (i.e., Early LPC) only provides the starting point for an evaluation. Then, only after evaluative processing is completed can the stimulus be categorized (i.e., Late LPC) and a response be chosen. Thus, when evaluative processing is necessary, there is a splitting of the processing normally associated with the LPC split into two temporally separated pieces.

Based on the logic presented by Johnson and colleagues (2011, in preparation), the occurrence of the Early LPC marks the formation of a stimulus representation for both Semantic and Perceptual evaluations. Consistent with findings of numerous past studies of the LPC (e.g., Johnson, 1989), the presence of an earlier, by approximately 42 ms, Early LPC for Perceptual compared to Semantic judgments indicates that the visual stimuli used here were processed more rapidly than the pairs of animal names. There were no latency differences on Early LPC across Judgment Types. No significant difference in the amplitude of the Late LPC was found as a function of Judgment Type or Domain suggesting that all judgments end with similar processing associated with stimulus categorization and that the level of difficulty between Domains and Judgment Types was approximately equal. When trials were divided based on Judgment Difficulty, a significant effect of Judgment Difficulty was found on the amplitude of the Late LPC for both Objective Semantic and Perceptual judgments. Overall, the results revealed that an evaluative interval demarcated by the Early and Late LPCs, whose duration varied as a function of Judgment Difficulty, was elicited by all judgments.

Effect of Judgment Difficulty on Duration of Evaluative Processing.

An initial examination of the pattern of ERP activity elicited by groupings based on the a priori difficulty categories revealed a significant degree in overlap of the ERP components elicited by the different groupings. Specifically, the ERPs elicited by medium Objective Perceptual judgments overlapped the ERPs elicited by both easy and difficulty judgments. This overlap in ERP activity reflected the overlap in RT distributions between the categories of difficulty defined in an a priori manner. Thus, a tertile split on RT was used to create three Judgment Difficulty groupings, with non-overlapping RT distributions within each individual. When trials were divided in this manner, the different groupings produced ERP activity with clearly different durations of evaluative processing.

According to the IR model, the duration of the reprocessing that occurs in the iterative loop is posited to increase with judgment difficulty. Given that it is only possible to manipulate difficulty for Objective judgments, they were the primary focus of study here, despite the fact that the model was proposed to explain subjective judgments. Similarly, in Accumulator models difficulty is posited to increase the amount of time it takes to reach a judgment due to changes in the drift rate (i.e., speed) of accumulation of information relevant to the judgment. Therefore, Judgment Difficulty was manipulated for Objective Perceptual judgments to assess the effect of difficulty on duration of processing. Even though the difficulty manipulations were necessarily different within each domain due to the nature of the stimuli, analogous levels of difficulty were created within each domain to allow for across domain comparisons of the effect of difficulty.

Objective Semantic Judgments. Overall, the results here confirm the tenets of the IR model for Objective Semantic judgments as ERPs elicited over left posterior temporal cortex, DLPFC, left VLPFC, and central medial frontal scalp were found to increase in duration directly with increases in Judgment Difficulty (Hypothesis 8). The first activity for Objective Semantic judgments was seen as a negative slow wave over left posterior temporal cortex, with the onset of this activity occurring coincident with the Early LPC in stimulus-synchronized waveforms regardless of Judgment Difficulty level. This negative slow wave also showed the same end □□ □□ □□□□□□□□□□□□□□□□□È□□□□□□□□□□□□□□□□□□□□□□□□□□□Ĉ□□□□ □□□□□□□□□□□□□□□□□□□□□□□□n the CSD maps indicates that this activity was locally generated in the underlying cortex. Thus, these data are consistent with fMRI results showing activity in left temporal areas for semantic storage for information concerning animals (Hillis & Caramazza, 1991). The timing of this activity, which began and ended at the same time regardless of Judgment Difficulty level, indicates the presence of access to semantic memory throughout the evaluative interval. This pattern of activity was obtained independent of Judgment Type as activity over left posterior temporal cortex was seen for both Objective and Subjective Semantic judgments. Further, as the start and end points of this activity were the same regardless of Judgment Difficulty, the duration of this activity increased directly with Judgment Difficulty. The finding of activity over posterior temporal scalp, which began before scalp, which began before activity in frontal areas is consistent with previous ERP studies of an episodic memory tasks, which found a delay of some 100 ms between evidence of memory retrieval (e.g., parietal EM effect) and activity over DLPFC indicative of working memory (Johnson et al., 1998). The timing of these results as activity over frontal regions only began after semantic memory retrieval, support that, at least for Objective Semantic judgments, activity over frontal scalp areas represents working with information retrieved from memory (cf., Moscovitch, 1992; Johnson et al., 2011).

The next activity elicited by Objective Semantic judgments appeared approximately 400 ms or more after the onset of the left posterior temporal activity over three frontal areas (DLPFC, left VLPFC, and central medial frontal). This activity was apparent as a negative slow wave, where the duration varied with Judgment Difficulty. The onset of activity over frontal scalp appears earliest by about 100 ms over central medial frontal scalp, followed by onset of activity over left DLPFC, which was followed approximately another 100 ms later by onset of activity over left VLPFC. Over all three frontal brain areas, the difference in onset times of the ERPs elicited by Difficult compared to Medium and Medium compared to Easy judgments was approximately 200 ms (Figure 20). The fact that differences in onset times were constant at 200 ms and not equal to the differences in RT between difficulty groupings (between Easy – Medium = 255 ms, between Medium – Difficult = 380 ms), supports that this difference in onset times represents a process that is working on a cyclical basis.

