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A thesis submitted to the Faculty of Emory College of Arts and Sciences
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Abstract

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Our memories guide our decisions, influence our social interactions, and determine our overall learning abilities. One defining characteristic of our personal memories is the temporal order of events. The crucial ability to recall the sequence of personal events in time, or temporal-order information from autobiographical events, enables us create cohesive narratives which shape both how we view ourselves and how we wish to be viewed by others.

This present study investigated if children between the ages of 7- and 11-years old have developed the important ability to retrieve the temporal order of autobiographical events comparable to adult-like capability. During the encoding task at the Fernbank Museum of Natural History, 21children took 120 pictures of specified objects in a determined order. One to 2 days later, the participants were asked to retrieve temporal-order information about pictures presented in a pair in order to determine which picture was taken first at the museum.

Through behavioral and electrophysiological testing, we determined the impact of the time lag between picture pairs and the physical order of the pictures in the pair on retrieval success, while also comparing the neural processing of these conditions during the retrieval task. As hypothesized, accuracy scores improved with longer durations between pictures in pair. The electrophysiological results demonstrated that there is no differential neural processing between correct and incorrect responses, but there is a robust main effect of lag with trials in which pictures that were further apart in time exhibited more neural activity. We also found a main effect of congruency with greater neural activity in trials in which the bottom picture was taken before the top picture. This finding, which may be due to familiarity, was confined to the right hemisphere frontocentral electrodes in trials where the pictures in the pair were taken close together in time at the museum.

This study contributes to the limited research on the development of temporal-order information retrieval for autobiographical events and the neural processing involved in this retrieval task. This field of research can contribute greatly toward better understanding neurological disorders that are characterized by abnormal retrieval of temporal-order information of personal events, the reliability of school-age children testimonials in abuse court cases, and the most effective teaching methods for this age range.

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Introduction

Autobiographical memories are commonly defined as episodic memories “infused with a sense of personal involvement and ownership” (Bauer, 2007, p. 21). These memories guide decisions, influence social interactions, and determine overall learning abilities; therefore, they serve a crucial role in an individual’s social, emotional, and cognitive well-being. As the cognitive processes that are responsible for several of the defining characteristics of autobiographical memory develop, there are significant improvements in autobiographical memory capabilities (Campbell & Spear, 1972; Kail & Hagen, 1977; Ornstein, 1978; Siegler, 1978). While several specific changes have been demonstrated (Refer to Bauer et al., 2006 and Bauer & Pathman, 2008 for such research), there is still much to be learned about the cognitive development of the ability to form and retrieve this type of memory.

The temporal context of autobiographical memories is one key feature that distinguishes this memory type from others. When remembering personal past experiences in one’s own life, information about *what* happened is coupled with *when* the event occurred (Tulving, 1983). It is the temporal information of memories that allows us to create narrative about our lives, and in turn, our autobiographies. Despite the significance of the temporal component of autobiographical memory, there is limited literature on the development of temporal-order memory in children. The lack of research is partially due to the inability to study autobiographical memories in a laboratory setting. However, the novel photo paradigm has recently allowed for the ability to systematically test controlled autobiographical memories (Cabeza, 2004). The primary aim of this present research was to determine if children between the ages of 7- and 11-years-old have the ability to retrieve temporal order information for autobiographical events. Through event-related potential (ERP) recording, we aimed to also provide a more complete view of the neural processing involved in this retrieval process.

A strong understanding of how autobiographical memories are formed and recalled has both direct scientific and practical benefits. This early-deteriorating memory type is a main feature of several neurodegenerative diseases such as Alzheimer’s. By understanding the distinct processes and systems involved in normal memory formation and retrieval, the cause and progression of such neurological and psychological disorders can be further understood. A strong understanding of the memory capabilities of school-age children would allow teachers to utilize more appropriate teaching methods, and in turn, more effectively teach for both normal and cognitively-impaired children. Another practical significance for understanding the ability of children to retrieve temporal-order information about memories pertains to the use of children testimonials in court cases. Due to the increase in national child abuse court cases in the United States, there has also been a growing interest in the reliability of children’s memories in the court room (Gaudiosi, 2007). Therefore, this cognitive developmental study can provide useful information regarding the ability for school-age children to form, store, and retrieve temporal information about personal life events.

Memory as a misnomer: Memory Types

While the singular word ‘memory’ is often used to refer to the general process of remembering past information, previous studies with amnesic and normal adults have demonstrated that there are several memory types. Each type differs in both the memory content and the neural structures involved for storage and retrieval. For example, sensory memory is the exact impression of a sensory stimulus that is retained for about one to two seconds after the stimulus is no longer present. This memory type is relatively localized to the specific brain region involved in processing the sensory signal. However, sensory information that catches the observer’s attention can become encoded into a different memory type, short term memory. Memories in the short term memory storage can finally be transferred into the more stable, long-term memory storage via consolidation. Consolidation occurs at both the synaptic and cortical level. Synaptic connections between the activated neurons involved in that particular memory are strengthened. The retention of such memories is improved by associating emotions and personal meaning to the information; thereby, requiring additional cortical structures for formation, storage, and retrieval. The knowledge stored in long-term memories is what is commonly viewed as a ‘memory’, because it is this information that affects social, emotional, and cognitive health.

Long-term memories can be further broken down into several memory types. This present research focuses on one specific type of long-term memory, autobiographical memory (AM). AMs are commonly defined as a subtype of episodic memories, because while episodic memories contain information about events that pertain to the self, AMs involve an added sense of personal involvement to that particular event (Bauer, 2007, p. 21). The classification of AM as a subtype of episodic memory is, however, a controversial topic. The similarities and differences that pertain to this project will be discussed throughout this paper.

In order to understand and appreciate both the complexity of AM and the importance of its further research, knowledge about episodic memories is required. In 1972, Tulving first introduced the concept of episodic memory by stating what it was not, namely, long-term procedural memory or semantic memory. Procedural, or implicit, memory can be referred to as "remembering how", because it involves stimulus-based reflexive motor and perceptual skills that enable one to remember how to perform a task without any conscious effort (Wheeler et al., 1997). While slow to acquire, this memory type is retained for a long period of time. Thus, this memory type is exemplified by the commonly used phrase, "You never forget how to ride a bike." Contrastingly, episodic memories are classified as long-term declarative, or explicit, memories. Declarative memory is "remembering that" because it describes the details of the event including the what, when, where, and why of the experience. This fast, specialized learning forms associations between arbitrarily different stimuli (Squire, 1995). When given an internal or external cue that relates to the produced mental association, these memories can be accessed and recalled. This recollection process, however, requires conscious effort and awareness.

The distinction between declarative and procedural memory is also evident by the different neural structures involved in the formation, storage, and retrieval of each memory type (Squire, 1995). The ability to form procedural memory depends on the developmental rate of the brain regions involved, which are the cerebellum, amygdala, and both the sensory and motor systems required for the particular learned task (Kandel et al. 2000). It has been proposed that the ability to form declarative memory develops later in childhood because it depends on structures that mature throughout childhood and into adolescence, such as the medial temporal (Mishkin, 1982; Zola-Morgan, 1986) and frontal lobe (Schacter, 1987; Tulving, 1985) regions.

Declarative memory is further divided into episodic and semantic memory based on the level of consciousness necessary for memory retrieval (Tulving, 1972). While semantic and episodic memories are both consciously accessible, the level of consciousness differs between the two memory types. Semantic memory is objective as it includes non-judgmental facts of what occurred including what was seen and heard (Wheeler et al., 1997). Therefore, this memory type requires noetic consciousness, which is general knowledge about an event. However, episodic memory is enriched with the sense of self. Self-knowledge, or autonoetic consciousness, is required for episodic memory retrieval because these memories include the subjective, personal viewpoint of the observer.

Another distinguishing factor between semantic and episodic memory is the temporal component involved in episodic, and therefore autobiographical, memory. While the definition of episodic memory has been significantly modified and expanded since its initial conceptualization in 1972, the temporal order of events has remained a principle component (Tulving 1983, 1985, 1991, 2001). "Recalling a personal event seems an incomplete experience without at least some accompanying sense of when the event occurred" (Friedman, 2004, p 531). Retrieval requires mental time-travel in order to re-experience a past event in the present. Episodic memory is the only memory type that is infused with this sense of "pastness" (Nelson, 1993a, 1993b, 2000; Wheeler et al., 1997). Since episodic memories contain subjective information, the temporal-order information is also subjective. The past experience is remembered from the observer's representation of time in the event. Therefore, episodic memory is rooted in the capacity to mentally represent and become aware of personalized experiences in subjective time (Wheeler et al., 1997).

Autonoetic consciousness is required to recall details from personal events. This level of consciousness allows individuals "to apprehend their subjective experiences throughout time and to perceive the present moment as both a continuation of their past and as a prelude to their future" (Wheeler et al., 1997, p 335). The ability to recall the events that occurred throughout a day, which heavily relies on temporal-order memory, is important for both the remembrance of past events and the coherent planning of future actions (Conway, 2009). When re-experiencing past events, a person simultaneously reflects upon the impact this event has on his/her future goals and actions. Episodic memory is, thereby, characterized by a subjective sense of past, present, and future time, which is referred to as chronesthesia.

Neural structures involved in AM formation and retrieval

The neural regions necessary for the increased level of consciousness and temporal component are mainly the frontal and medial temporal lobe regions. Frontal lobe lesion studies have demonstrated its role in the formation and retrieval of temporal order memory, the understanding of self, and the control of executive functions. Patients with frontal lobe lesions have reported difficulty accessing the temporal dimension of past events, thus, greatly hindering their memory retrieval abilities (Tulving, 1995).

Neuroimaging studies have also supported the role of the prefrontal regions in temporal order tasks (Zorrilla et al., 1996; Cabeza et al., 1997; Henson et al., 1999). Additionally, lesioned patients have lost their understanding of self. For example, Squire (1987) reported that these patients lost “personal familiarity and connectedness” to recent events. As discussed in the previous section, both an understanding of self and the ability to mentally time travel through personal experiences are important qualities for future planning. The frontal lobe controls executive functions, which regulate goal-directed future activities such as planning and anticipation of information. Therefore, a frontal lobe lesion also prevents the ability to make decisions about future actions.

Different areas of the prefrontal cortex are specialized for specific aspects of retrieval (Buckner & Wheeler, 2001; Moscovitch, 1992). For example, search processing activates the lateral prefrontal cortex (Svoboda et al., 2006; Maguire, 2001), monitoring processing is associated with the ventromedial PFC (Gilboa, 2004), and self-referential processing activates with the medial PFC (Cabeza et al., 2004; Gusnard et al., 2001). Searching processing involves sifting through memories, while monitor processing involves selecting memories that relate to the task at hand. Self-referential processing involves reflecting on personal emotions and thoughts associated with particular life events (Cabeza et al., 2004).

Rugg et al. (1996) further demonstrated the role of the prefrontal cortex in memory retrieval using positron emission tomography (PET) scans. They demonstrated that the prefrontal cortex, especially the right hemisphere, is more activated when information is successfully retrieved compared to unsuccessful retrieval. Rugg et al. (1996) study proposes the interesting research question of whether there is differential neural processing for successful versus unsuccessful retrieval, and why this may be lateralized. Our present study, which focuses on temporal-order memory for autobiographical events, further investigates these questions.

It is believed that the connection between the prefrontal cortex and the temporal lobe regions (i.e. the temporal-cortical network) is critical to episodic and autobiographical memory (Wheeler et al., 1997). Human (Ekstrom et al., 2003), primate (Wirth et al., 2003; Yanike et al., 2004), and rodent (Wood et al., 1999; Fortin et al., 2002) research have shown that medial temporal region, particularly the hippocampus, is critical for the temporal organization of episodic events. The study conducted by Fortin et al. (2002) is particularly interesting, because they studied the impact of varying time lag conditions on the retrieval of temporal information from memories. Each rat was presented with a series of five odors of common household items in a particular order. After a delay, rats were presented with pairs of nonadjacent odors and were rewarded for choosing the odor that appeared earlier in the series. The different lag conditions were represented in the odor pairings that were separated by 2, 3 or 4 odors. After the rats learned the task, they received lesions in the hippocampus. Although the rats that received the lesion were able to post-operatively recognize previous odors, their performance did not differ from chance in the odor choice task. They also demonstrated that accuracy was dependent upon the duration of the lag, with longer lags allowing for better performance. Since the control rats that received sham surgeries performed well in the choice task, this study demonstrated the critical role of the hippocampus in retrieval of memory for temporal order. The role of the hippocampus in this type of retrieval has been supported by patients who have difficulty recalling personal past events (retrograde) or forming new personal memories (anterograde) after brain injuries resulting from trauma or neurodegenerative disease. After inspection, the injuries have most often resulted in lesions in the hippocampus and other medial temporal regions (Deweer et al, 2001).

Autobiographical memory (AM) versus episodic memory (EM)

The distinction between autobiographical and episodic memory is controversial. Some memory theorists believe they are the same construct because both require recollection of contextual information related to personal events (Gardiner, 2001). This theory is supported by neuroimaging studies that have demonstrated that the same neural regions involved in recollective processing (i.e. frontal and medial temporal lobe regions) are activated in both AM and EM during retrieval tasks. This supports the idea that AM and EM are the same memory type because they require the same processing.

Others have stated that there is a distinction based on memory content. While episodic memories involve general information about one’s self from personal experiences, autobiographical memories only result when these events leave a lasting impression on the person. Therefore, only episodic memories that are infused with a sense of emotional connection and ownership to the experience can be classified as AMs (Bauer, 2007; Nelson, 2003, Wheeler et al., 1997).

ERP and neuroimaging studies lend further support to this distinction. An ERP study has demonstrated that AM and EM exhibit differential neural processing. This was examined by comparing neural activity between trials when participants identified pictures they had taken themselves (autobiographical) and pictures that they had seen before but were taken by a stranger (episodic) of the same location (Pathman et al., 2010). The neural processing involved in these two trial types was different, thereby, demonstrating distinct neural processing for AM and EM.

The neuroimaging studies reported differences in the neural activations between AM and EM that are related to the significant differences, the increased level of self-referential processing, emotional content, and visual imagery involved in AMs compared to EMs. The increased self-referential processing leads to more activation in the mPFC, the area responsible for this function as previously discussed. This was further supported by other studies that have focused on the relationship between self-referential processing and the mPFC (Kelley et al., 2002; Gusnard et al., 2001; Craik et al., 1999; Lane et al., 1997). Similarly, AMs exhibit more activation in visual regions due to the enhanced visual imagery, or increased use of the environment to remember a specific personal moment. Lesion studies in the visual cortex have also been shown to impair AM (Rubin & Greenberg, 1998).

The controversy, however, still remains, particularly because it has been difficult to truly compare episodic memories and AM in the laboratory setting. Episodic memories are often tested in the laboratory by introducing participants to various “event” (i.e. words or pictures) and asking them to retrieve information about those events. Autobiographical memories, however, are tested by first asking participants or parents of participants to recall events from their lives and later asking them to recall those events (e.g. Bauer et al., 2007). These two different methods are not conducive to comparison; therefore, the similarities and differences between these two memory types cannot be assessed.

Additionally, using these methods, it is difficult to assess retrieval accuracy for autobiographical memories. Autobiographical memory retrieval is the correct identification of picture taken by oneself versus those taken by others (St. Jacques et al., 2008). In addition, compared to episodic memories, AMs involve more emotional content and more remote experiences. These differences have made it difficult to compare these two types of memories in a controlled laboratory setting. However, Cabeza et al. (2004) created the ‘photo paradigm’ that controls for these differences, thereby, allowing for direct comparison of the episodic and autobiographical memories. In this paradigm, participants are asked to take specified photos in a particular environment. In the following day or two, these participants are asked to assess if they could identify photos that they had taken (autobiographical events) versus photos other participants had taken (episodic events). The memories personally taken through this paradigm contain greater self-referential processing, visual imagery, and recollection compared to the EMs created in the laboratory. Using this paradigm, the age and emotional content of the memories, which usually differ between these two memory types, are controlled to be equivalent. This paradigm also allows for an objective measure of successful autobiographical memory retrieval. Thus, the two types of memory retrieval can be accurately compared. The photo paradigm allows for the direct comparison of episodic and autobiographical memories. Even though this present study does not compare AM and EM, the paradigm is important because it allows researchers to study controlled AMs in the laboratory setting.

