

A Multimodal Analysis of the Time-Course and Neuroanatomy of Real-World Comprehension  
and its Implications for Schizophrenia

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### **Abstract**

Deficits in real-world knowledge may underlie both abnormal comprehension and behavior in schizophrenia, contributing to patients' disability. Previous findings suggest that patients with schizophrenia may under-recruit dorsolateral prefrontal cortex (DLPFC) when comprehension requires knowledge of principles of goal-directed actions. One possible explanation for this is that patients were distracted by goal-irrelevant but salient aspects of visual scenes (e.g., patterns of object motion) and consequently adopted a less optimal comprehension strategy. Characterizing the rapid spatiotemporal neural dynamics during real-world comprehension can help to examine this possibility. Here we present high-temporal-resolution multimodal-imaging data in healthy participants that motivate applying this paradigm to schizophrenia. Electroencephalography (EEG) and magnetoencephalography (MEG) were recorded simultaneously while participants reported whether they understood the goals of activities depicted in short video-clips that included either usual or unconventional objects and object-specific or non-specific actions. Magnetic resonance imaging (MRI) was used to account for individual differences in cortical folding and head shape when analyzing EEG/MEG activity. Late positivity in event-related potentials revealed increased efforts for integrating unconventional objects and non-specific actions. Analysis of EEG and MEG statistical parametric maps localized activity in response to conventional objects and object-specific actions in the temporal cortex (implicated in the knowledge of objects) at ~300ms, while unconventional objects and non-specific motions were linked to later activity in the DLPFC. Thus, it is possible that familiar yet goal-irrelevant aspects of real-world activities, which are processed rapidly in temporal cortex, may draw processing resources away from the later DLPFC-mediated analysis.

*Keywords:* Real-world comprehension, schizophrenia, dorsolateral prefrontal cortex.

## A Multimodal Analysis of the Time-Course and Neuroanatomy of Real-World Comprehension and its Implications for Schizophrenia

Daily experiences serve as an exhibition of our astounding ability to be flexible in completing tasks. For instance, without an umbrella, we might cover ourselves with a newspaper in the rain. Without a piece of paper to write on, we are likely to use our hand. These behaviors are unique in that one's solution to a problem is not confined to a single target. With no prior exposure to an alternate solution, one is able to find an unconventional object and execute a task effectively. Deriving the neural correlates of this flexibility has been the subject of intense research over the past decade. In the following report, we aim to describe the current understanding and to advance the knowledge for this remarkable behavior. First, we will elaborate on the abilities of the prefrontal cortex to organize and prioritize incoming stimuli in working memory as well as to formulate a goal representation, as both are critical to respond flexibly. Localizing function within the prefrontal cortex, experiments have implicated the dorsolateral prefrontal cortex as the evaluative component of incoming stimuli and, therefore, crucial to identifying goal-relevant features for a flexible response. However, as evidence demonstrates the possibility of different neural mechanisms for relying on previous experiences and for responding flexibly, the goal of this study was to characterize those systems, to elucidate the relationship between them, and to gain insight into conditions for their activation.

The organizational and prioritizing capabilities of the prefrontal cortex, identified in working memory, are crucial elements for goal-directed comprehension. Prefrontal cortex activity in the context of encoding a memory has been revealed through dual-task paradigms. For instance, when subjects were asked to semantically organize a list of words for recall, a decreased level of organization in the presented list corresponded to increased activity in the left

prefrontal cortex (Fletcher et al., 1998a). From these observations, the prefrontal cortex can be linked to establishing structure of items during working memory encoding. This internal organization of list items plays a critical role in retrieval. Integration of the organization in working memory has been correlated with activation in the right prefrontal cortex. Subjects informed to pay attention to a list's structure as a memory aide (internally cued retrieval) revealed activity in the right dorsal prefrontal cortex during recall. In contrast, when given a category of the structured list during recall (externally cued retrieval), subjects were observed to have right ventral prefrontal activation. These experiments not only show the integration of stimulus organization in the right prefrontal cortex, but also sub-specialization during an online working memory task (Fletcher et al., 1998b). The prefrontal cortex, therefore, plays a critical role in the optimization of working memory, from encoding to retrieval, to generate a response.