The pattern of activity, in terms of the waveshape and timing was similar between the activity elicited over left DLPFC and central medial frontal scalp. However, as there were two foci of activity, over DLPFC and ACC, apparent in the CSD maps, the similarities in the waveforms suggests that these brain areas are working together and do not simply reflect volume conductance of a single neural source to multiple electrodes. Over both the ACC and DLPFC, for all Judgment Difficulty levels, there was a ramping up of activity, which reached a plateau and remained on at a continuous level until just before the response. The length of time maintained in the activated state increased directly with Judgment Difficulty, reflecting that this processing is necessary over a longer period of time for more difficult judgments. The activity elicited over central medial frontal scalp is consistent with previous research showing that the ACC is associated with processing of conflict and monitoring of performance (Bush et al., 2000; Pochon et al., 2008) or executive attention (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). The increases in the duration of activity over this area with increased Judgment Difficulty, indicates the need for monitoring or attention over longer periods of time for more difficult judgments. The negative ERPs elicited over left DLPFC are consistent with similar negative potentials which have been found in cued semantic recall tasks (Johnson et al., 1998) and other tasks requiring working memory (e.g., Ruchkin et al., 1992), where increased negativity is associated with greater working memory demands. Negative potentials elicited over DLPFC have been implicated in working memory processes as the cortex directly underneath has been shown to be activated in working memory paradigms in fMRI studies (D’Esposito et al., 1999; Nee et al., 2012). Thus, the results here indicate that a longer duration of working memory was needed for more difficult judgments. Thus, monitoring (ACC) and working memory (DLPFC) are both part of a network (i.e., the local network) involved in completing Objective Semantic judgments.

Following the onset of activity over left DLPFC by approximately 100 ms, Difficult judgments elicited a negativity over left VLPFC. Although the presence of a negative slow potential lasting approximately 700 ms for Difficult judgments over left VLPFC is clear, the pattern of activity appears more mixed for the other difficulty levels. Whereas the onset of activity for ERPs elicited over left VLPFC by Medium and Easy judgments follows the same pattern of activations with approximately 200 ms lags, as the potentials are not negative, it is unclear if these potentials represent the same underlying process. The increased negativity for Difficult judgments fits with previous findings of Nessler and colleagues (2006), as increased task demands for semantic selection resulted in increased negativity when compared to a task, which requires less semantic selection. Thus, the results here suggest the need for semantic selection, especially for Difficult Objective Semantic judgments. Finally, all Objective Semantic judgments end with a categorization of a response, which is reflected in the Late LPC. Due to greater levels of uncertainty concerning which is the correct answer (Johnson et al., 1978) the Late LPC elicited by Difficult judgments was smaller than those elicited by Easy and Medium judgments.

As discussed in the introduction, two theories have been proposed to explain how the judgment used in the Objective Semantic task (i.e., which animal is larger?) is completed. One theory posits that the comparisons between animals are based on visual images, while the other posits that the judgment is based on verbal propositions stored in semantic memory (e.g., elephants are large). The finding of variable duration of semantic memory access as a function of Judgment Difficulty and increased activity over left VLPFC for Difficult judgments indicating a greater need for cognitive control (Badre & Wagner, 2002) or semantic selection (Thompson-Schill et al., 1997) supports the latter theory. Increased need for semantic selection, as evidence by increased activity elicited over VLPFC reflects that while retrieving that an elephant is large likely occurs quickly, additional semantic selection is necessary to retrieve information relevant to determining whether a snail or bee is larger. Similarly, there is a need for controlled retrieval in order to focus on task relevant information, in this case information about animal size, while inhibiting more salient non-task related features about the animals (e.g., that a bee is likely to sting you). Thus, it appears that information about animals is stored as verbal propositions, which are retrieved and then compared in working memory, with the amount of working memory required varying with Judgment Difficulty.

Overall, the present ERP results shed light on the processes and timing of aspects of the IR model, which were underspecified when the model was proposed (Cunningham & Zelazo, 2007; Cunningham et al., 2007). Consistent with the proposed role of working memory in evaluations according to the IR model, activity consistent with working memory was found over DLPFC. Similarly, a role for VLPFC was included in the IR model, although the cognitive processes instantiated in this brain area were unspecified. The results here suggests that, at least for Objective Semantic judgments, the left VLPFC is involved in selection from among retrieved semantic memories as the ERPs elicited here were similar to those previously associated with semantic selection. According to the IR model, the ACC is involved in signaling that more reflective processing is necessary (Cunningham & Zelazo, 2007; Cunningham et al., 2007). Activity in ACC elicited during Objective Semantic judgments is consistent with this proposal and may reflect monitoring of the information retrieved form semantic memory in order to determine if additional information is needed. ERPs revealed that access to semantic memories began 400 ms or more before activity over frontal brain regions. This finding suggests that for Objective Semantic judgments access to memory precedes evaluative processing, which is inconsistent with the proposal in the IR model that information from the stimulus begins evaluative processing and then calls upon memory for additional information to be incorporated into the reprocessing of the initial evaluation (Figure 1A, solid boxes). The difference in timing of memory access may reflect that the judgments being discussed here were objective and based only on information stored in semantic memory, whereas the IR model was proposed about attitude evaluations, which are likely based on both implicit associations of valence and information stored in memory. The cycle time for the iterative loop was proposed to occur in the theta band, based on the timing of working memory (Vertes et al., 2004; Raghavachari et al., 2001). The timing of the onset of ERPs elicited over the three frontal areas examined differed by approximately 200 ms between Judgment Difficulty levels. Thus, this pattern of timing differences supports the proposed cycle time within the theta band of the iterative loop, at least in frontal brain areas associated with executive processes (i.e., working memory).