Development of autobiographical memory

The ability to form and retrieve AM is an emergent process without any distinct age marking the beginning or completion of its development. The ability to form and retrieve AMs develops with the maturation of prefrontal cortex regions that are responsible for executive functions, self-referential processing, and temporal-order memory retrieval. Since prefrontal cortex synapse pruning to adult levels progresses into adolescence, this ability is theorized to improve during adolescence (Huttenlocher, 1979). Similarly, the development of medial temporal regions, mainly the hippocampus, is directly related to temporal-order memory formation capabilities (Moscovitch, 1995b). Myelination of hippocampal neurons (Arnold & Trojanowski, 1996) and increases in hippocampal volume (Gogtay et al., 2004) both develop into late adolescence. Bauer (2007) demonstrate that children exhibit age-related improvements in recall of autobiographical memory. These improvements parallel the protracted development of the neural structures important for autobiographical memories, namely the prefrontal and medial temporal regions. Formation and retrieval of AMs is dependent not only on both of these regions, but also the connections between the two regions.

Since a sense of 'self' is necessary for AM formation, recognition of the self marks the earliest age for this memory capability. Howe and Courage (1993, 1997) argue that this awareness of the cognitive self occurs around the age of two-years-old. This awareness equips infants with "a new organizer" that allows for the personalization of experiences into what can eventually, but certainly does not always, become autobiographical memories (Howe et al., 2003). Awareness of the cognitive self is evident in mirror tasks when infants recognize themselves (see Lewis & Brooks-Gunn, 1979 for one such study).

However, self-recognition is only one component of the self-awareness. Self-awareness “implies more than recognition of one’s physical features, it is a fundamental aspect of social cognitive development that has roots in the early weeks of life and continues to evolve throughout childhood and adolescences” (Howe et al., 2003). Children are able to retain more autobiographical information with age, probably due to both age-related improvements in the neural structures that allow for encoding, storage, and retrieval of memories as well as changes in sociolinguistic and metacognitive skills that enable more sophisticated narratives and the ability to extend oneself in time (Nelson, 1993a). Sociolinguistic improvements allow for expression of one’s experiences through narrative and the development of metacognition provides recognition of one’s own mental processes. Both of these age-related developments that occur between the ages of four and five contribute to the ability to retain more autobiographical information. The understanding of the “temporally-extended” self occurs around the same age as sociolinguistic and metacognitive improvements (Povinelli et al., 1996). The temporally-extended self allows for the recognition of the present self compared to the self in the recent and remote past. As previously discussed, an understanding of the past, present, and future is a defining characteristic of autobiographical memory. This emergent process develops throughout childhood and into adolescence because it relies on the maturation of brain areas, particularly the prefrontal cortex and medial temporal regions.

Development the ability to retrieve temporal order information for AM

In the present study, we analyzed the development of temporal order for autobiographical events by coupling behavioral and electrophysiological testing. Even though the temporal component is a key factor in autobiographical memories, there has been limited research on development of the capability to form and retrieve temporal order information about AMs. A series of studies were conducted in which participants were asked to judge how long ago a particular event occurred either by choosing the more recent of two events (Friedman, 1991; Friedman et al., 1995; Friedman & Kemp, 1998) or by physically judging time along a ruler (Friedman & Kemp, 1998). Two studies further assessed the ability to reconstruct temporal information about past events by asking participants to recall temporal information (i.e. time of day, day of the week, month, or season) about two staged, in-school events. One study had a seven week retention interval between the encoding and the testing phases (Friedman, 1991) and the other study has a three month delay (Friedman & Lyon, 2005). Friedman & Lyon (2005) performed two in-class demonstrations that were separated by a few days in eight separate age levels ranging from preschool to seventh grade children (4- to 13-years old). After a three month delay, the children were asked to order the two events. Children of all grade levels, except preschool, had an accuracy level greater than chance. Age-related improvements in recall were evident because while four-year-olds were able to remember the general context of both events, the 6-and 7-year-olds recalled more specific details that enabled better retrieval accuracy. The 6- and 7-year olds also demonstrated the ability to evaluate temporally relevant information in order to reconstruct the order of the events. Friedman and Lyon (2005) suggest that in order to form and retrieve autobiographical information the experience must contain temporally relevant information, the child must have a general awareness of time, and the neural regions responsible for executive processes must be developed.

Another study assessed the accuracy of retrieving temporal information about autobiographical events by asking children between the ages of 7- and 10-years old to produce a personal event for fourteen cues words (Bauer et al, 2007). They then judged their own age and season in which the event occurred, and their mothers were asked to assess the accuracy of participants' judgments. Bauer et al. (2007) demonstrate that children in this age range can provide accurate temporal information because 89% correctly judged their age and 79% correctly judged the season.

These behavioral studies demonstrate that school-age children between the ages of 7- and 11- years old) begin to develop the ability to recall temporal-order information from memories. Therefore, the present study focused on this age range. Most recently, another behavioral study demonstrated that children between 8- to 12-years-old were able to remember information that allowed them to localize the events in time in at least an approximate way (Friedman et al., 2010). Additionally, this period of childhood was selected because it has been identified as the "final critical phase of brain growth" and the difficult task of recalling temporal-order information about memory requires the development of the temporal-cortical network that develops towards the end of neural development (Caniness et al., 1996).

Most of these behavioral studies did not focus on retrieval of temporal order but instead just any temporal information about life events. Additionally, these behavioral studies lack a consistent way of encoding the "autobiographical memories" used for testing. Lastly, the results do not provide any provide any information about the neural processing involved in retrieval of temporal information. The photo paradigm previous mentioned provides for a consistent encoding process across participants and neuroimaging or ERP studies can provide more information about neural activity during retrieval. St. Jacques et al. (2008) conducted an fMRI study in which adults participated in an encoding task using the photo paradigm. They each took pictures of 80 locations across the Duke University campus in a specified order during the encoding task. The encoding memories were controlled autobiographical memories that exhibited autobiographical qualities, specifically, self-referential processing, visual imagery, and recollection. During the testing phase, participants were presented with picture pairs in 3 time lag conditions- short, medium, and long. They defined short lag as 1 to 9 pictures apart, medium lag as 10 to 39 pictures apart, and long as 40 to 80 pictures apart. They paired the behavioral testing with fMRI neuroimaging in order to study the neural structures involved in temporal order autobiographical memories through analysis of adult fMRI. However, St. Jacques et al. (2008) did not focus on the development of this memory capability because they only used adult participants.

The behavioral component of this present study is largely based on the study design used in St. Jacques et al. (2008), because we used the photo paradigm to test autobiographical memories. In addition to the judgment and lag conditions present in both the Fortin et al. (2002) and the St. Jacques (2008) studies, we also assessed if the physical orientation of the picture pair affected judgment. It is also important to note that this present study is one of a series of studies investigating the capability to form and retrieve autobiographical memory on children.

The electrophysiology component of the present study involved event-related potential (ERP) recording to investigate the neural processing involved in each condition.

The present study complements the previous research by using school-age children in a temporal-order memory task using both behavioral and electrophysiological measures. Specifically, the ERP technique used in the present study provides high temporal resolution that complements the high spatial but poor temporal resolution of fMRI studies. Previous studies have used ERP to examine temporal memory judgments in episodic memory in adults (e.g. Curran & Friedman, 2003; Tendolkar & Rugg, 1998), however, this present study is the first to study development using ERP on children in the age range specified to develop this ability to form and retrieve temporal-order information of autobiographical memories. Riggins et al. (2009) is the only other study that has used ERP to investigate the recollective processes involved in recalling temporally ordered episodic events, but they focus on preschool-age children (ages 3 and 4). Additionally, they studied episodic memory in general, not autobiographical memory. The behavioral results support the trend of an age-related increase in accuracy in the literature and the ERP findings demonstrate that there may be particular components involved in retrieval of episodic memories.

The ERP technique allows researchers to record the naturally emitted neural activity via electrodes placed on the scalp surface. Since an electroencephalogram (EEG) is conglomeration of hundreds of different neural sources of activity, it is difficult to isolate a specific cognitive process. However, an ERP is time-locked to a particular event. All of the events of a certain condition can be averaged, allowing for researchers to view the neural signaling time-locked to that condition only. This allows for analysis of the neural processing for each condition of interest. This technique used to be referred to as evoked potential, because the recorded potentials are the result of the synchronous brain activity that changes in response to a stimulus (Luck, 2005). When the physical stimulus is changed a new condition is formed, and changes in the participant's neural signals provide the experimenter with information about the different underlying neurophysiologic mechanisms of each condition (Murray et al., 2008).

The high temporal resolution of ERP recording allows researchers to determine which specific stages of processing are influenced by the experimental manipulation. Also, this approach is relatively inexpensive and noninvasive compared to the other neurological techniques. It provides children a comfortable atmosphere compared to fMRIs, does not involved any injection of contrast agents as used in PET scans, and leaves parents assured that there is low risk because the neural signals recorded are naturally emitted. ERP recording additionally provides several benefits for cognitive developmental research in particular because it can be used along the entire lifespan (see De Haan et al., 2007 for review of ERP studies in the developmental literature). Therefore, the neural processing of different age groups can be directly compared using the same paradigm.

Our exploratory study had two specific aims. We aimed to determine if children between the ages of 7 and 11 years old have the ability to retrieve the temporal order of autobiographical memories. Additionally, we used the electrophysiological data to assess if there is differential neural activity for successful versus unsuccessful retrieval of temporal-order information for autobiographical memories. ERP also allowed us to manipulate the conditions in which the picture pairs were presented in order to determine if lag (short or long) or physical orientation of stimulus (congruent or incongruent) cause differential neural processing during temporal-order memory retrieval. For behavioral testing, we predicted that children would be more accurate than chance and would perform better on trials in the long lag conditions. For the electrophysiological testing, we predict that children will show differentiation of event-related potential (ERP) waveforms for correct versus incorrect responses, congruent versus incongruent temporal order, and short versus long lag conditions. By analyzing the neural responses involved in retrieving, we may able to provide a more complete view of neural processing involved in autobiographical memory retrieval.

Methods

Participants

Twenty-one children between the ages of 7- and 11-years-old were tested (13 females, mean age = 8 years and 6 months old). One participant's electrophysiological data was not analyzed due to technical difficulties, but her behavioral data was included in the behavioral analyses since she completed the testing phase. Another participant's behavioral and electrophysiological data were excluded because a parent took several pictures during the encoding session and the participant exhibited excessive movement during the entire duration of the testing phase. Therefore, there are twenty participants for behavioral analyses and nineteen for ERP analyses.

The children were recruited from the Child Study Center family directory, which includes families that have volunteered to be in other studies, including families that have participated in research studies conducted by the Bauer Laboratory in the past. All children were compensated for their time and efforts with a small toy and a ten dollar certificate to a local merchant. Both verbal assent from child and written consent from accompanying parent were collected for both the encoding and testing session prior to the first session.

Procedure for session 1: Encoding

This study protocol is an expansion on the St. Jacques et al. (2008) study previously explained. All participants were asked to take two consecutive pictures of 120 specified objects in the Fernbank Museum of Natural History in Atlanta, Georgia during the encoding task. The participants used a digital camera (6 megapixel HP Photosmart E457) provided by the laboratory. This location, as opposed to a local university campus that was used in the St. Jacques et al. (2008), was selected for this study in order to control for familiarity to the location. The purpose of the duplicate picture is to ensure that one picture is useable for the test session. Therefore, the better of the two pictures is selected for use in the second session.

During consenting, all participants were informed that the purpose of the study is to assess temporal-order memory for autobiographical events. In order to ensure that each picture taken is a controlled autobiographical event, each child was highly encouraged to pay attention to the environment and details and how they particularly feel as they take each picture during the approximately two hour encoding session. This session was divided into two parts of sixty pictures separated by an optional snack break. All participants chose to take the break.

A research assistant guided each participant from room-to-room in order to ensure that participants took the pictures in the correct order, did not use the zoom features, did not view pictures taken, and remained focused on the task and purpose of the study for the entire session. Also, the research assistants limited the break to less than ten minutes and took notes about any abnormal occurrences during the session. Parents and siblings were welcome to follow the participant and research assistant throughout the trial; however, discourse between family members was limited.

Stimuli Selection

The 120 items and the order of the pictures were chosen by three researchers before the study was started. The only constraint for selection of the items is that they had to be in a permanent exhibit. The order of the pictures had two constraints, which to accommodate the break and to reduce the correlation between temporal distance and spatial distance. Each room was visited at least twice and both the order of rooms within each floor and objects within each room were randomized in order to ensure that the participants' answers were dependent solely on temporal order and not impacted by spatial order. Pilot studies with several orders were conducted to find a reasonable compromise between the reduction of spatial cues and the feasibility in terms of time and energy required to finish the session. Two orders with the same 120 objects were used for counterbalancing. In order to accommodate the break that took place in the Fernbank café on the first floor, participants either ended of the first part or began the second part on the first floor. This reduced the number of stairs involved during the session, which increased the feasibility to complete the photo-taking task. We also controlled for the time of day by running the first session between 10:00 am and 2:00 pm on either a Saturday or Sunday for all participants. This is because previous research has shown that time of day can affect memory (Friedman & Lyon, 2005).

Procedure for session 2: Testing

The participants came to the laboratory for the test phase after a 1 or 2 day delay from the encoding session (mean delay = 34 hours, 26 minutes). This session includes simultaneous behavioral and electrophysiological testing.

Behavioral testing

Participants viewed 120 trials (or 120 pairs of pictures) in the same randomized order. Participants were asked to view each picture pair, or trial, and respond to the question “Did I take picture A (top) before picture B (bottom)? They responded via button press with one button representing the congruent order and another representing the incongruent order. Congruent order referred to picture A taken before picture B following the question format. Incongruent order referred to picture B taken after picture A, which is the opposite of the order posed in the question. Half of the trials were presented in the congruent order and the other half were presented in the incongruent order.

Sixty trials were presented in the short lag condition, which was a separation of ten pictures taken during session 1 at the museum. The other half of the trials were in the long lag condition in which one picture is always from the first part of session 1 and the second picture is always from after the break. The trials in the long lag condition were separated by forty to eighty pictures. The two different lag conditions were used in order to create two levels of difficulty. The more difficult short lag condition challenges the participants more than the long lag condition, and, therefore, may require different neural activations for successful recall. Additionally, participants saw each picture two times during the testing phase. The picture was paired in the short lag condition once and in the long lag condition the other time.

Participants were seated approximately two feet from the monitor in a blocked-off area, which separates the participants from the testing environment including parents and experimenters. The Advanced Source Analysis (ASA) software (Version 4.6.0.3; Advanced Neuro Technology (ANT)) Eevoke program was used to display picture pairs on the monitor. Each trial lasted for 6000 milliseconds in which a picture pair was displayed on the monitor. A 3000 millisecond inter-trial interval (ITI) followed each trial during which the monitor displayed a black screen. There was also a jitter, an inter-stimulus interval time that varies between 1 and 150 milliseconds. The jitter ensured that the neural responses were specific to the stimulus and not impacted by predictable time lapses. Participants were asked to respond about the temporal order of the pictures during the ITI. Since they were instructed to make their responses only during the ITI, reaction times were not analyzed even though they were collected.

ERP testing

Prior to beginning the behavioral testing, participants (n = 19) were fitted for an ANT Waveguard EEG cap. The elastic lycra cap is available in several different sizes. This is an important factor for this study since the size of the head varies greatly between a 7-year-old and an 11-year-old. The different caps controlled for electrode distribution across the scalp which provided consistency across participants. ASA allows for the simultaneous collection of behavioral and ERP data. This allows researchers to make the association between the different conditions of the visual stimuli and the differential neural processing evident in the ERP recordings. There were three tested conditioned in this present study (Refer to Table 1 for the conditions and their definitions). The response conditions depended on the participant, while the lag and congruency conditions depended on the stimulus. The response conditions represent the judgment the participant made about the order of the pictures. Their response was either correct or incorrect. The trials were presented in either the congruent or incongruent condition and in either the short or long lag condition. Therefore, there were four possible conditions available for analysis based on the stimulus (i.e. short lag congruent, short lag incongruent, long lag congruent, long lag incongruent).

The pictures were presented in the vertical arrangement with one picture above the other. This arrangement was selected based on pilot study results, the capabilities of the recording apparatus, and the potential bias caused by the English language. The main difference between the two arrangements is the direction the eyes must glance in order to view the pictures in the pair. These glances cause eye saccades, which are a specific type of artifact for electrophysiological data recording. If artifacts produce deflections greater than 150 microvolts in the ERP data, the trial is eliminated from analysis. Therefore, we analyzed which arrangement resulted in fewer eye saccades, thereby allowing for the most number of trials. The pilot study (n = 6 adults) demonstrated that there was no significant difference between the number of trials attained from the vertical versus horizontal arrangement (vertical: M = 20.17, SD = 4.12; horizontal: M = 23.33, SD = 1.97). The vertical arrangement was selected because the program used for ERP data collection (Advanced Neuro Technology (ANT) Advanced Source Analysis (ASA) software Version 4.6.0.3) is able to identify vertical eye saccades but the identification of horizontal eye saccades requires two additional electrodes be placed on the participant's face. Lastly, since all participants were English speakers and the written language is written left to right, there may be a bias to believe that the picture on the left side of the picture pair was taken first.