However, while we often rely on learned usual features of our environment in generating responses, such behavior might not be advantageous in less routine contexts when usual attributes may be irrelevant. In these instances, a representation of the goal must be maintained to succeed in the task at hand. A classic case demonstrating the importance of goal-oriented thought occurs in the Stroop task (Stroop, 1935). In the task, participants are instructed to read the written color word or name the color in which the word is written. For instance, when viewing the word "RED" written in green color, a response for the reading condition would be "red", while the response for the color condition would be "green". Because of the dominance of reading words as opposed to naming their colors, the participant must make an effort in attending to the color of a word to succeed in the color-naming condition. Therefore, the goal in the color-naming condition is to pick the weaker yet task-relevant stimulus (word color) when it competes with the stronger, task-irrelevant stimulus (written word). Achieving the goal in the Stroop task

requires control of attention, which has been strongly associated with the prefrontal cortex (Funahashi, 2001). Therefore, activity in the prefrontal cortex during goal-directed comprehension presents a mechanism to choose the weaker, task-relevant stimulus over the stronger, task-irrelevant stimulus.

Yet, unlike the single stimulus-response associations in the Stroop task, real-world situations often feature a few critical stimuli that must be found amidst many distracting stimuli to initiate the correct response. Therefore, a mechanism must exist to evaluate incoming stimuli according to task-specific constraints and to select those that will help achieve a goal. This rule-based response selection has been investigated across visual, auditory, and spatial stimuli and activation overlap across the modalities has highlighted the dorsolateral prefrontal cortex (Bunge et al., 2002; Jiang & Kanwisher 2003). These experiments suggest the importance of the dorsolateral prefrontal cortex (DLPFC) in making a goal-related evaluation of stimuli. This function of the DLPFC has garnered much support through computational models. The DLPFC has been shown to maintain patterns of neural activity over time against other distracting inputs and can generate new rule-like representations (Rougier et al., 2005). The extensive network from the DLPFC to the rest of the cortex also enables it to modulate processing in other cortical areas (Miller & Cohen, 2001; Ridderinkhof et al., 2004). These aspects of the DLPFC support its suitability for flexible cognitive control and the ability to adapt in a dynamic environment.

Because some environments are familiar and others are not, an individual can either rely on stored representations of real-world knowledge or engage flexible comprehension, respectively. A previous study (Sitnikova et al., 2008) used electroencephalography (EEG) to dissociate these two cognitive capacities. EEG is a methodology that can measure differences in polarity and topography of electrophysiological waveforms between experimental conditions and

serves to reflect distinctions in the underlying neuronal sources (Kutas, 1993; Holcomb et al., 1999). The excellent temporal resolution of EEG permits researchers to time-lock the recording to the onset of the stimulus and measure brain activity as amplitude changes throughout the time course on the order of milliseconds.

Two waveforms of interest for the previous study's paradigm include the N400 and the P600. The N400 is a negative deflection of brain waves at approximately 400ms post-stimulus onset (Kutas & Hillyard 1980a; Kutas & Hillyard 1980b). In terms of neurocognitive processing, the N400 has been linked to violations of semantic expectations during both language and picture presentations (Nigam et al., 1992). Topographical distinctions in the N400 have been identified according to the stimulus presented. Violations during language comprehension exhibited a parietal-occipital scalp distribution (Friederici et al., 1993; Hagoort and Brown, 2000), while violations during picture presentation resulted in more anterior electrode sites demonstrating an N400 (Barrett & Rugg, 1990; Ganis et al., 1996; West & Holcomb, 2002; Ganis & Kutas, 2003). Therefore, evoked to language and picture stimuli, the N400 reflects semantic access, yet different topological distributions suggest access to different semantic memory networks (Holcomb & McPherson, 1994; Sitnikova et al., 2006). The modulation of the N400 amplitude has also been shown to be inversely modulated by the strength of the target stimulus to its prime (Kutas & Hillyard, 1980b; Grose-Fifer & Deacon, 2004). For instance, during presentation of visual scenes, N400 attenuation was reported to individual objects in congruous relative to incongruous conditions (Ganis & Kutas, 2003). These results suggest that the N400 indexes the difficulty of mapping stimuli onto semantic representations (Sitnikova et al., 2006). In contrast, the P600 marks a positive deflection of brain wave activity around 600ms. Early demonstrations of the P600 response were shown by syntactic ambiguities such as "The lawyer charged the