Objective Perceptual Judgments. Overall, the results obtained here for Objective Perceptual judgments, confirm the tenets of the Accumulator models as ERPs elicited over occipital cortex, mIPS, and DLPFC, were found to have variable durations in response to changes in Judgment Difficulty (Hypothesis 8). These judgments elicited activity soon after stimulus onset over both posterior (sensory areas, mIPS) and frontal (left VLPFC, bilateral DLPFC) brain areas. Consistent with previous research on both monkeys (e.g., Shadlen & Newsome, 2001) and humans (e.g., Heekeren et al., 2004; Kayser et al., 2010), ERPs over sensory areas involved in processing visual information, both medial (striate) and lateral (extrastriate) cortex, showed both increased duration of activity and decreased drift rate (i.e., slope) for more difficult judgments. This pattern of results supports that these areas are involved in accumulation of information from the stimulus. The slope of these ERPs mirrored the predictions from Accumulator models about changes in slope (i.e., drift rate) with increased difficulty (Figure 2C). The onset of activity over lateral occipital scalp in response-synchronized

ERPs (Figure 24) briefly precedes the onset of activity elicited over medial occipital scalp. This pattern suggests that the processing about form that occurs in extrastraite occipital cortex (e.g., V3) is fed back to medial occipital cortex, possibly to guide the examination of the stimuli. This finding is also consistent with the concept that a representation of the visual stimuli is maintained in working memory (i.e., persistence, Philiastides & Sajda, 2007) within the occipital cortex.

An additional posterior brain region, the mIPS, was found to show evidence of accumulation of information for Objective Perceptual judgments. In single unit recording studies in monkeys, the LIP was found to be involved in accumulation of information relevant to the judgment as the firing rate of neurons in this region could be used to predict response choice (Roitman & Shadlen, 2002; Shadlen & Newsome, 2001). The mIPS is the human homologue of the LIP in monkeys (Grefkes & Fink, 2005) and has also been implicated in the accumulation of information from the stimulus (Heekeren et al., 2006). Based on previous ERP studies, which have localized activity elicited over centroparietal scalp to the mIPS (Bledowski et al., 2004), the activity prior to the Late LPC was examined as an ERP correlate of activity in this region. This ERP activity appeared as a slow positivity beginning soon after stimulus onset for all Judgment Difficulty levels. The duration of this slow positivity increased, while the slope decreased for more difficult compared to easier judgments. This pattern of results supports that the mIPS is also involved in the accumulation of information relevant to the judgment.

When ERPs elicited by different Judgment Difficulty levels were synchronized to the time of the response, differential durations of ERPS were revealed over both DLPFC and VLPFC but not central medial frontal scalp. The pattern of activity over bilateral DLPFC and left VLPFC mirrored the timing of activity seen over posterior regions with increased duration of activity with increases in Judgment Difficulty. Despite the amount of previous research on

Accumulator models, the role of the DLPFC in objective perceptual judgments remains unclear. Some researchers have argued that the DLPFC is involved in accumulation of stimulus information or it may reflect working memory that is holding the level of accumulated information that is calculated elsewhere in the brain (Philiastides et al., 2011). Yet other researchers argue that the DLPFC is involved in some "decision variable" process that remained unspecified (Heekeren et al., 2004; Heekeren et al., 2006). In the current experiment, activity over bilateral DLPFC began soon after stimulus onset and was apparent as a positive slow wave. Previous ERP studies on working memory have found that increased working memory load results in increased negativity of the waveforms elicited over the DLPFC (Johnson et al., 1998b). Thus, it is unclear if the positive waveforms elicited over DLPFC for these judgments represent working memory or some other cognitive function. The timing of the ERP activity elicited here is consistent with the results of a study, which found that disturbing the functioning of the left DLPFC with rTMS reduced the drift rate (i.e., efficiency of accumulation of information) indicating that this brain areas is involved early in the decision making process (Philiastides et al., 2011). Thus, although it remains unclear if the DLPFC is involved in accumulation of information per se or if it simply maintains a representation of the accumulated information that is actually accumulated elsewhere, the results obtained here offer additional support that the DLPFC is involved during the whole decision-making process.