Participants were asked to respond during the ITI in order to minimize another type of artifact, motion artifact, during trials. To further reduce additional artifact, participants are asked to avoid excessive blinking and movements during trials. They were highly encouraged to blink during the ITI in which the recorded data was not analyzed. While ERP recording continued throughout the entire test phase, only the trials are of interest because that is the time the participants are asked to think about the stimulus. We used an event duration of 1700 millisecond (ms) for analyses. All collected data was stored for offline analysis. While the test phase lasted approximately 19 minutes, the entire session including the capping, instruction period, and test phase lasted approximately 60 minutes.

ERP acquisition: This experiment involved recording from a ground electrode and 32 shielded electrodes. Two of the 32 electrodes are the linked-ear reference electrodes, which are placed on the mastoid processes behind the ear. The linked-ear reference is commonly used in the cognitive developmental ERP research because the mastoid processes do not emit brain activity. Additionally, the two electrodes on either side of the head are algebraically linked and provide for comparison of electrodes to their respective reference. The International 10/20 system has determined the location of the electrodes. Specifically, eleven electrodes are placed over the frontal lobes (Fp1, Fpz, Fp2, F3, F4, F7, F8, FC1, FC2, and FC6), two over the temporal lobes (T7 and T8), nine over the parietal lobes (P3, P4, P7, P8, POz, CP1, CP2, CP5, and CP6), three over the occipital lobes (O1, O2, and Oz), two over the center of the scalp (C3 and C4), three along the midline of the center of the scalp (Fz, Cz, and Pz), and the two over the mastoid processes (M1 and M2).

ERP Reduction: After the test phase was completed, the digital information collected was processed using ASA. In order to attenuate for extreme frequencies (extremely high or low) in the waveforms, the data were amplified with a bandpass filter of 0.1 to 30 hertz. Next, trials containing artifacts, such as eye-blinks and excessive movements that had either negative or positive deflections greater than 150 microvolts were excluded.

In order to minimize the number of trials that were excluded four particular actions were taken. The first three strategies have already been discussed. The first strategy was the vertical arrangement. The second and third methods were responding via button press during the ITI and minimizing any excessive movements. Lastly, we attempted to correct for the eye blinks instead of rejecting them using independent component analysis (ICA) through Matrix Laboratory (MATLAB). The basis of this computational technique relies on the fact that EEG data is collected from electrodes that summate neuronal potentials from various sources within the brain (Ungureanu, 2004). Each artifact is another source. When an eye blink occurs, the same voltage is potentiated to all scalp electrodes with the electrodes closest to the eye more affected than those in the back of the head. Therefore, all electrodes record the eye artifact voltage multiplied by a specific propagation factor (Luck, 2005). ICA separates the EEG into its source voltage, or components. The eye blink component can then be subtracted out from each electrode. If a component is found, it was eliminated from the filtered data, thereby correcting for the blink frequency instead of eliminating all of the trials that exhibit the artifact. If a component was found, the ICA filtered file was used for further data reduction processes, but if no particular component was found then the original filter file was used for following steps.

The data is then separated by condition. Since in this present study we were interested in the effects of response (correct or incorrect), physical orientation of the stimulus (congruent or incongruent), and lag differences (short or long) on neural processing, we analyzed the data in two separate ways for thorough analysis. Processing 1 compared all correct judgments versus all incorrect judgments. Although not realistically possible, there was a maximum of 120 correct responses possible. This processing was aimed at determining if there was differential neural activity between trials that exhibited correct versus incorrect responses. We incorporated the effects of lag (number of pictures between the pictures presented in the stimulus) and congruency (physical orientation of the pictures in the pair) on neural processing in Processing 2. This processing method collapsed across all trials including both correct and incorrect responses. As opposed to the two conditions in the previous processing method, there are four conditions in this processing method. The conditions are short lag congruent order, short lag incongruent order, long lag congruent order, and long lag incongruent order.

The data for each participant was averaged. This process involves the extraction of the EEG event following the particular stimulus of interest from the rest of the EEG data. This step, therefore, created the ERP waveform of interest from the EEG data recorded. These trials were time-locked to the event and averaged together. Any participant who had fewer than ten trials in any one condition was excluded from the analysis in order to maximize the signal to noise ratio. Lastly, the grand average of all the data files was calculated using ASA Experiment Manager (ExMan). The grand average waveforms, which represents the average of the ERP waveforms for each participant and each condition, were then analyzed.

ERP Data Analysis: Since this was an exploratory study, there were no particular components of interest. Components are particular peaks or valleys in the ERP waveform. While most ERP research (i.e. 'old/new effects') focuses on early components in the 200-500 ms time range, the difficulty of this task requires sustained cognitive processing in which the later time windows will be important. Memories for contextual details, such as temporal order, are reported in the literature to be represented by later processing activity (Duarte et al., 2004; Friedman & Johnson, 2000). Therefore, for both Processing 1 and 2, time windows from the later portion of the ERP waveforms were chosen via ocular analysis of the grand average waveforms. In Processing 1, which compared correct versus incorrect responses, the time window from 500-1700 ms was analyzed. The same time window, 500-1700 ms, was used for Processing 2 to provide consistency across the two processing methods and because it exhibits a trend different from the rest of the waveform. Figure 1 and 2 provide visual depictions of the time window for Processing 1 and 2, respectively. In order to reduce the number of dependent variables and because this time window revealed few definitive peaks, an area score was calculated for the selected waveforms. Area score is calculated by the average area between the waveform to baseline across the particular time window.

The low spatial resolution of ERP prevents researchers from making any direct correlations between any particular electrode and any source location. Instead, electrode clusters on commonly used for analysis in the ERP literature. These clusters are based on electrodes that demonstrate the same trend in the grand average waveform. All electrodes cannot be grouped together, because a natural change in signal deflection occurs from the front to the back of the head across all scalp electrodes. Therefore, an electrode cluster comprised of frontal and parietal electrodes may lead to a false negative finding. Electrode clusters were created prior to analysis. Figure 3 and 4 contain the electrode clusters for Processing 1 and 2, respectively. For Processing 1, six electrode clusters were created. For the remainder of this paper, the two electrode clusters including F3, F7, FC1, FC5, F4, F8, FC2, and FC6 will be referred to as "frontocentral electrodes", the two electrode clusters including Fz, Cz, and Pz will be referred to as the "midline electrodes", and the two electrode clusters including P3, P7, CP1, CP5, P4, P8, CP2, and CP6 will be referred to as "partietal electrodes". For Processing 2, 8 electrode clusters were created. The two additional electrode clusters, which include C3, CP1, CP5, C4, CP2, and CP6, will be referred to as the "central electrodes". The central electrodes were used in Processing 2 but not Processing 1 because they exhibit a distinct trend in the Processing 2 grand average while in Processing 1 they follow the same trend as the frontal electrodes except with lower amplitudes.

For each processing, Statistical Analysis System (SAS) was used to conduct a four-way (hemisphere x electrode x lag x congruency) analysis of variance (ANOVA) calculating area score for each time window and electrode cluster (frontocentral, midline, parietal, and central when applicable). A Tukey Studentized Range (HSD) test for area post-hoc was conducted for any significant ($p < 0.05$) effects. Any interactions from the ANOVA were followed-up with a one- or two-way ANOVA depending on the number of variables in the interaction. The accuracy score for the behavioral data was calculated by the proportion of correct trials. The accuracy scores were compared for the four possible lag by congruency conditions (i.e. short lag congruent, short lag incongruent, long lag congruent, long lag incongruent).

Results

First, a brief summary of all of the findings is provided. The results are then divided two testing sections, behavioral and ERP, in which the specific values from analyses will be included.

The behavioral findings of this present study demonstrate that the participants make more correct versus incorrect responses and that accuracy in judgment is dependent on the lag condition. Trials in the longer lag exhibit higher accuracy scores than those in the short lag condition. The electrophysiological results demonstrate that there is no differential neural processing between correct and incorrect judgments. There is, however, a robust main effect of lag with trials in the long lag condition exhibiting larger amplitudes than those in the short lag condition. This same effect is seen across the entire scalp except for the right hemisphere frontocentral electrodes in the congruent condition. Therefore, while the right hemisphere frontocentral electrodes exhibit the same main effect of lag as the rest of the scalp, it is confined to the incongruent condition. Additionally, we found a main effect of congruency with higher amplitudes in congruent trials compared to incongruent trials specifically in the right hemisphere frontocentral electrodes in the short lag condition.

The results pertaining to our primary aim, which was to determine if children between the ages of 7- and 11-years old have the ability to retrieve the temporal order of autobiographical memories, will be presented first. Next, the electrophysiological results, which relate to our secondary aim of assessing the neural processing involved in the retrieval of temporal-order information for autobiographical events, will be presented. The order of information will follow the summarized results above and will be further divided by the electrode clusters analyzed (Figure 3 and 4). Table 1 includes the variables that are discussed in the following behavioral and ERP results and their definitions.

Behavioral Results

On average, participants (n = 20) made more correct rather than incorrect responses (correct: M = 63.1, SD = 9.580133; incorrect: M = 55.7, SD = 9.68504). The behavioral data from each of the four lag by congruency conditions were analyzed. The means for each condition are displayed in Figure 5. As predicted, the means of both the congruent and incongruent long lag conditions (long lag congruent: M = 0.5717, SD =

0.1258; long lag incongruent: M = 0.5533, SD = 0.1196) exceeded the means of both the congruent and incongruent short lag conditions (short lag congruent: M = 0.5053, SD: 1321; short lag incongruent: M = 0.4943, SD = 0.1087).

The results for each of the four lag by congruency conditions were analyzed using one-sample t-tests compared to chance, which is 50% since there are two responses (correct and incorrect) possible. This analysis revealed a significant difference between trials in the long lag congruent condition and chance, $t(19) = 2.55$, $p < 0.05$. The mean of the trials in the long lag incongruent condition compared to chance approached significance, $t(19) = 1.99$, $p = 0.0608$. Participants performed at about chance in both trials in the short lag congruent condition ($t(19) = 0.18$, $p = 0.8604$) and in trials in the short lag incongruent condition ($t(19) = -0.23$, $p = 0.8173$). These results demonstrate that it was more difficult to successfully retrieve temporal-order information for trials in the short lag conditions compared to the trials in the long lag conditions.

Since participants had either a one-day delay (n = 11) or a two-day delay (n = 9), an independent samples t-tests were used to assess if a difference in delay affected accuracy. This analysis revealed no significant differences between the accuracy of the one-day delay group and two-day delay group in any of the four lag by congruency conditions (short lag congruent: $t(18) = -0.835$, $p = 0.415$; short lag incongruent: $t(18) = -0.700$, $p = 0.493$; long lag congruent: $t(18) = 0.390$, $p = 0.701$; long lag incongruent: $t(18) = 1.920$, $p = 0.070$).

Age correlations were performed to determine if age-related improvements were seen in the accuracy scores within the cohort. The Pearson correlation did not reveal any significant relations between age and accuracy (all p-values > 0.05).

ERP results

In this present study, we were interested in determining if any of three specified conditions (response, congruency, or lag) impacted the neural processing involved during retrieval of temporal-order information for autobiographical events. Therefore, only the main effects or interactions involving any of these conditions were pursued with follow up analyses. While all significant findings including those not related to any condition will be reported in this paper, for specific mean amplitude values for any effects or interactions refer to Table 2 for Processing 1 analyses and Table 3 for Processing 2 analyses.

Processing 1

Our first approach was to compare the neural signals between the trials where participants responded correctly about the order of the physical stimuli (the picture order) versus those where they responded incorrectly. We predicted that children would show differentiation of ERP waveforms for correct versus incorrect responses. A difference would be consistent with the hypothesis that participants exhibit differential neural processing between when they successfully (correct) versus unsuccessfully (incorrect) retrieve temporal order information. The grand average of this processing exhibited higher amplitudes for correct trials, particularly in the frontocentral electrodes (Figure 1). However, the differential effects were not significant. Repeated-measure multifactorial ANOVAs were performed for each of the 5 electrode clusters to compare ERP differences across the response condition. Refer to Figure 3 for the specific electrodes in each cluster.

Frontal electrodes: A 3-way (Hemisphere x Electrode x Response condition) repeated measures ANOVA for the frontocentral electrodes revealed a main effect of electrode, F(3, 18) = 7.30, $p < .001$. Further analysis was not conducted because there were no effects or interactions involving condition.

Parietal electrodes: A 3-way (hemisphere by electrode by condition) repeated measures ANOVA for the parietal electrodes did not reveal a main effect of condition or any interactions involving condition, but it revealed a main effect of both hemisphere and electrode (Table 2). For hemisphere, there was a higher amplitude in the left compared to the right hemisphere, F(1, 18) = 4.58, $p <0.05$. For electrode, all of the electrodes exhibited different amplitudes for each electrode, F(3, 18) = 136.88, $p < 0.0001$.

Midline electrodes: The 3-way repeated measure ANOVA for the midline electrodes (Fz, Cz, and Pz) revealed a main effect of electrode, F(2, 18) = 69.76, $p < 0.01$ (Table 2). There were no other significant effects.

Summary: The results from the electrode clusters analyses for Processing 1 reveal no evidence for differential neural processing on trials with correct responses compared to trials with incorrect responses.

Processing 2

Since there were no differences in the judgment condition, the ERP waveforms were collapsed across correct and incorrect responses for all further processing. We were interested in the effect of lag and congruency on neural processing. We predicted that participants will exhibit differential neural processing for both congruency conditions (congruent versus incongruent) and lag conditions (short versus long). Processing 2 includes two conditions, congruency and lag. Therefore, 4-way (Hemisphere x Electrode x Lag x Congruency) repeated measures ANOVAs were conducted for each of the 8 electrode cluster during the 500 to 1700ms time window. Refer to Figure 4 for specific electrodes in each cluster.

Midline electrodes: This electrode cluster revealed a main effect of lag, F(1, 17) = 4.61, $p < 0.05$ (Table 3). Trials in the long lag condition exhibited a greater amplitude (or negative deflection) compared to those in the short lag condition (Figure 6). Refer to Figure 2 Panel C to view the lag effect evident in the grand average waveform for a representative electrode from this cluster.

Central electrodes: This electrode cluster exhibited the same main effect of lag with a larger negative deflection in the long lag condition, F(1, 17) = 12.11, $p < 0.01$ (Table 3, Figure 6). In Figure 2, the lag effect can be seen in the grand average waveforms of two representative electrodes, one from each hemisphere electrode cluster (right: Panel D; left: Panel E). The central electrodes also exhibited a main effect of electrode, F(1, 17), $p < 0.01$ (Table 3). The Tukey post-hoc analysis demonstrated that this effect stems from all three electrodes displaying different amplitudes from each other. There were no other main effects or interactions between variables in the central electrodes.

Parietal electrodes: This electrode cluster exhibited the same main effect of lag with a larger negative deflection in the long lag condition, F(1, 17) = 12.90, $p < 0.01$ (Figure 6). The lag effect was apparent in the grand average waveform. Refer to Figure

2 Panel F and G for two representative parietal electrodes from the right and left hemispheres, respectively. In addition to the main effect in lag, the parietal electrodes revealed two interactions, Hemisphere x Electrode, $F(3, 17) = 3.11$, $p < 0.05$, and Lag x Electrode, $F(3, 17) = 3.63$, $p < 0.05$). Since ERP does not have the high spatial resolution required to identify the source of an effect in one electrode, interactions with electrode were not further pursued.

Frontocentral electrodes: Similarly, the frontal electrodes displayed the main effect of lag with a larger negative deflection in the long lag condition, $F(1, 17) = 6.14$, $p < 0.05$. These electrodes also exhibited two interactions, Hemisphere x Lag x Congruency ($F(1, 17) = 5.17$, $p < 0.05$) and Hemisphere x Electrode x Lag x Congruency ($F(1, 17) = 3.59$, $p < 0.05$). Follow-up repeated measures 2-way ANOVAs for the 3-way interaction of Hemisphere x Lag x Congruency were conducted. The analysis of the interaction by hemisphere demonstrated the same main effect of lag with longer lag conditions exhibiting larger amplitudes, $F(1, 17) = 8.18$, $p < 0.05$. This main effect of lag was only seen in the left hemisphere, and no other main effects or interactions were revealed in this hemisphere. While the right hemisphere showed no main effects, it did reveal an Lag x Congruency interaction, $F(1, 17) = 4.89$, $p < 0.05$. A 1-way repeated measure ANOVA for this interaction by congruency was conducted and revealed the same main effect of lag. However, this effect was specific to the incongruent trials, $F(1, 17) = 7.81$, $p < 0.05$. A 1-way repeated measure ANOVA for the Lag X Congruency interaction by lag demonstrated a main effect of congruency in the short lag trials, $F(1, 17) = 6.48$, $p < 0.05$. There was a larger negative deflection in the neural signals for the congruent trials compared to the incongruent trials (Figure 7). This was the first analysis that revealed a congruency effect, and it is specific to the frontal electrodes in the right hemisphere for the more difficult short lag condition.