defendant was lying.” While initially interpreted as “The lawyer laid blame on the defendant”, the sentence would need reinterpreted to understand that “The lawyer who charged the defendant was lying” (Osterhout et al., 1994). Verb-argument violations have also been shown to elicit the P600 response. In phrases such as “At the basketball game the gym would throw,” the entity of a gym does not have the capacity to throw but the action of throwing (a ball, for instance) is strongly associated with the gym. The P600 amplitude was also found to increase as integration between the verb and noun argument became more difficult (Kuperberg et al., 2006; Kuperberg et al., 2007). From this evidence, the P600 likely reflects the mental effort to make sense of actions and entities according to goal-related requirements (Sitnikova et al., 2010). Therefore, for an incoming stimulus, the N400 describes how it maps onto stored semantic representations while the P600 describes how it is integrated for comprehension.

As a means to capture and dissociate the two cognitive capacities for real-world comprehension, short movie clips portraying daily activities were shown to participants. The silent movie clips consisted of a 6-s context depicting a common real-world activity and a 2-s congruous or anomalous final scene. The 6-s context of each video was designed to establish a goal and, therefore, to highly constrain the target object that would achieve the goal in the final scene. For instance, a man approaching a sink, washing his face, applying shaving cream, and reaching out of the scene at the end of the context suggests that a razor will be the target object in the final scene so that the man can shave. The congruous condition was formed by portraying the man shaving with a razor in the final scene. However, an anomalous condition was also created, whereby the target object in the final scene would violate the expected target object in light of the context’s goal. For instance, the anomalous final scene for the aforementioned context was the man rubbing a rolling pin over his cheek. With the presentation of real-world activities

captured in video clips, it was predicted that target objects in congruous endings would result in activation of stored representations while target objects in incongruous endings would fail to elicit a familiar response and would engage efforts of flexible integration. After averaging EEG responses across 20 healthy participants, a significant increase emerged in N400 response for the anomalous final scene relative to the congruous final scene (Sitnikova et al., 2003). This effect supports the N400 as a reflection of comprehension processes involving stored semantic representations of real-world associations (Van Petten & Luka, 2005). There was also significant late electrophysiological positivity (LPC) found for the anomalous relative to congruous movies. Like the P600, LPC effects have been reported in the processing of unusual real-world events, and might suggest reevaluation of initial expectations (Kuperberg et al., 2003; Xu et al., 2005). These findings with event-related potentials suggest that the two mechanisms for comprehension, relying on stored semantic associations or engaging flexibility integration, might have specific electrophysiological signatures during real-world comprehension.

Taking advantage of the spatial localization of fMRI, a follow-up study on these EEG findings has provided insight into areas specialized for the two neurocognitive processes in real-world comprehension. Significant activity for anomalous movies relative to congruous movies was observed in the lateral and ventral temporal, inferior prefrontal, and dorsolateral prefrontal cortices. While there was no way to differentiate between these activations with respect to the electrophysiological findings due to the poor temporal resolution of fMRI, functional connectivity studies have suggested that these cortical areas are part of separate cognitive streams. The activity in the lateral and ventral temporal cortex and inferior prefrontal cortex has been implicated as part of the fronto-temporal system, evidenced to activate upon access to semantic associations in memory (Van Petten & Luka, 2005). Conversely, the dorsolateral



prefrontal cortex has been linked to the fronto-parietal system, activated during tasks requiring the formation and maintenance of goal-related requirements. This latter system is predicted to be essential for flexible comprehension (Vincent et al., 2008). Augmenting this argument, the follow-up study included 20 patients with schizophrenia, who clinically demonstrate a loosening of thought, whereby consecutive, related ideas cannot be integrated into a coherent progression (American Psychiatric Association, 1994). Previous evidence has suggested a hyperactivation of semantic associations and an under-recruitment of the prefrontal cortex, specifically the dorsolateral prefrontal cortex, in sentential and visual comprehension tasks (Sitnikova et al. 2010). Adding to these observations, patients exhibited activity in the temporal and inferior frontal cortices, yet dorsolateral prefrontal cortex (DLPFC) activity was absent for anomalous movies relative to congruous movies. These findings suggest that functional localization exists for the two mechanisms of real-world comprehension and, more specifically, highlight the importance of the DLPFC in flexible integration.