Although the VLPFC has not been included in the neural basis of Accumulator models (i.e., not in Figure 2C), studies of objective perceptual judgments have found increased activity in this area for difficult compared to easy judgments (Binder et al, 2004; Heekeren et al., 2006). The role of the VLPFC in perceptual tasks is unclear, as some authors argued it is involved in increasing attention (Heekeren et al., 2006), while research involving semantic tasks has argued that the VLPFC plays a role in control of retrieval or selection among retrieved memories (Badre & Wagner, 2002; Thompson-Schill et al., 1997). As was seen for Objective Semantic judgments, the ERPS elicited over left VLPFC showed differential duration of activity as a function of Judgment Difficulty for Objective Perceptual judgments. However, while the waveforms elicited by Objective Semantic judgments were negative, the waveforms elicited by Objective Perceptual judgments were positive. Given that previous research has found increased negativities elicited over this area are associated with increased selection demands (Nessler et al., 2006), it is not known what the increased positivities elicited over this area represent. It is possible that despite the difference in polarity, this activity represents selection processing, such as selecting among the information available in the perceptual stimuli in order to complete the judgment. However, it is also possible that these positive waveforms represent another cognitive function.

Compared to the patterns seen over DLPFC and VLPFC, a different pattern of results was obtained over central medial frontal scalp, as no differences as a function of Judgment Difficulty for the Objective Perceptual judgments were found. This result is also different from the variable duration of activity found over this area for the different Judgment Difficulty levels for Objective Semantic judgments. The differing pattern of results suggests that less monitoring as evidenced by activity over central medial frontal scalp was evoked during the Objective Perceptual compared to Objective Semantic judgments.

The waveforms elicited by Objective Perceptual judgments showed similarity in the waveshape and timing of activity over both posterior (occipital, mIPS) and frontal regions (DLPFC, VLPFC). This similarity suggests that these brain regions are working together in a parallel manner in a network (i.e., global network) involved in accumulating information from the stimulus and comparing it to a pre-set decision threshold. The timing of onset of activity for the different Judgment Difficulty levels is more synchronized with stimulus onset, than was the case for Objective Semantic judgments.

The intention of the Judgment Difficulty manipulation was to create an interval of evaluative processing for all difficulty levels. This was overall accomplished as an evaluative processing interval between the Early and Late LPCs was present for all judgments, except for Easy Objective Perceptual judgments. For these judgments, a truncated evaluation process was present as the average RT was only 67 ms after the peak of the Early LPC. For these judgments, it appears that all the information necessary to complete the judgment was presented in the stimulus and thus forming the stimulus representation also resulted in the categorization of the stimulus for a response. Thus, a single LPC was elicited, which reflected both the formation of the stimulus representation and the categorization of the stimulus. Consistent with the finding of a single LPC, Easy judgments elicited significantly larger Late LPCs than Medium or Difficult Objective Perceptual judgments. The short duration of the waveforms elicited over frontal areas for Easy Objective Perceptual judgments suggests that these judgments required less evaluative processing than the judgments at the other difficulty levels.

Kayser and colleagues (2010) argued that their fMRI results showing increased activity for difficult compared to easy judgments should be interpreted as increased duration of activity rather than increased activity over a shorter interval. However, this was only an argument, as the temporal parameters of the fMRI do not allow for examination of duration of processing. Using ERPs, the results of the current study revealed direct evidence that the increased activation seen in fMRI studies comparing difficult and easy perceptual judgments results from an increase in the duration of processing. The findings here suggest that as ERPs measure the summed electrical activity in the brain, the patterns of ERP obtained are similar to the results obtained in single unit recording studies. This concept was supported as the slope of the ERPs, especially in response-synchronized ERPs, mimicked the drift rate proposed in Accumulator models, and found in single-unit studies. Thus, the results obtained here offer some of the first direct evidence from human studies in support of the tenets of Accumulator models, which predicted increased duration of processing in sensory, mIPS, and frontal areas as a function of Judgment Difficulty.

Effect of Judgment Type and Domain.

The ERP results revealed clear evidence of two different brain networks underlying decision-making, which differed in the pattern of activity elicited over mIPS and in the polarity, time course, and scalp topography of the ERP activity elicited over frontal areas. However, as will be discussed below, the two putative networks did not divide decision-related brain activity along the predicted dimensions of either Judgment Type (Objective, Subjective) or Domain (Semantic, Perceptual).

Consistent with Hypothesis 3, Domain-related differences in ERP activity appeared early, immediately after initial sensory processing over sensory cortex (e.g., occipital cortex), with Perceptual judgments eliciting significantly more positive waveforms than Semantic judgments. The early ERP activity over occipital cortex (e.g., 300 to 600 ms post-stimulus onset) likely reflects initial sensory processing in order to form a stimulus representation prior to initial categorization and elicitation of the Early LPC (Johnson et al., 2011). The amount of information available in the stimuli inherently differs between Perceptual and Semantic conditions as all information necessary to complete an Objective Perceptual judgment is contained therein whereas each stimulus pair only presents the starting point for a subsequent series of memory retrievals for Objective Semantic judgments. Analysis of Judgment Difficulty revealed that the positivities elicited over medial and lateral occipital cortex continued after the Early LPC suggesting that these sensory areas play a continuing role in providing stimulus information to accumulator areas until the accumulated information reaches the decision threshold and the stimulus can be categorized. Conversely, the ERP activity elicited over these same brain areas indicates that visual processing of animal names during Semantic judgments ends when the items are categorized as words.