A follow-up 3-way repeated measure ANOVA by hemisphere was conducted for the 4-factor Hemisphere x Electrode x Condition x Lag interaction. This analysis demonstrated the same results from the previous interaction follow-up, with the main effect of lag in the left hemisphere ($F(1, 17) = 8.18$, $p < 0.05$) and a Lag x Congruency interaction in the right hemisphere ($F(1, 17) = 4.89$, $p < 0.409$. An additional main effect of electrode was also demonstrated, $F(1, 17) = 3.91$, $p < 0.05$. Since we are not interested in electrode effects and no other effects or interactions involving our conditions of interest were revealed, no further analyses were conducted.

Summary: In summary, there is a robust main effect for lag, specifically with trials in the long lag condition exhibiting greater amplitudes than those in the short lag condition (Figure 8). This main effect of lag is seen across the scalp, except for the right hemisphere frontocentral electrodes in the congruent condition. While the left hemisphere frontocentral electrodes showed the main effect of lag in both congruency conditions, the right hemisphere frontocentral electrodes demonstrated the main effect for lag only in the incongruent conditions. There is also a main effect of congruency that is confined to the right hemisphere frontocentral electrodes only in the short lag conditions.

Discussion

The main aim of the present study was to determine if children between the ages of 7- and 11-years old have the ability to retrieve temporal order information about autobiographical events. Event-related potential (ERP) recording was obtained to provide insight about the neural processes involved in the retrieval task. The temporal component of autobiographical memories is a defining feature of this memory type; however, the research on this topic is limited. The ability to recall a day’s events in the order in which they occurred is an important aspect of coherent planning and goal pursuit. These memories serve as measure of progress towards one’s goals, which in turn guides the planning of future actions and goals. Additionally, the temporal order of personal events outlines our personal narratives, and in turn, our autobiographies. We use these narratives to define how we view ourselves and how we want to be perceived by others.

Our participants engaged in a rich encoding task at the Fernbank Museum of Natural History where they took pictures of 120 objects. One to two days later the participants were presented with picture pairs and responded with which picture they believe they took first. During this decision making task, we obtained participant’s neural signals via ERP recording. This technology has been powerful in cognitive neuroscience research because it allows researchers to assess the underlying neural processes in response to mnemonic information. Differences in the grand average waveforms of two conditions can be interpreted as differences in neural processing related to cognition for the two conditions (Riggins et al., 2009).

The behavioral results demonstrate that the participants judged the order of the physical stimulus more accurately when the photo pairs were presented in the less difficult long lag condition. They performed the best in the long lag congruent condition, which was hypothesized to be the least difficult condition. For the ERP data, we hypothesized that there would be differential neural processing for correct versus incorrect trials, short versus long lag conditions, and congruent versus incongruent order of stimuli. Analysis of the grand average waveforms for correct versus incorrect responses, however, did not demonstrate differential neural processing. The results do support our hypothesis about lag and congruency effects, because both conditions exhibit differential neural processing. While the effect of lag was evident across the entire scalp, the effect of congruency was confined to the right hemisphere frontocentral electrodes in the short lag, congruent condition with congruent trials exhibiting higher amplitudes than incongruent trials.

Behavioral Results

In this present study, we supported our prediction that children would perform better during trials presented in the long lag condition compared to those presented in the short lag condition. These results are also consistent with the literature that has demonstrated greater accuracy in trials with longer time lags between stimuli (Fortin et al., 2002; Friedman, 1993; St. Jacques et al. 2008). St. Jacques et al. (2008) showed a near linear relationship between percent correct trials and time lag. Similarly, Fortin et al. (2002) demonstrated that rats performed better in the odor choice task when there was a longer lag between the odor pairs. Friedman (1993) also showed that accuracy for serial order judgments is associated with the space between events.

Our results demonstrated that performance did not differ from chance in the short lag condition. This may be because the short lag condition in which the pictures occurred closer together in time are more confusable, and therefore, may require additional cognitive demands in order to successfully retrieve temporal-order information about the events. The difficulty of this task was anticipated; therefore, participants were deliberately informed about the purpose of the study before they began the encoding task. Since there are 120 trials and each picture is a part of two of those trials, it was important for participants to be attentive from the start of the session. The strategy to tell the participants the goal of the study encouraged participants to be attentive from the beginning of the encoding task. It also motivated participants to strategically look at each picture and take into consideration how they think they may be able to remember it in a day or two (i.e. the physical color or orientation of the object and their own personal feelings while taking the picture).

We further assessed if differences within the cohort could have contributed to accuracy scores. Analysis of the two delay groups did not reveal any significant differences between the one-day and two-day delay groups. This finding demonstrates that this difference did not affect behavioral performance. We also analyzed if there was an effect of age on accuracy. The literature strongly supports age-related improvements in AM retrieval due to the development of the cognitive abilities in school-age children that enable autonoetic consciousness and memory retrieval (see Bauer et al., 2007; Friedman & Lyons, 2005; Picard et al., in press; Piolino et al., 2006). However, our analysis did not reveal an age-related improvement in performance. This may be due to the small sample size or the particular temporal-order task involved. Future studies should test a larger cohort of school-age children via different temporal-order tasks. Other tasks may involve asking participants to report retrieved contextual information after the testing phase in order to quantify how much was remembered by each age group. Older children may report more contextual details than younger children. Another possible variation is to include longer delays between the encoding and testing phases. Longer delays would introduce another level of difficulty which may emphasize the ability of the older children to retrieve temporal order information better than younger children.

In order to assess the behavioral results, it is important to understand the strengths and limitations of the photo paradigm used during the encoding task. A previous study demonstrated that the photo paradigm is feasible for children (Pathman et al., 2010). They obtained ERP recording that demonstrated the ability to use the photo paradigm to encode controlled AMs. These AMs exhibit differential neural processing compared to EMs and novel events. It is important to note that these AMs are not "pure" because the age of memories and emotional content are controlled in order to allow for controlled laboratory testing. However, this photo paradigm was used during the encoding task of an fMRI study, and these controlled AMs contain increased AM qualities, such as greater self-referential processing, visual imagery, and recollection (St. Jacques, 2008). Therefore, they can be classified as controlled AMs for the purpose of this present study.

A future study using the photo paradigm to encode "pure" AMs should be conducted. Compared to these controlled AMs, "pure" AMs are more memorable and contain more contextual information accessible for retrieval. In this future study, participant should take pictures of more personal life events over a controlled amount of time. After the picture taking period, the participants would be asked to retrieve temporal-order information regarding the life events by answering the same question used in this present study (Pathman & Bauer, in progress). Participants are predicted to have higher behavioral accuracy scores in this future study. ERP recording may also demonstrate greater neural activity associated with the increase level of self-involvement and emotional content.

ERP Results

The present study is only the second study using ERP to look at temporal-order information retrieval for autobiographical memories and the first study look at this particular age group. The exploratory nature of this study provides for exciting research, but limits the number of definite interpretations that can be drawn from the results. Therefore, the following are one set of speculations about what the ERP findings could signify. Also, ERP studies often select components of interest *a priori* based on the literature. However, due to the novelty of this research and very limited literature on retrieval of temporal-order information for autobiographical memories, the entire event duration (200ms before and 1700 ms after the stimuli is introduction) was analyzed.

A growing body of literature support the theory that components of the electrophysiological response can be divided into an earlier time window with components reflecting familiarity processing and a later time windows reflecting recollective processing (Riggins et al., 2009; Duarte et al., 2004; Friedman & Johnson, 2000). Familiarity processing, also referred to as the old/new effect in the literature, occurs in response to recognition of the stimuli. Retrieval of contextual information about events involves recollective processing. This distribution of familiarity and recollective processes has been demonstrated in the developmental ERP literature during middle childhood to adolescence (Cycowicz, Friedman & Duff, 2003; Czernochowski et al., 2005). Behavioral studies with amnesics exhibiting MTL damage further support this distinction, because these patients present with great deficits in recollection but not familiarity tasks (Aggleton and Shaw, 1996). These findings associate neural areas that are involved in temporal order retrieval to recollective processing. Therefore, since this present study focuses on the difficult task of retrieving contextual information regarding the temporal order of events, the later time window of 500-1700ms associated with recollective process was chosen for analysis in both processing methods.

The neural signals recorded using ERP reflect neuronal firing. Since neurons fire with the same potential each time, higher amplitude in ERP recordings is commonly interpreted in the literature as increased synchronous neuronal firing due to the recruitment of additional neural resources. This is the interpretation that will be used throughout this discussion as well. The interesting findings of the present study are each discussed individually.

No differential neural processing between correct and incorrect judgments

The results demonstrate no significant difference in neural processing between trials where participants made correct versus incorrect responses about the temporal order of the photo pair. This may be because the participants are asked to answer the same question for each trial, “Did you take picture A (top) before picture B (bottom) or the opposite, B before A?” Therefore, they may be using the same strategy for all trials and making the choice that they believe to be correct in all trials. No matter if the judgment was correct or not, participants chose the picture that they believed they took first. This interpretation is supported by the mixed results in the literature about activity surrounding accurate and inaccurate retrieval (Friedman & Johnson, 2000). While right prefrontal scalp activity was thought to reflect successful retrieval (Wilding and Rugg 1996, 1997), there is also evidence showing that the same region is activated when retrieval was unsuccessful (Trott et al., 1999). Future studies that assess the confidence of participants as they make each judgment may show the hypothesized differential neural processing.

Main effect in lags with trials in the long lag condition exhibiting larger amplitude

We do not yet know exactly how experiential processing is transformed into episodic information. While there are several separate theories for how experiential processing is transformed into episodic memory (see Baddeley, 2001 for one such theory), the exact mechanism is not yet discovered. Memory theorists do agree on, however, several concepts of how episodic memories are formed, stored, and retrieved. While the formation and storage of episodic and autobiographical memories is largely non-conscious and occurs via unintentional processes, recall of these memories requires conscious effort.

The finding that long lag conditions exhibit larger amplitudes coupled with the interpretation that an increased amplitude signifies the recruitment of more neural resources in order to make a judgment (accurate or not), calls into question how memory theorists view memory storage. Using the present views for memory storage processes, we initially theorized that since it would be more challenging to successfully retrieve temporal-order information for trials presented in the short lag condition, this condition would also show greater neural activity. However, the findings of this present study demonstrate the opposite with trials in the long lag condition exhibiting larger amplitudes. This finding can be supported by altering our view of memory storage. Instead of viewing the encoding task as one episodic event, participants may have viewed the picture taking task as two separate events with one before the break and one after the break. All participants chose to take the optional 5 to 10 minute break, which may have provided a natural mental breaking point in the encoding task. While the short lag trials always compare two photos that were taken within the same event, the long lag trials compare two photos that occur across the two events. Thus, trials in the short lag condition would require participants to recall temporal-order information about one of the events. On the other hand, trials in the long lag condition, which include one picture from before the break and one picture from after the break, would require participants to recruit neural resources that contain contextual information from both events.

This finding is consistent with previous studies in which participants retrieve words within a life event and across two life events (Reese et al., 2008; Habermas & de Silveria, 2008; Suzuki et al., 2002). Reese et al. (2008) demonstrate that the ability of recalling the chronology of life events in children increases into early adolescence, while Habermas and de Silveria (2008) show an increase in the ability to mark chronology across events into late adolescence. This concept of within versus between events has been heavily researched using different types of events, such as word lists. One such study is Suzuki et al. (2002) in which they demonstrated differential neural activations for the within list versus between list task (specific findings are discussed in the next section). Therefore, there is support in the literature for this interpretation. Neuroimaging studies should be conducted in the future to demonstrate if different brain areas or different regions within the same brain area are active when assessing contextual information across events compared to within an event.

It is important to note that the neural signaling in ERP is not a direct measure of the difficulty of a task, but instead in a representation of the neural activity involved in processing the stimuli. In support of this concept, it has been reported that children perform better when ordering the personal photographs from across events than within events (Burt et al., 2000). This finding is consistent with the behavioral results of this present study because we demonstrated that children were more successful at accurately retrieving temporal-order information for trials presented in the long lag condition (across events) than those in the short lag condition (within events). The trials presented in the less difficult long lag condition demonstrate the use of more neural resources not because they are more challenging but because they require different neural processing that that involved in the short lag condition.

Main effect of lag in the incongruent condition for right frontocentral electrode cluster

Incongruent trials: This robust main effect for lag where the long lag condition had larger amplitude than the short lag condition was seen across both hemispheres and all electrode clusters except for the right hemisphere frontocental electrodes in the congruent condition. It is not clear why these particular electrodes do not exhibit the effect of lag. The effect of lag may be confined to the incongruent condition in the right hemisphere frontocentral electrodes because this is the more difficult of the two congruency conditions.

Right frontocentral electrodes: This differential neural activity between the two hemispheres in the frontal regions is consistent with a previous neuroimaging study which reported that the “right prefrontal activity was associated with temporal order judgment of items between lists whereas left prefrontal activity was related to temporal order judgment of items within a list" (Suzuki et al., 2002; p. 1790). These findings further suggest that there are different neural processes involved in the retrieval of temporal order information within versus across events.

Main effect of congruency with higher amplitudes for the congruent condition

The results of this present study demonstrate that congruent trials exhibit higher amplitudes compared to incongruent trials. This may be because the congruent condition displays the picture pair in the same order in which the task question was phrased ("Is picture A (top) taken before picture B (bottom)?); whereas, the incongruent order represents the pictures with picture B on the top and picture A on the bottom. Therefore, the differences in processing between the congruent and incongruent trials in trials presented in the short lag condition in the right frontocentral electrodes may caused by prior experience. When the picture pair is congruent with the task question, the participants may recognize the picture pair in that particular order which may in turn elicit neural activations involved with this familiarity.

Main effect for congruency only in right hemisphere frontocentral electrodes

The finding that there is a congruency effect in the right frontocentral electrodes during a memory retrieval task is consistent with previous research that linked the left prefrontal cortex with episodic encoding and the right prefrontal cortex with episodic retrieval (Tulving et al., 1994). The finding that the familiarity response is responsible for the congruency effect seen is also consistent with previous findings that demonstrate the familiarity response is specific to right frontal regions. Neuroimaging studies that have investigated temporal-context memory have reported right dorsolateral pre-frontal cortex activation (Cabeza et al,, 1997; Konishi et al., 2002; Suzuki et al., 2002). The St. Jacques et al. (2008) further support the role of the right frontal regions in temporal order memory tasks and this present study's design is heavily based on that used in St. Jacques et al. (2008). Johnson et al. (1998a) conducted an ERP study in which they associated recognition to a far-frontal negative-going component during the 600-1000 ms time window. Several other ERP studies have demonstrated this same component beginning between 500 to 590 ms and lasting the entire trial duration over the right frontocentral scalp (Allan & Rugg, 1997; Johnson, 1995a; Wilding and Rugg, 1996, 1997).

It is interesting to note that we see the most differentiation between conditions during this 500-590 ms time window. The grand average waveform for a frontocentral electrode from Processing 2 demonstrates this differentiation (Figure 9). The differentiation seen here is consistent with both of the findings in this study in relation to the frontocentral electrodes. The lag effect is evident because the trials in the long lag condition exhibit a greater negative deflection compared to those in the short lag condition. The congruency effect is demonstrated by the trials in the congruent condition exhibits a greater negative deflection compared to those in the incongruent condition. Therefore, the long lag, congruent condition is pulling apart from the other conditions to the most.

Main effect for congruency and specific effect of lag in frontal electrodes only

It is noteworthy that the right hemisphere frontal electrodes exhibited the main effect of congruency only in the more challenging short lag condition and the main effect of lag only in the more challenging incongruent condition. These findings in the frontal electrodes suggest that in the more challenging conditions (short lag and incongruent), participants are required to retrieve additional contextual information in order to make a correct judgment. Therefore, in trials in the short lag condition, participants notice the physical representation of the stimulus. Likewise, during trials in the incongruent condition participants notice the time difference between events.

Although ERP data does not provide the spatial resolution required to draw conclusions about the underlying sources for the neural recordings, it is noteworthy that the condition effects evident in this study occur in the frontocentral scalp regions. This finding parallels the developmental literature that suggests that the ability to retrieve contextual information and recollecting processes increase with the development of frontal lobe structures (Cycowicz et al., 2001). There is, also, a growing interest in the field in making connections between the results of neuroimaging studies and ERP studies that address the same conditions in order to motivate future studies (see Friedman & Johnson, 2000 for review). Interestingly, most of the overlap occurs in the frontal scalp/cortical regions. For example, both ERP and fMRI studies demonstrate significant activations in the right frontal areas, which both groups attribute to “retrieval verification or monitoring processes” (Buckner et al., 1998b; p 163; see also Wilding, 1996). Therefore, the frontal cortical areas may be involved in the monitoring and verifying of temporal-order information in order to aid in the retrieval of autobiographical events.

Implications and future research

This study is one step toward understanding when the important ability of determining the correct order of life events develops and the underlying neural processes involved in such retrieval. This study provides insight about the ability of school-age children to retrieve temporal-order information for autobiographical events. The results demonstrated that the lag condition affects behavioral accuracy and also involve differential neural activity. Therefore, it must be an important factor when making judgments about the temporal order of personal memories.

Further research is required to investigate the interpretation that greater neural activity in the trials presented in the long lag condition is due to retrieval of memories across two separate events. One possible study could use a medium lag, in which the pictures in the pair are from within the same event (either before or after the break) but have a larger time lag such as 40 to 60 pictures. A difference between this medium lag condition and the original long lag condition could provide further evidence for this "within event versus between events" speculation.

Another speculation for the greater neural activity in the long lag condition could be that the children actually try to respond correctly for the trials in the long lag condition; whereas, they nearly give-up for the more challenging trials in the short lag condition. This would also provide insight about why the congruency effect is only seen in the short lag condition. Since the trials in the short lag condition are difficult, the children may be more likely to try in trials that are most familiar (i.e. in the short lag, congruent order). However, they may merely guess for trials in the more difficult and unfamiliar condition (short lag, incongruent). The picture pairs presented in the short lag, congruent condition were taken in near succession during the encoding task; therefore, these trials are the most likely to be classified as familiar. In order to demonstrate that this is not the case, a future study should collect confidence ratings in order to access if the children merely guessed or if they knew the answer. The comparison of only confident responses in the short lag condition and the confident responses in the long lag condition would provide a base level of effort. Additionally, this study did not collect reaction times, because participants were told to respond during the ITI only. A future study should collect reaction times for a more objective measure of confidence and potentially even familiarity.

Future research should be conducted on adults using the same paradigm and testing phase procedure in order to allow for direct comparison between children and adults. If adult accuracy scores are comparable to those of the children in this present study, then school-age children may have fully developed the capability for temporal-order memory retrieval. However, if adults perform significantly better than the school-age children in this study, then an older cohort of children should be used for further research on temporal-order memory retrieval. Additionally, the same study should be conducted with younger age groups in order to better understand the youngest age group that attains the ability to retrieve temporal-order memory for autobiographical events most comparable to adults.

The electrophysiological recording would be interesting as well because it would be the first ERP study to test this type of memory retrieval in adults using the photo paradigm. Adults may process the stimuli differently than children leading to differential neural activity patterns distinct from those seen in this study. This study would provide additional insight about whether the differential neural activity for both lag and congruency evident in this study are greater for children because this task is significantly more challenging for them, or if the differential neural activity is consistent across all ages because it is necessary for temporal-order information retrieval of autobiographical events.

Since there is minimal research on controlled AMs, and even less on retrieval of temporal-order information for this memory type, the findings of this study should be viewed as one of the initial steps for understanding the complexity of AM retrieval. The results of this study present interesting questions for further research, such as how memory theorists and developmental psychologists view the storage of time information in memories. Further investigation of these questions requires coupling these studies with studies that provide high spatial resolution. This is because while ERP provides the temporal resolution that is required to track the neural processing involved in retrieval of contextual details from memories, it cannot provide information about the neural source of the processing. Therefore, this same study should be performed with an increase in the density of electrode array (e.g. use a 64 channels of cap) in order to provide slightly better spatial resolution. Additionally, magnetoencephalography (MEG) can be used to increase spatial resolution because it involved a dense electrode array specific to a brain region. This technique can be further used to investigate the speculations made about the right frontocentral region made in this study. This current study could also be coupled with an fMRI study in order to further explore the neural regions involved in this retrieval task and speculated to demonstrate interesting neural activity trends in this study.

Conclusions

This present novel study contributes greatly to the developmental field investigating temporal-order memory in school-age children. The suggested future studies would provide further insight about the interpretations suggested in this paper, such as the effect of lag due to within event versus between events processing and the familiarity response evident in the more challenging short lag. Further investigation of the retrieval of temporal-order information for AMs is necessary to better understand when we attain the powerful ability to outline our pasts and shape our futures; thereby creating our autobiographies.

Appendix

Table 1

Conditions and Definitions

Condition		Definition
Response		Participants judgment about order of stimuli
	Correct	Response matches order of stimuli
	Incorrect	Response does not match order of stimuli
Lag		Time between the pictures in pair (measured in number of photos)
	Short	Pictures in pair were taken within 1-10 photos of each other during encoding task
	Long	Pictures in pair were taken within 40-80 photos of each other during encoding task
Congruency		Physical presentation of stimuli
	Congruent	Top picture was taken before bottom picture
	Incongruent	Bottom picture was taken before top picture

Table 2

Processing 1 main effects

	Main Effect of Electrode			Main Effect of Hemisphere			
	M	SD				M	SD
F3, F4 (Frontocentral)	-12989.8479	5307.94982		P3, P4, CP1, CP2, CP5, CP6 (Parietals)	Left	-3745.88427	7063.446
F7, F8 (Frontocentral)	-11945.6749	7866.48378			Right	-2315.14905	8127.633
FC1, FC2 (Frontocentral)	-12942.5494	5274.50599					
FC5, FC6 (Frontocentral)	-11141.0463	5175.1277					
P3, P4 (Parietals)	-2320.88234	6142.45943					
P7, P8 (Parietals)	5235.57805	4989.70578					
CP1, CP2 (Parietals)	-9046.29705	5806.01538					
CP5, CP6 (Parietals)	-5990.4653	4887.22574					
Fz (Midline)	-13593.8603	5039.13185					
Cz (Midline)	-12174.9094	5773.21837					
Pz (Midline)	-5728.731	6161.32364					

Table 3

Processing 2 main effects

	Main effects			
Electrode Clusters	Main Effect		Mean	SD
Midline	Lag			
		long	-11378.9454	6438.37185
		short	-10395.6224	5970.27855
Parietal	Lag			
		long	-3969.2116	7403.37015
		short	-2905.34474	6923.50342
Frontocentral	Lag			
		long	-13028.8056	6366.39292
		short	-11758.4891	5792.73468
Central	Lag	long	-9534.8377	5514.38679
		short	-8157.82185	5236.93624
	Electrode			
		C3, 4	-10880.6528	5118.41682
		CP1, CP2	-9415.9902	5280.22983
		CP5, CP6	-6242.3463	4643.41334

Figure 1

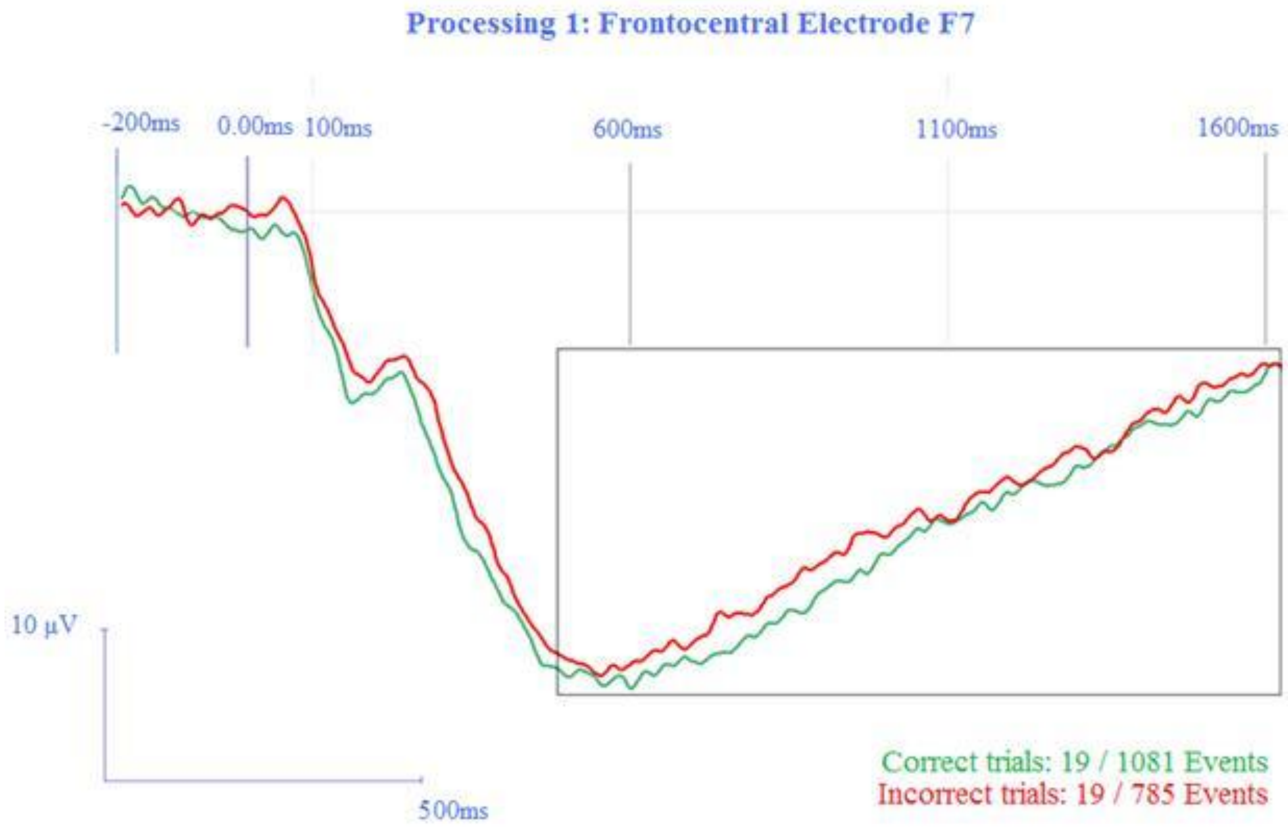
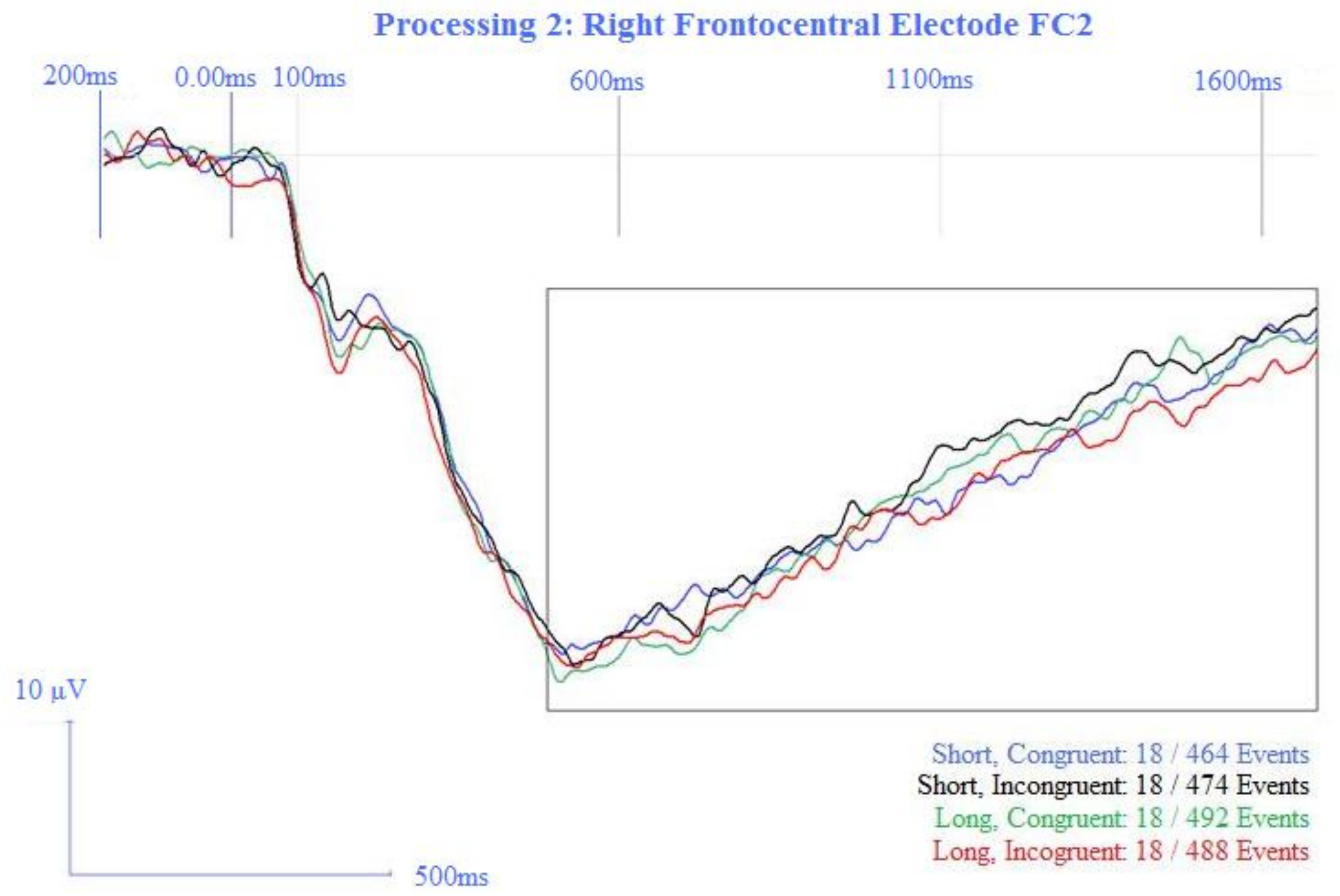
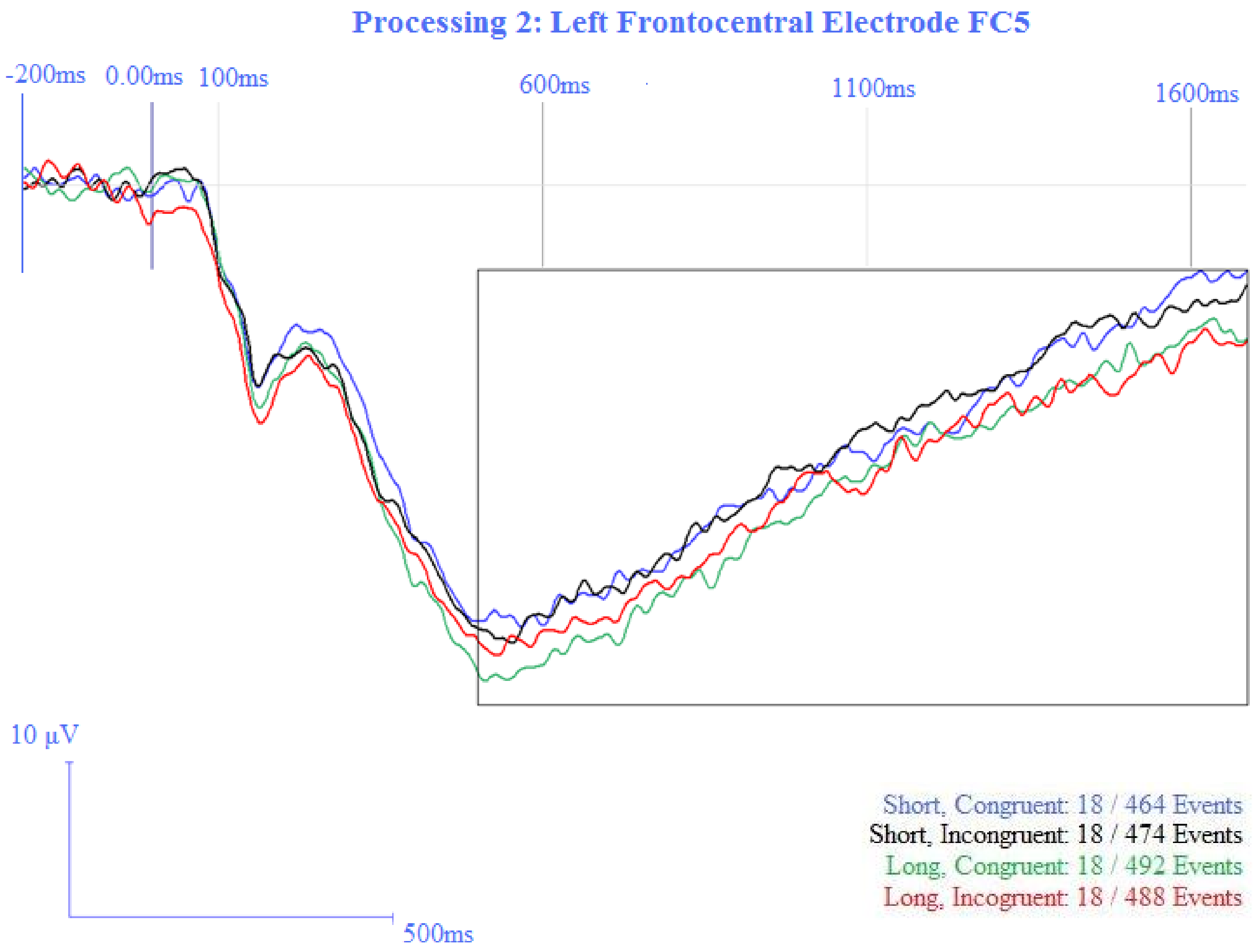