In accord with previous studies of perceptual judgments (Heekeren et al., 2004; Kayser et al., 2010; Shadlen & Newsome, 2001) ERP activity was present during the entire evaluative processing interval over striate and extrastriate cortex. As predicted in Hypothesis 4, that there would be less sensory processing for Subjective compared to Objective judgments was confirmed for Perceptual judgments over occipital scalp. Thus, whereas both Objective and Subjective Perceptual judgments elicited positive slow waves over primary and secondary visual cortex the waveforms elicited by Subjective judgments were significantly less positive during the second half of the evaluative interval. These amplitude differences suggest that during Subjective Perceptual judgments there is a switch from taking in specific sensory information to a less detailed analysis of the stimulus.

Whereas Judgment Type had an effect on the intake of information from the stimulus for Perceptual judgments, a different pattern of results was obtained over left posterior temporal scalp for Semantic judgments. That is, over left posterior temporal scalp both Objective and Subjective Semantic judgments elicited waveforms of the same duration and extent. This lack of difference suggests that the amount of semantic memory retrieved was similar across Judgment

Types. These results suggests that whereas participants varied the amount of perceptual information taken in from the stimuli based on Judgment Type, the amount of semantic information accessed about the animals presented was not affected by Judgment Type.

The results obtained here expand on previous studies which showed that the mIPs was involved in accumulation of information for objective perceptual judgments (Heekeren et al., 2006), to include a role of the mIPS in, not only Objective Perceptual, but also Subjective Perceptual, and perhaps Subjective Semantic judgments. As discussed above, ERP activity elicited over mIPS by Objective Perceptual judgments when divided by Judgment Difficulty showed both increased duration of activity and decreased drift rate (i.e., slope) for more difficult judgments, supporting that this area was involved in accumulation. Thus, a long duration positive slow wave elicited over this area reflects an accumulation processes. In the interval prior to the Late LPC, there was a borderline significant effect of Domain on the response-synchronized ERPs elicited over centroparietal scalp, as Perceptual judgments elicited larger positive ERPs compared to Semantic judgments. While the Objective Semantic judgments remained near baseline, Subjective Semantic judgments elicited a waveform that was somewhat in between that elicited by Perceptual and Objective Semantic judgments. The fact that both Objective and Subjective Perceptual judgments elicited a long duration positive slow wave prior to the Late LPC, supports that accumulation of evidence is involved in both judgments. By contrast, no equivalent pattern of activity was elicited for Objective Semantic judgments.

A possible alternative hypothesis concerning the differences found in the ERP activity elicited over mIPS in the interval leading up to the Late LPC is that the differences reflect increases in attention (Shulman et al., 2010); however, the pattern of results here does not support this hypothesis. If attentional processing differed as a function of Domain, then the effect on the ERPs elicited at the different Judgment Difficulty levels would be expected to be similar across Domains (i.e., no differences in extent or timing of the pre-Late LPC positive slow waves). However, that is not the case here as increases in the duration of processing as a function of Judgment Difficulty were present for Objective Perceptual judgments, but no differences as a function of Judgment Difficulty were apparent for Objective Semantic judgments. Moreover, attentional demands should be lesser for Perceptual judgments given the RT results showing that Perceptual judgments were overall faster than the Semantic judgments. Thus, the differences observed between the Semantic and Perceptual judgments indicate the presence of a process (i.e., accumulation) other than attention that differs between the judgments.

ERP activity was elicited by all judgments during the evaluative interval over three frontal brain areas previously associated with executive processing (e.g., left VLPFC, bilateral DLPFC, and central medial frontal scalp) (Badre, 2008; Stuss & Alexander, 2000; Wagner, Maril, Bjork, & Schacter, 2001). However, the pattern of ERPs differed as Objective Semantic judgments elicited negative waveforms while the other three judgments (Objective Perceptual, Subjective Semantic, Subjective Perceptual) elicited waveforms that were at baseline or positive. In addition, the timing of these potentials was different with the negativities beginning later relative to stimulus for Objective Semantic judgments compared to the onset of the positivities for the other three judgments. Further, while Objective Semantic judgments showed an effect of Judgment Difficulty on the duration of processing in all three brain areas, Objective Perceptual judgments only showed an effect over DLPFC and VLPFC, but not central medial frontal scalp.