Processing 1: Frontocentral Electrode F7
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Correct trials: 19 / 1081 Events
Incorrect trials: 19 / 785 Events

Figure 2

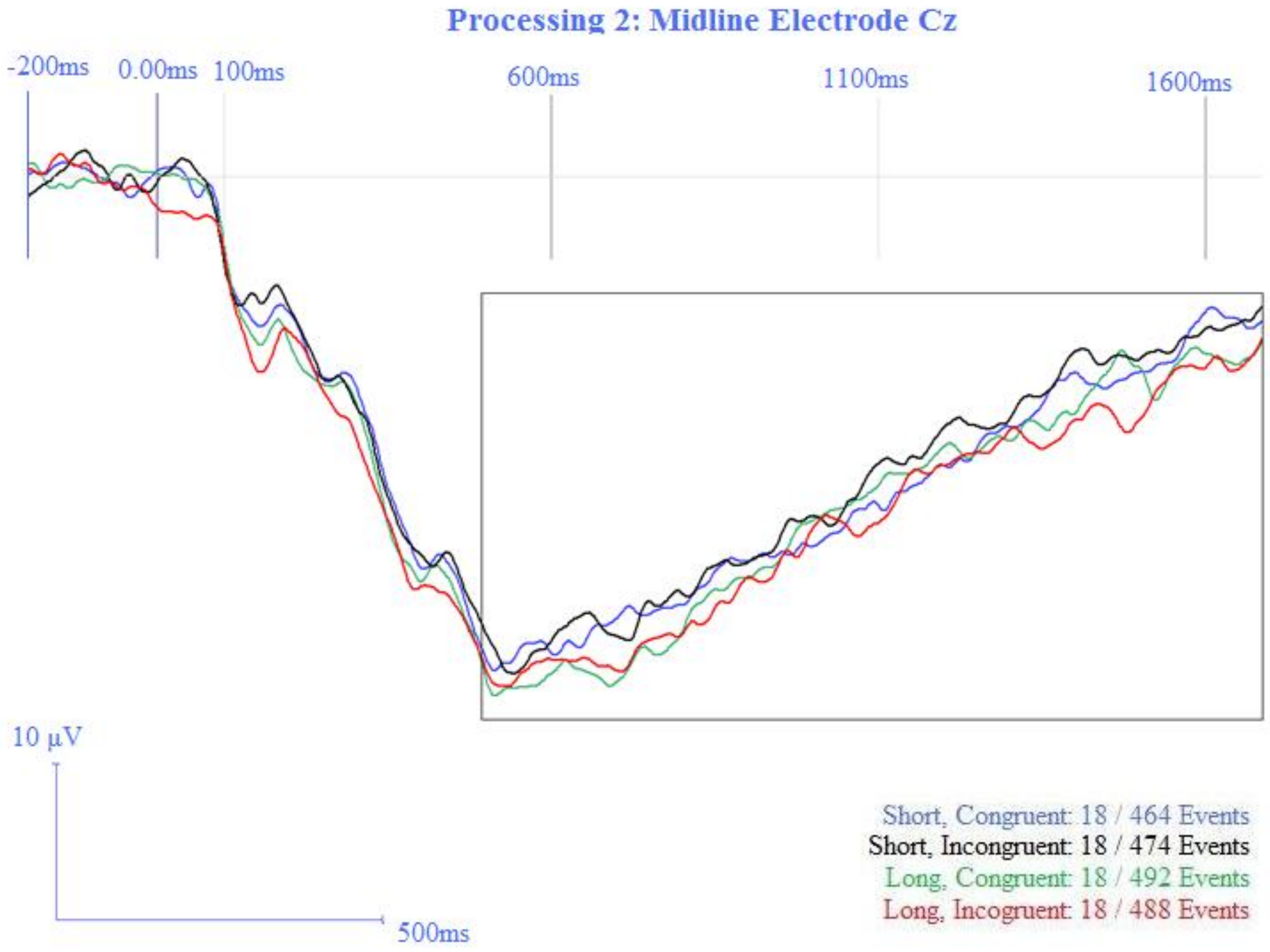
Panel A



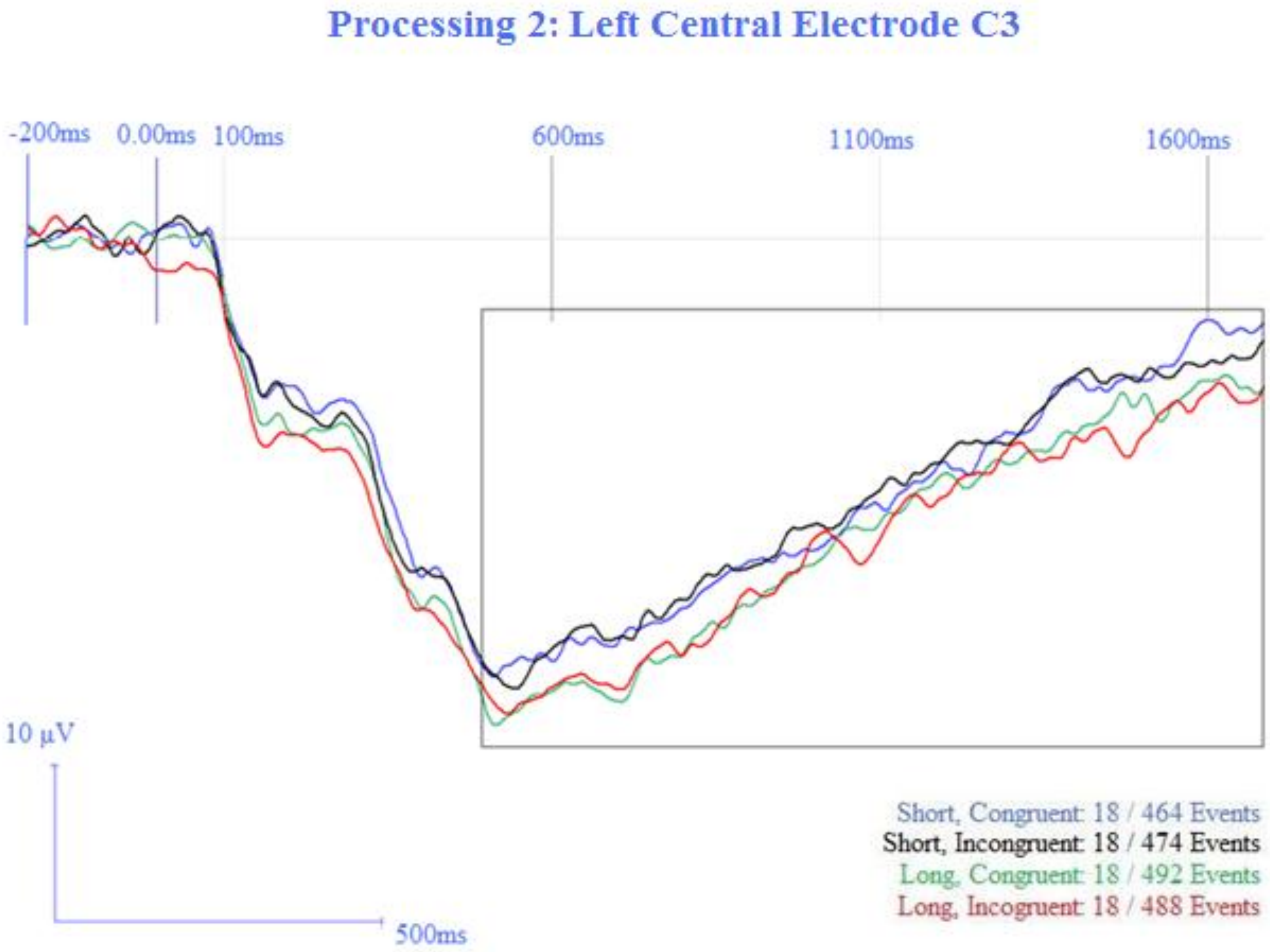
Panel B


Processing 2: Left Frontocentral Electrode FC5
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

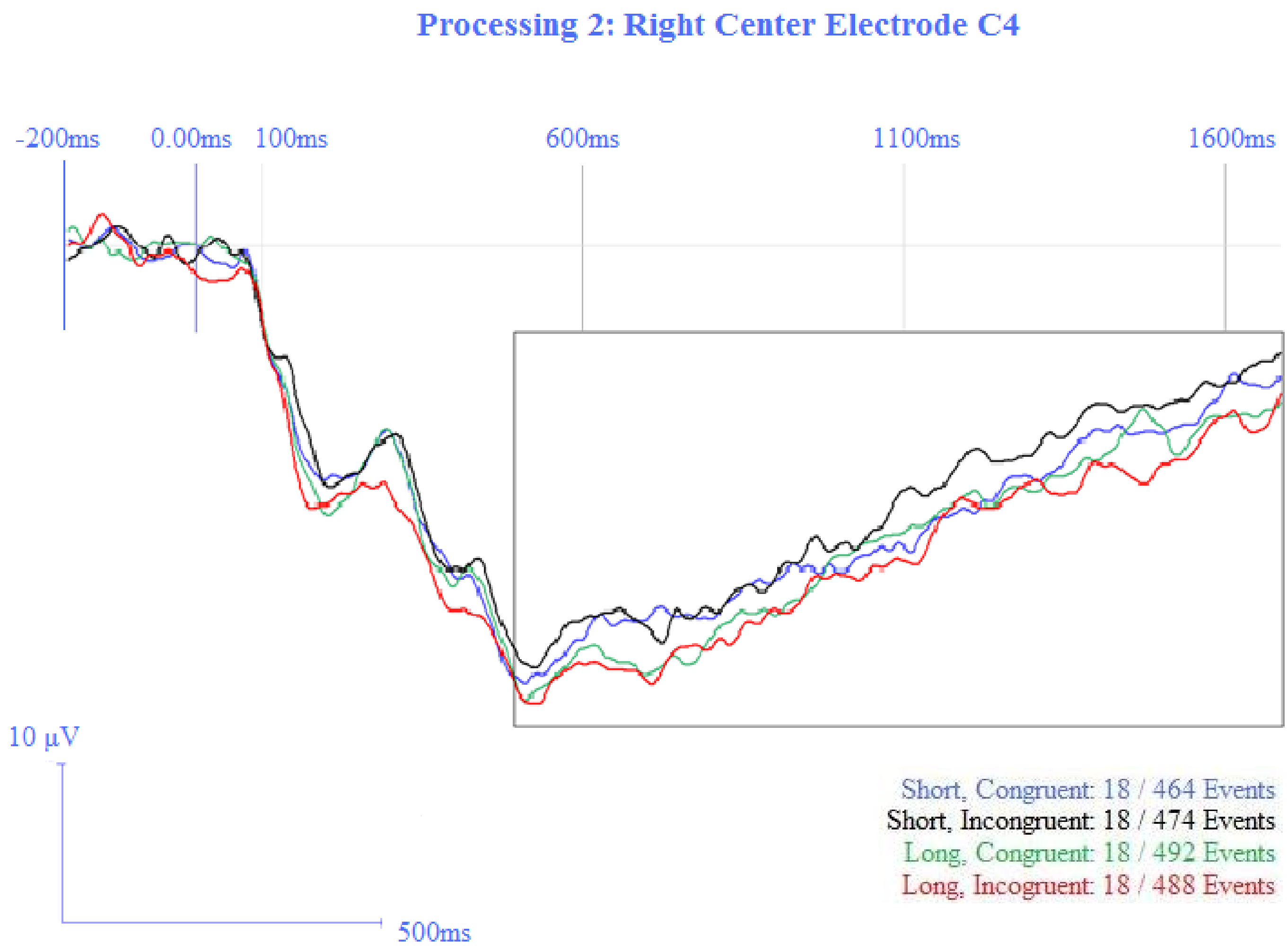
Panel C


Processing 2: Midline Electrode Cz
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

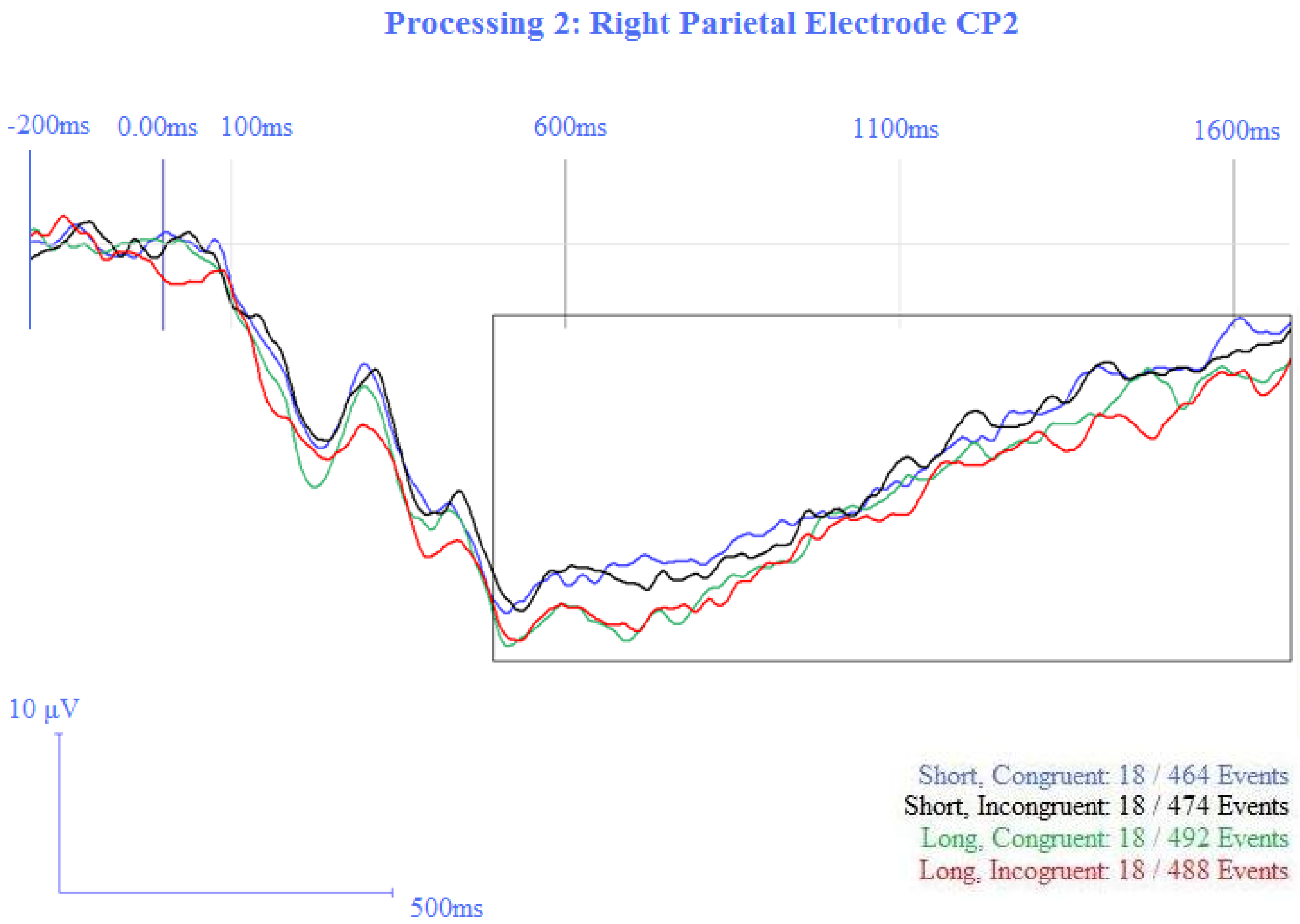
Panel D


Processing 2: Left Central Electrode C3
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