As discussed above, activity elicited over central medial frontal scalp likely reflects processing in the ACC, which has previously been associated with monitoring (Bush et al., 2000) or executive attention. The finding of significantly more negative ERPs elicited by Objective

Semantic judgments suggests that these judgments required a greater amount of monitoring or attention compared to the other judgments. Similarly, negative ERPs elicited over DLPFC have been associated with the central executive component of working memory (Johnson et al., 1998b; Ruchkin et al., 1992). Thus, the negative potentials elicited by Objective Semantic judgments are consistent with there being a central role for working memory to complete those judgments. Conversely, the other three judgments elicited positive waveforms at the same electrodes and it is unclear what cognitive function those waveforms reflect. Based on previous research finding preferential activation in left DLPFC for verbal working memory (Owen et al., 2005; Wager & Smith, 2003), a lateralization difference was predicted based on the material of information being processed (i.e., Domain). Although the focus of activity in CSD maps was left lateralized for Objective Semantic judgments, as the other three judgments elicited more bilaterally symmetrical waveforms, no overall effect of Domain on lateralization of activity was found. The third frontal area examined was the left VLPFC, which has been implicated in selection from among retrieved semantic representations (Thompson-Schill et al., 1997, 1999) or control of semantic memory retrieval (Badre & Wagner, 2002). Increased negativity of ERPs elicited over this area has been associated with increased selection requirements (Nessler et al., 2006). Thus, the negative waveform elicited by Objective Semantic judgments is consistent with a need for selection among retrieved semantic memories or the need for controlled semantic retrieval in these judgments. The waveforms elicited by the other three judgments were positive and the duration of the positive waveforms elicited by Objective Perceptual judgments increased directly with Judgment Difficulty, suggesting that this area is involved in evaluative processing. Johnson and colleagues previously found positive waveforms elicited over frontal brain regions during evaluations of attitudes (Johnson et al., 2008, 2011) and traits (Henkell et al., 2008).

Thus, the results here extend the finding of positivities over frontal scalp to Objective Perceptual judgments. Although the nature of the processing reflected by these waveforms remains unclear, it appears that similar processing underlies both Objective Perceptual judgments and judgments that are based on an internal scale (i.e., preferences or evaluations about attitudes or traits).

Another difference between the ERPs elicited by Objective Semantic judgments and the other three judgments was found in a comparison of the onset time of activity over frontal brain areas. A comparison of the ERPs elicited over posterior and frontal brain areas revealed evidence of both serial and parallel processing during the evaluative processing interval. For Objective Semantic judgments, the processing was more serial with the onset of the negativities delayed by hundreds of milliseconds relative to the onset of the negative slow potentials over posterior temporal cortex. Conversely, the ERPs elicited by the other three judgments began more simultaneously over posterior and frontal brain regions, suggesting more parallel processing. These timing differences provide another piece of evidence that the processing underlying Objective Semantic is qualitatively and quantitatively different from that used for the other three types of judgments. Objective Semantic judgments appear to be processed in a serial manner, with memory retrieval followed by evaluative processing. By contrast, the other three types of judgments appear to be processed in a more parallel manner as after initial processing in visual cortex, evidence of processing over both posterior (mIPS) and frontal regions overlap both in terms of onset and duration of processing. Thus, while Objective Semantic judgments can be considered a working-with-memory task (e.g., Johnson et al., 2011; Moscovitch, 1992), the other three types of judgments are better explained by Accumulator models.

The ERP results revealed that the posterior brain areas involved in decision-making are domain specific. Further, even within each domain the specific brain areas involved in decision-making vary as a function of the types of stimulus information being processed. For example, whereas activity was elicited over lateral extrastriate cortex, presumably V3, in the current experiment because the Perceptual judgments were based on form, previous research found activation of V5/MT during motion-based judgments (Kayser et al., 2010; Shadlen & Newsome, 2001) or activation of the fusiform face area for face-based judgments (Heekeren et al., 2004). Further, as the current study examined both Domain and Judgment Type, the results revealed that the posterior brain areas involved in decision-making are Judgment Type independent. That is, both Objective and Subjective judgments within each Domain (Semantic, Perceptual) were processed in the same brain areas (temporal, occipital).

By contrast to the Domain specific areas in posterior brain regions, anterior brain regions consist of amodal processing areas that process information from multiple domains (e.g., with multiple codes – verbal, visual). That is, the same frontal brain areas were found to be involved in the processing of both perceptual and semantic information. However, comparing the four judgments used in this experiment revealed two patterns of ERP activity over frontal scalp. As just reviewed, the Objective Semantic judgments elicited a different pattern of ERPs over frontal scalp, while the other three judgments elicited very similar patterns. Thus, the differences in the processing underlying decision-making crosses both Judgment Type and Domain as the three evaluations that elicited very similar patterns of ERP activity includes both Objective and Subjective Perceptual judgments, as well as Subjective Semantic judgments. Examining the timing of this frontal activity revealed that over left DLPFC the waveforms for Objective Semantic began later relative to response than the Subjective Semantic judgments. That finding combined with the lack of difference in RT between these conditions indicates that whatever processing is reflected in this activity for Subjective Semantic judgments begins earlier than for

Objective Semantic judgments. Interestingly, the differences over frontal scalp between Objective and Subjective Semantic judgments are obtained, despite similar levels of semantic access observed for both Judgment Types.