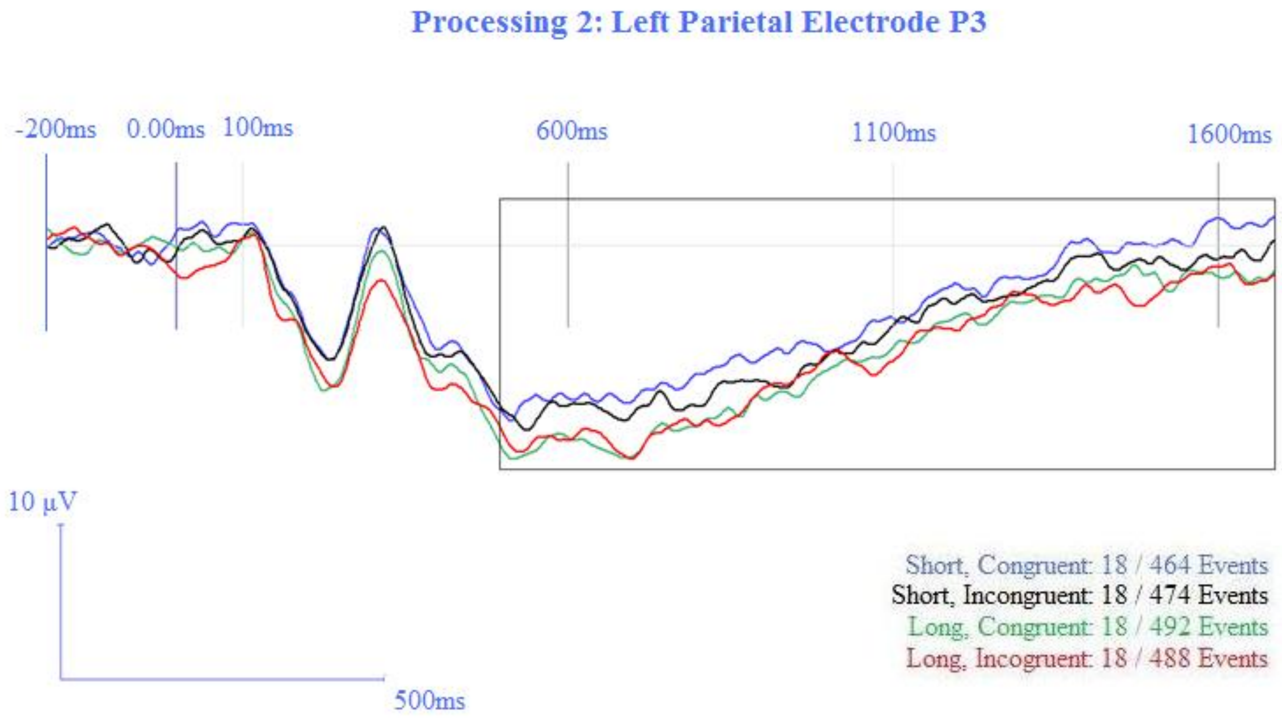
Panel E


Processing 2: Right Center Electrode C4
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

Panel F


Processing 2: Right Parietal Electrode CP2
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

Panel G



Processing 2: Left Parietal Electrode P3

Figure 3

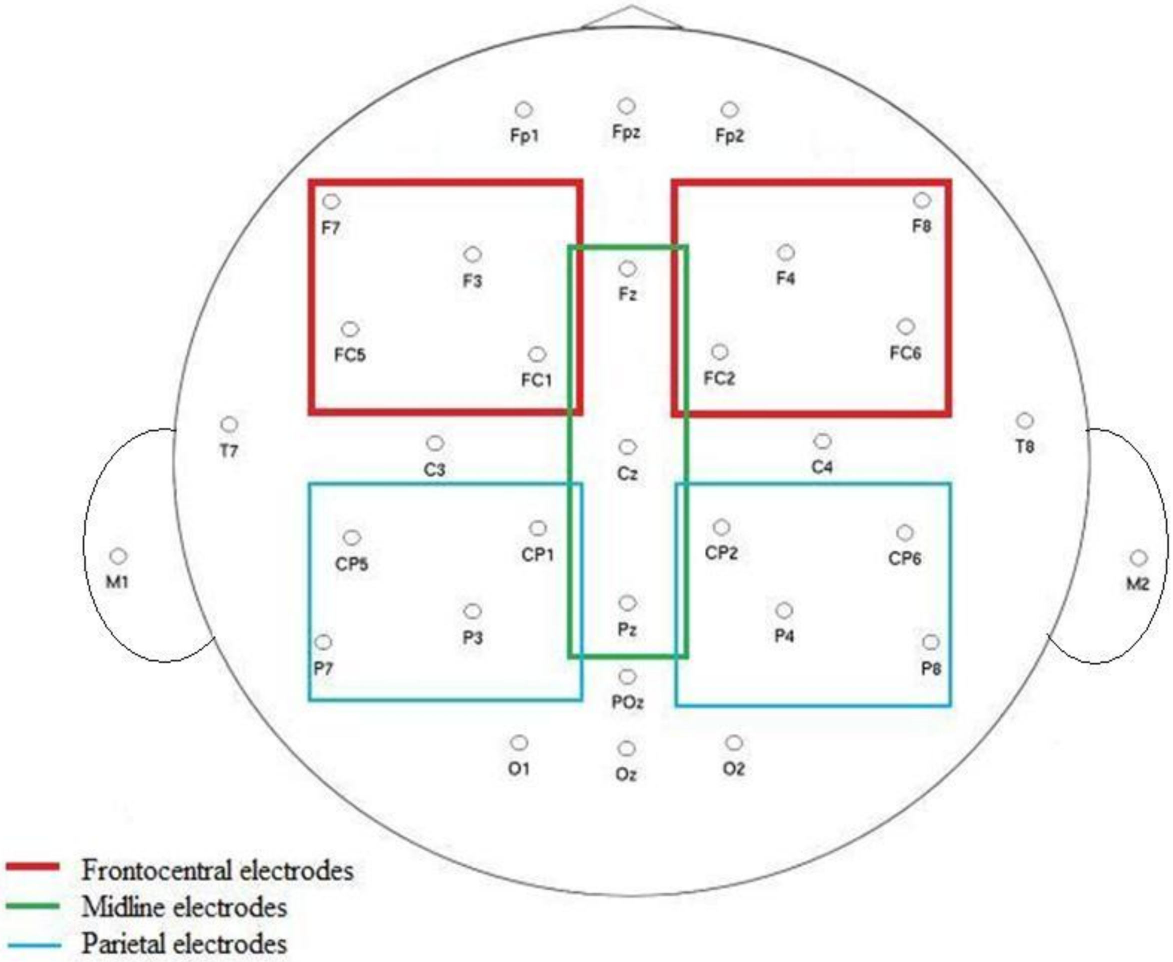

Fp1
Fpz
Fp2
F7
F3
Fz
F4
F8
FC5
FC1
FC2
FC6
T7
C3
Cz
C4
T8
M1
CP5
CP1
CP2
CP6
M2
P7
P3
Pz
P4
P8
POz
O1
Oz
O2
🟥 Frontocentral electrodes
🟩 Midline electrodes
🟦 Parietal electrodes

Figure 4

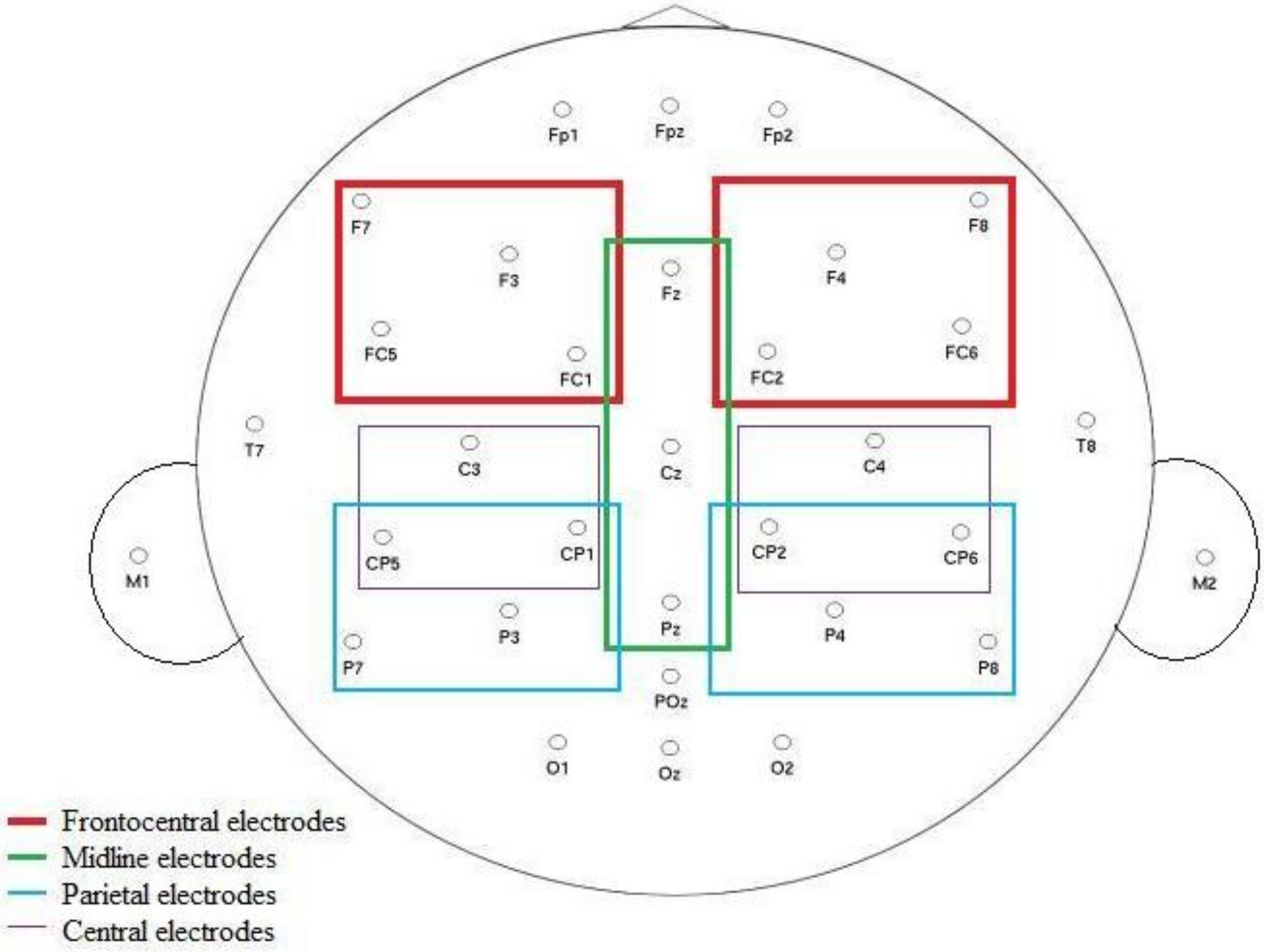

Fp1
Fpz
Fp2
F7
F3
Fz
F4
F8
FC5
FC1
FC2
FC6
T7
C3
Cz
C4
T8
M1
CP5
CP1
CP2
CP6
M2
P7
P3
Pz
P4
P8
POz
O1
Oz
O2
🟥 Frontocentral electrodes
🟩 Midline electrodes
🟦 Parietal electrodes
— Central electrodes

Figure 5

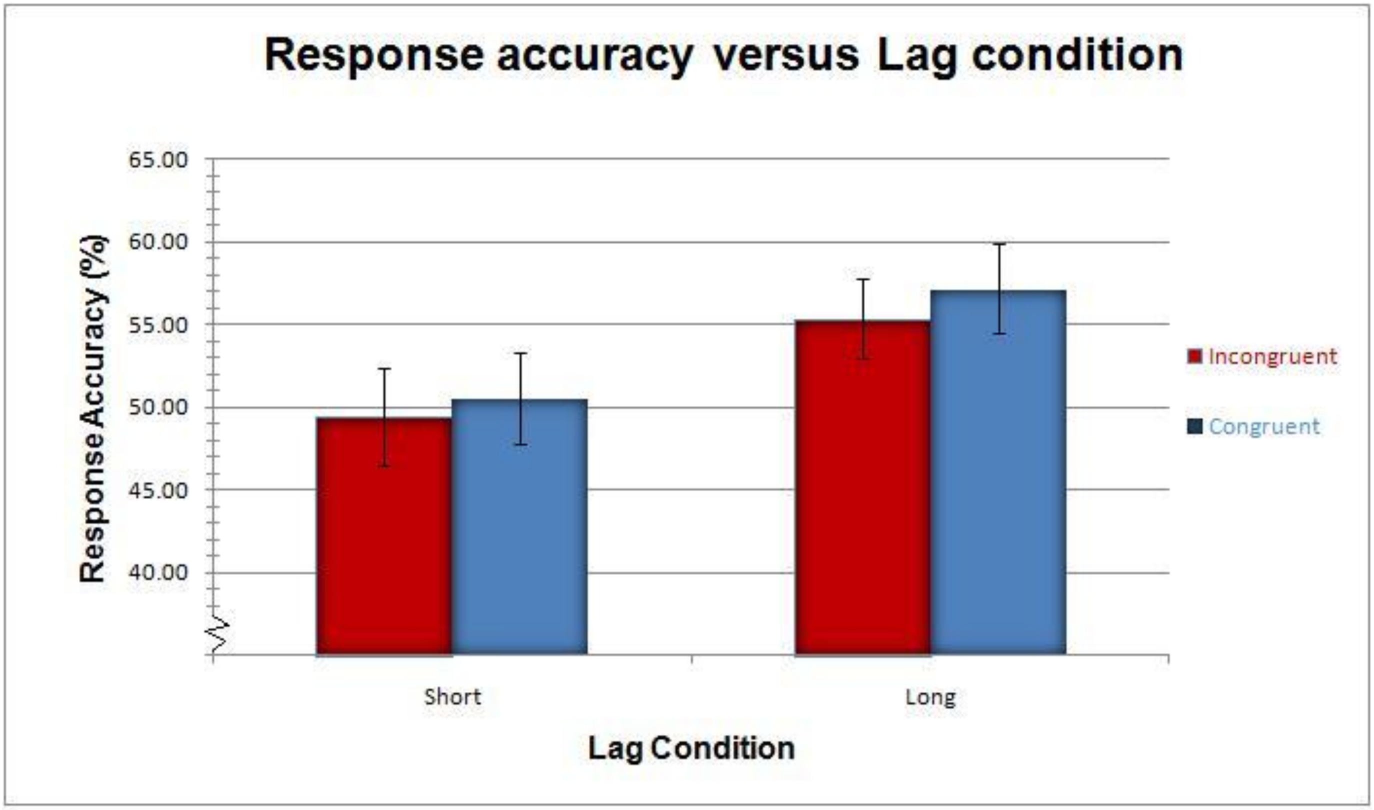

Response accuracy versus Lag condition
Response Accuracy (%)
65.00
60.00
55.00
50.00
45.00
40.00
Short
Long
Lag Condition
Incongruent
Congruent

Figure 6

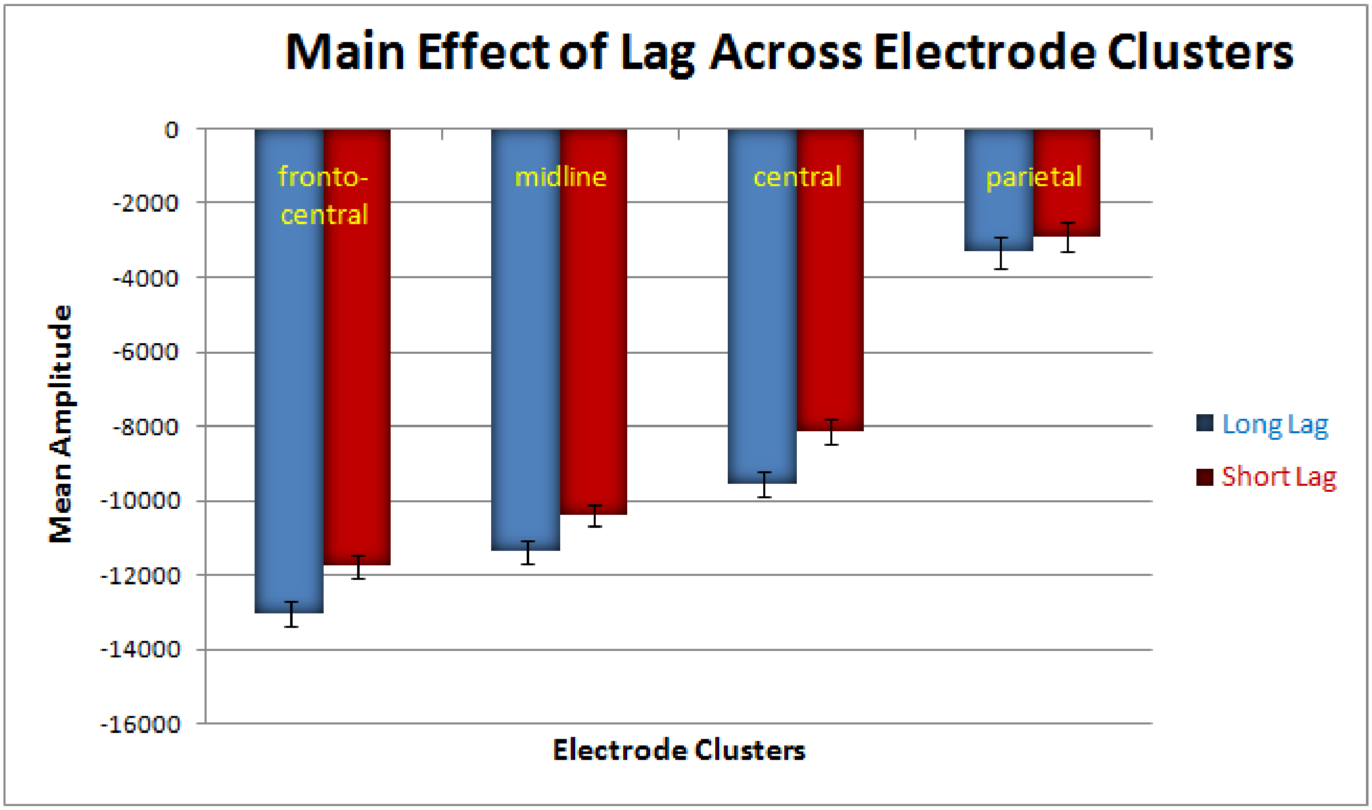

Main Effect of Lag Across Electrode Clusters
0
-2000
-4000
-6000
-8000
-10000
-12000
-14000
-16000
Mean Amplitude
fronto-central
midline
central
parietal
Electrode Clusters
Long Lag
Short Lag