Limitations

In order to maintain the 2-by-2 design, there were some compromises made in terms of the stimuli and tasks used. Whereas the objective judgments were realistic as there was an objectively correct answer and difficulty could be manipulated in an a priori manner, this is less possible for preference judgments. As the subjective judgments were designed as a derivative of the objective task only the task changed while the stimuli were kept very similar across judgment types within each domain. This design was a compromise so that only one aspect of the situation (the task) changed while other aspects of the situation (the stimuli) were held constant. Although participants made each choice in the preference task equally often and took comparable amounts of time to make Subjective judgments as to make Objective judgments, it is possible that RTs would have been longer in the Subjective conditions if the task had been more realistic. In addition, although each response choice was chosen approximately half the time, whether participants were responding in agreement with their actual preferences was not assessed. This was not examined because while repeated pairs in opposite orders (i.e., Horse-Dog, Dog-Horse) were included in the Subjective Semantic condition, each pair was unique in the Subjective Perceptual condition as thus, there is no way to assess consistency of responding. Although preferences will differ between individuals, it is possible to compare each individual's ratings during the ERP session to their preference ratings obtained during an interview or debriefing session. Although this would not be equivalent to accuracy in the Objective conditions, as answers would differ between individuals, it would allow the examination of whether or not participants were responding consistently about their preferences. Further, if these ratings were completed in an initial interview, it may be possible to manipulate the "difficulty" of a subjective judgment by varying the similarity of the ratings between items in each pair.

Conclusions.

Although it is clear that the decision process starts with a stimulus and ends with a response, the implementation of the processing stages that occur in between occur too quickly for introspection to elucidate what processes are involved. Thus, ERPs, which allow us to look at the timing and location of the brain processes that occur during decision-making, provide valuable information concerning how decision-making is instantiated in brain networks.

Overall, the results found here provide some of the first evidence of increased duration of activity as a function of Judgment Difficulty in humans as proposed in both the IR and Accumulator models. Specifically, the results from the difficulty manipulations for Objective Semantic judgments support the tenets of the IR model as the ERP activity elicited over brain areas posited to be involved in semantic storage (left posterior temporal cortex) and evaluative processes (DLPFC, VLPFC, ACC) increased in duration along with Judgment Difficulty. Conversely, the effects of the difficulty manipulation on Objective Perceptual judgments support the tenets of the Accumulator model as the ERP activity elicited by these judgments over brain areas related to visual processing (occipital cortex), accumulation (mIPS), and decision variables (DLPFC) increased in duration along with Judgment Difficulty. Despite some support for each of the models within the domain (i.e., conceptual, perceptual) they were proposed about, the results of the current experiment indicate that although there are two networks underlying different types of judgments, these networks are not divisible based on Judgment Type (Objective, Subjective) or Domain (Semantic, Perceptual). Instead, the data suggest that the two brain networks that underlie decision-making differ on the level of processing involved in the decision. That is, the putative two networks can be characterized based on whether the details on which the decision is based are analyzed according to their global or local properties. That is, the division between networks is based on whether the judgment involves fitting things together into a whole (e.g., global) (Objective Perceptual, Subjective Perceptual, Subjective Semantic) or can be decided based on only a few specific details (e.g., local) (Objective Semantic).

The brain areas comprising a “local” decision network include areas related to memory retrieval (i.e., left temporal cortex) and working memory (DLPFC), which is involved in the evaluation of the retrieved memories. In this decision pathway, which is consistent with the tenets of the IR model, there is no continuous accumulation of evidence for or against a particular decision but rather a punctuate process in which the next piece of information retrieved may or may not provide the piece of evidence necessary to reach the decision threshold. Although one purpose of the proposed study was to validate the tenets of the IR model for subjective judgments and extend it to objective judgments, only the latter goal was accomplished. Hence, based on the results here, the IR model appears to provide a good account of objective but not subjective semantic decisions and have no power to explain perceptual judgments. Thus, it appears that the IR model describes the local network underlying judgments that can be based on an examination of the details or parts of the stimuli, which are compared consciously in working memory.

Subjective Semantic judgments could be completed in the same manner as Objective Semantic judgments by basing one’s answer on a single concept (e.g., furriness). If that were the case, it would be expected that Objective and Subjective Semantic judgments would show similar patterns of activity across the scalp. Overall, the ERP activity elicited by these two judgments over posterior temporal scalp was essentially indistinguishable in onset, duration, and extent (i.e., amplitude) indicating that information was retrieved from semantic memory similarly for both Objective and Subjective Semantic judgments. However, although memory retrieval played a role in both judgment types within the semantic domain, the retrieval products appeared to not be sent to working memory for Subjective Semantic judgments. Instead, the ERP results suggest that retrieved memories are accumulated in the mIPS, as the duration of processing over this area increased with increased judgment-time for Subjective Semantic judgments (unpublished results). Further, as the pattern of ERP activity elicited over multiple frontal areas was significantly different for Objective and Subjective Semantic judgments, the results indicate that they are processed in different ways by a different brain network.

The global network is consistent with Accumulator models and the results of previous single-unit studies in monkeys (Roitman & Shadlen, 2002; Shadlen & Newsome, 2001) and hemodynamic studies of humans (Kayser et al., 2010; Heekeren et al., 2004, 2006) on the neural basis of perceptual decisions. Accumulator models posit that judgments are reached by accumulating information until a decision threshold is crossed (Smith & Ratcliff, 2004; Usher & McClelland, 2001). Evidence in support of these models has come almost exclusively from studies on objective perceptual judgments (Ho et al., 2009; Ploran et al., 2011). Thus, the results here of similar ERPs elicited over mIPS and frontal regions by three of the judgments examined, extends the Accumulator model from Objective Perceptual to Subjective Perceptual judgments, as well as Subjective Semantic judgments. The similarity between these judgments is that they all require processing at a global level of the stimulus. For example, in an Objective Perceptual judgment in the current experiment, one needs to pay attention to the whole of each square because paying attention to only a piece (e.g., upper right corner) will likely result in an incorrect answer as the details alone do not provide enough information to complete the judgment correctly.