Figure 7

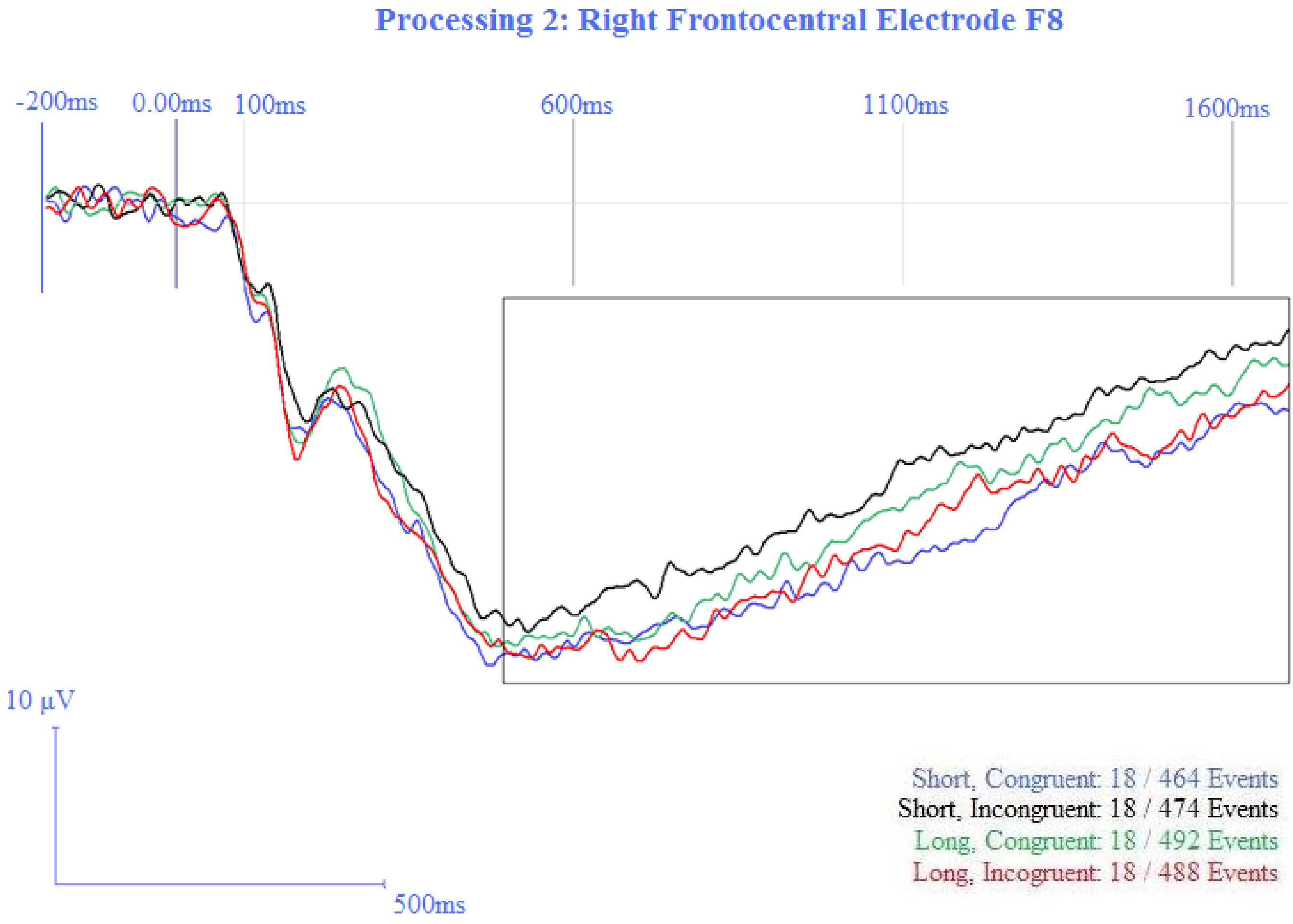
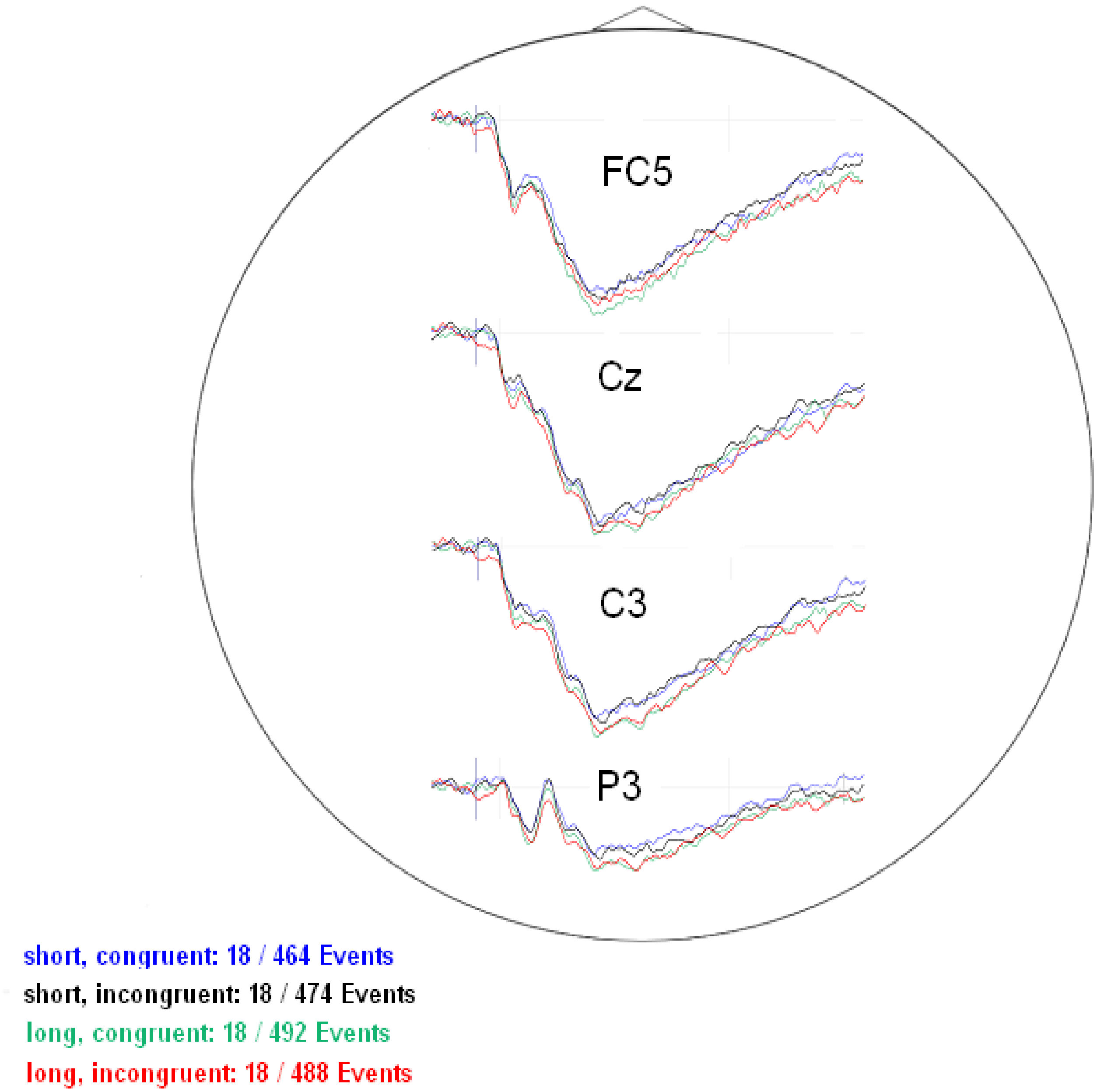

Processing 2: Right Frontocentral Electrode F8
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

Figure 8



Note. There image depicts one representative electrode per analyzed electrode cluster collapsed across hemisphere.

Figure 9

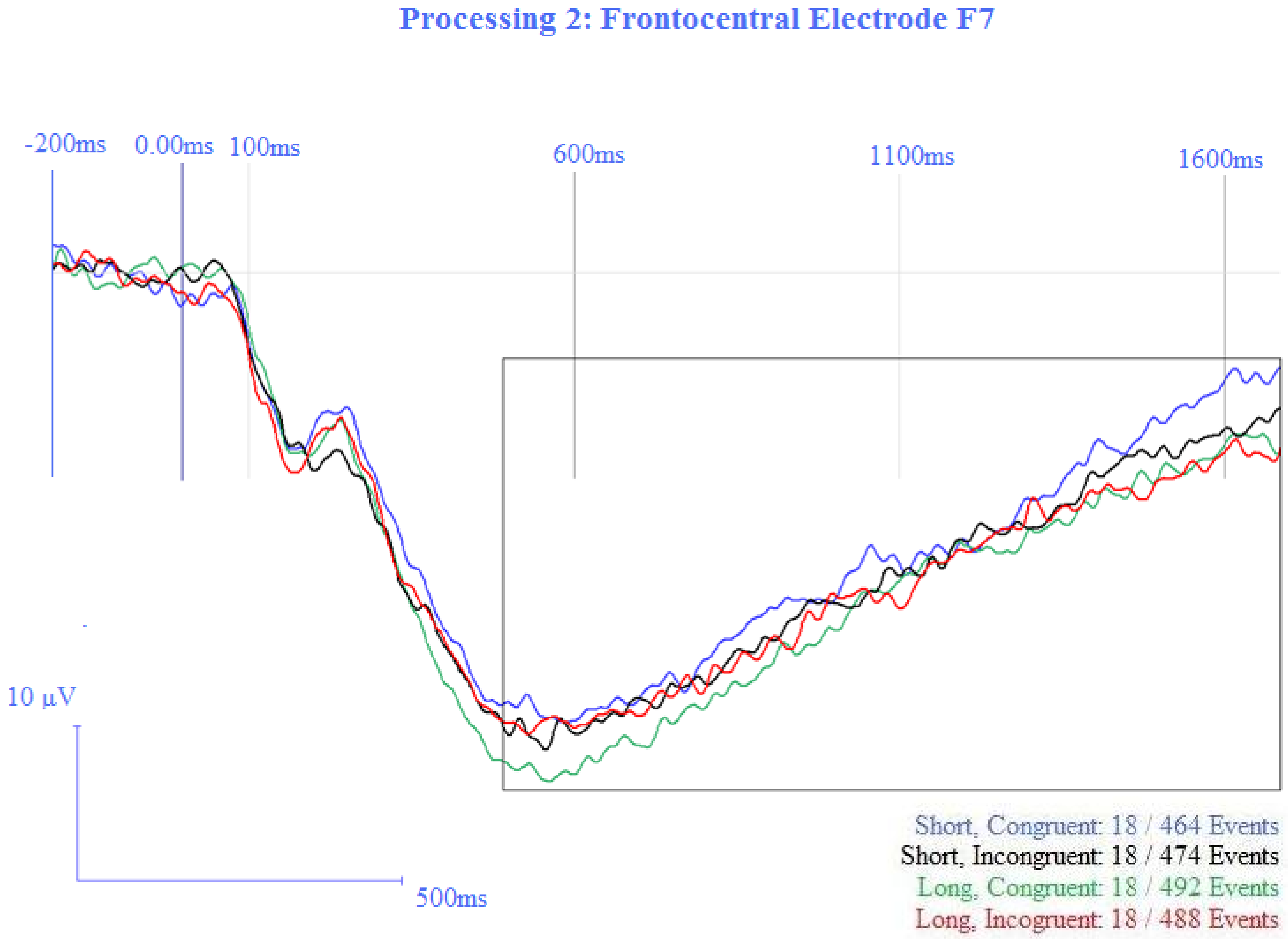

Processing 2: Frontocentral Electrode F7
-200ms
0.00ms
100ms
600ms
1100ms
1600ms
10 µV
500ms
Short, Congruent: 18 / 464 Events
Short, Incongruent: 18 / 474 Events
Long, Congruent: 18 / 492 Events
Long, Incogruent: 18 / 488 Events

Figure Captions

Table 1: Conditions and Definitions. The three conditions of interest (response, lag, and congruency) are defined in order to provide clarity throughout the paper.

Table 2: Processing 1 main effects. The significant main effects of electrode and hemisphere from Processing 1 analyses are reported including the means and the standard deviations. Note that values are measured in μV. Negative values indicated a negative deflection from zero line.

Table 3: Processing 2 main effects. The main effects from the Processing 2 analyses, including the consistent main effect of lag across the scalp, are summarized including the mean and standard deviations. Note that values are measured in μV. Negative values indicated a negative deflection from zero line.

Figure 1: Processing 1: Frontocentral Electrode F7. The grand average waveform for a representative electrode from Processing 1 is depicted. Although not statistically significant, a separation between the correct and incorrect conditions was seen in the waveform across the scalp. The black box outlines the time window of interest, 500-1700ms.

Figure 2: A representative electrode from each of the 7 electrode clusters analyzed in Processing 2 is presented. The long lag conditions exhibit larger amplitude (greater negative deflection) across scalp electrodes. The black box outlines the time window of interest, 500-1700ms

Panel A: FC2 from the right frontocentral electrode cluster; Panel B: FC5 from the left frontocentral electrode clusters; Panel C: Cz from the midline electrode cluster; Panel D: C3 from the left central electrode cluster; Panel E: C4 from the right central electrode cluster; Panel F: CP2 from the right parietal electrode cluster; Panel G: P3 from the left parietal electrode cluster.

Figure 3: Processing 1 electrode montages. The 5 electrode clusters analyzed for Processing 1 are depicted.

Figure 4: Processing 2 electrode montages. The 7 electrode clusters analyzed for Processing 1 are depicted.

Figure 5: Response accuracy versus Lag condition. The behavioral accuracy score means for each of the four conditions tested are graphed. The trials in the long lag condition exhibit higher accuracy scores for both congruent and incongruent orders. The error bars denote ± standard error. The bold horizontal bars indicate performance at chance level.

Figure 6: Main effect of lag across electrode clusters. The main effect of lag from all 3 Processing 2 electrode clusters (collapsed across hemisphere). For all of the electrodes, the long lag condition exhibits larger amplitude. Note that the error bars are ± standard error.

Figure 7: Processing 2: Right Frontocentral Electrode F8. The main effect of congruency that was demonstrated in the right hemisphere frontocentral electrode cluster in the short lag condition is shown through F8, a right hemisphere frontocentral electrode. In the short lag condition (blue and black), the congruent (blue) trials deflected more negatively compared to the incongruent (black) trials. This separation between the two conditions is evident in this illustration.

Figure 8: Robust effect of lag across scalp. A representative electrode from all 4 Processing 2 electrode clusters (collapsed across hemisphere) was selected in order to demonstrate the robust effect lag that is evident across the entire scalp.

Figure 9: Processing 2: Frontocentral Electrode F7. This study demonstrated a main effect of lag in which the long lag conditions exhibiting larger amplitudes. Also, a congruency effect was found in the frontocentral electrode with the congruent trials have larger amplitudes than incongruent conditions. This illustrated depicts both of these findings because the long lag, congruent condition (green) is pulling apart from the other 3 conditions during the time window of interest (500-1700ms).

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Arnold, S.E. & Trojanowski, J.Q. (1996). Human fetal hippocampal development: I. Cytoarchitecture, myeloarchitecture, and neuronal morphologic features. *The Journal of comparative neurology*, 367 (2), 274-92.

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