Preferences can be considered a type of conceptual judgment as it is reasonable to speculate that what is being accumulated is information concerning previously stored and currently sensed positively- and negatively-valence associations about the stimulus. For example, when one judges whether they prefer rabbit or goat, both past and present positive and negative associations are accumulated with a drift rate that depends on the strength of the associations. Despite the fact that Subjective judgments can be seen as a type of conceptual judgments as they are based, at least in part on stored associations, the spatiotemporal ERP activity recorded here reveals that preference judgments, along with Objective Perceptual judgments, are best explained by Accumulator models. If Accumulator models explain Subjective judgments, the question arises about what brain areas are involved in the retrieval and accumulation of the valence associations. Functional hemodynamic research on preference judgments have revealed that the insula and ventromedial prefrontal cortex (VMPFC) (Paulus & Fink, 2003) are activated consistently. It is interesting to note that the insula is a brain structure that is included as part of the neural basis of Accumulator models and found to be activated to a greater extent by difficult compared to easy judgments in fMRI studies of objective perceptual judgments (Ho et al., 2009; Kayser et al., 2010). It is possible that the positive ERPs elicited at electrodes over bilateral DLPFC by the global judgments reflect activity in bilateral insula reflecting the accumulation of valence associations for the preference judgments. Further, it may be possible that the ERPs elicited at electrodes over left VLPFC reflect activity in the VMPFC.

Evidence that the positive waveforms elicited over these areas represents activity in different brain areas than that reflected by the negative waveforms elicited by Objective Semantic judgments arises from lack of clear foci over DLPFC in the CSD maps (Figure 13) for Objective Perceptual or Subjective judgments. If the activity elicited over frontal brain regions is shown to reflect activity in the insula and VMPFC, the timing of the ERPs offers support that these brain areas are involved in accumulation of information underlying preference judgments in the current experiment. Thus, it appears that subjective judgments function in much the same way as has been successfully modeled for perceptual judgments except that the information comes from conceptual (i.e., memory) rather than perceptual. This conceptualization also fits with aspects of the implicit/reflexive processes hypothesized to occur in dual process models of attitudes, a particular type of subjective judgment. Hence, processing of valence when making preference judgments appears to not be consciously mediated and thus does not involve working memory.

The division of judgments on a local/global dimension differs from simply describing the processing underlying a specific type of judgment within a specific domain as has been proposed in previous models of decision-making (Accumulator, IR). These models only focused on describing the processes underlying a single type of judgment and did not attempt to explain the broader context of the differences between judgments. While the local/global dimension is posited here, it is possible that the decision-making networks divide along another dichotomy. Alternative dichotomies could include differences in the meaningfulness, the familiarity, or the novelty of the judgment. However as the stimuli in both semantic tasks were known animal names these explanations do not explain the two decision-making networks found here. Further research examining multiple types of judgments about multiple domains in a single study is required to determine the relevant dimensions, which underlie the division of decision-making into two networks.

The results here reveal direct evidence from humans consistent with the proposal of increased duration of evaluative processing with increased difficulty as proposed by both the IR and Accumulator models. The manipulation of difficulty on Objective Perceptual judgments revealed ERPs of variable duration elicited by different Judgment Difficulty levels over areas involved in sensory processing (occipital cortex), accumulation (mIPS), and decision variables (DLPFC), providing direct evidence from humans that increased difficulty is associated with increased duration of processing. The fact that duration of ERPs elicited over areas involved in memory and working memory varied directly with Judgment Difficulty for Objective Semantic judgments provides the first direct evidence consistent with the presence of additional iterative loop cycles when judgment difficulty increased as proposed in the IR model. The study also revealed two networks underlying decision-making, which did not divide based on Judgment Type and Domain. Instead, two networks that divided on a global-local dimension were found to underlie the four types of judgments examined here. In summary, the results here expand the breadth of types of judgments that appear to be explained by Accumulator models and suggest that these models may provide accurate accounts of most of the types of decisions that humans make every day.

Appendix A

Acronyms (Alphabetical Order)	
ACC	Anterior cingulate cortex
BOLD	Blood oxygen level dependent method
CSD	Current source density
DLPFC	Dorsolateral prefrontal cortex
EM	Episodic memory effect
ERP	Event-related potential
FEF	frontal eye fields
fMRI	Functional magnetic resonance imaging
IR	Iterative Reprocessing
LIP	Lateral intraparietal cortex
LPC	Late positive component
mIPS	Middle intraparietal sulcus
MT	Middle temporal
OFC	Orbital frontal cortex
RMS	Root-mean square
RT	Reaction time
rTMS	Repetitive transcortical magnetic stimulation
SD	Standard Deviation
VLPFC	Ventrolateral prefrontal cortex
VMPFC	Ventromedial prefrontal cortex

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