Therefore, from these previous studies, evidence has demonstrated that the brain has both a capacity to activate real-world associations stored in semantic memory for trained behaviors and a capacity to engage executive control for flexible integration of novel objects in comprehension. It has also been suggested that the brain has areas specialized for each of these capacities. However, the spatiotemporal activation in these two processing streams has not yet been realized due to separation of temporally accurate (EEG) and spatially accurate (fMRI) techniques. Furthermore, what leads to the selection of the most advantageous mechanism in a real-world situation has not yet been addressed. Because healthy individuals are often able to respond adaptively in conventional and unconventional situations, a feature of the stimulus within its environment might lead to the induction of the appropriate mechanism. The aim of the

present study was to investigate the role of a stimulus feature to spatially and temporally dissociate these two neural mechanisms.

Eliciting real-world comprehension was achieved in a similar manner as in the previous study, yet the movies were characterized not only by the appropriateness of the target object in the final scene but also a feature of the target object. Combining the 80 videos from the previous study with an additional set prepared for this study, 150 movies were classified into a 2 x 2 design based on conventionality and pattern of motion of the target object. Conventionality addressed whether the target object in the final scene was a ‘usual’ or ‘unconventional’ solution to achieve the goal and was determined by goal-relevant properties of the target object. For instance, following a context where the goal is to hit a baseball, the ‘usual’ solution of a baseball bat has the properties of <sturdiness> and <length>, while the ‘unconventional’ solution of a map lacks those properties. The pattern of motion variable reflected an additional constraint by the action of the target object presented in the final scene. For instance, while a context might suggest the use of a knife to cut bread, the characteristic gliding movement of an iron over bread during the final scene might drive an individual to search for and activate semantic associations of the iron rather than staying focused on the goal of cutting. It has been shown previously that temporal cortex holds representations of mechanical and biological motion involved in object use (Hermsdörfer et al., 2007), and these motion constraints could have contributed to the N400 response and posterior temporal activity observed in the previous study. It is a possibility that the motion of the target object might play a role in determining which parts of the cortex are activated and whether flexible integration in the DLPFC is engaged during the video comprehension task. Therefore, each video was classified according to whether the target object

in the final scene exhibited a ‘typical motion’ or ‘non-typical motion’ as well as whether it was the usual or unconventional solution for the goal constrained by the context.

To observe spatiotemporal dynamics during this real-world comprehension task, the brain activation in response to the target object of each movie was measured by simultaneous electroencephalography (EEG) and magnetoencephalography (MEG). Because every electric field produces a perpendicular magnetic field, MEG recordings serve as a second method to localize dipoles (opposite charges separated by a certain distance). While the EEG specializes in detecting dipoles on the cortical surfaces of the gyri (radial dipoles), MEG specializes in detecting dipoles located deep in the walls of the sulci (tangential dipoles). And, while EEG can convey more signals with gyri being closer to sensors that are not as sensitive to external sources of noise, EEG signals are smeared when the currents pass through the skull and permit MEG to have 30% better dipole localization (Cohen and Halgren, 2009). This superior localization of MEG has been shown in the detection of the N100 response to auditory stimuli (Rogers et al., 1990). Therefore, looking at the activation in EEG and MEG statistical parametric maps, we aimed to accurately capture the extent of cortical activity generated in response to target objects in the video clips. A structural MRI was also obtained from each participant to factor in differences in cortical folding and head shape in EEG and MEG modeling. Furthermore, Sharon et al. (2007) demonstrated that combined EEG and MEG can provide a closer approximation to fMRI than either modality alone. Therefore, collecting simultaneous EEG/MEG also offers the potential for better localization. With EEG and MEG modeling to identify sources of activation and event-related potentials from EEG waveforms to monitor electrophysiological activity over a time course, this study aimed to examine the relationship between the N400/LPC effects and the brain areas associated with the two processing streams.

For how this paradigm would dissociate the two neurocognitive streams temporally and spatially, we predicted that target objects that were conventional or exhibited typical motion would lead to early activation of the semantic access stream in the temporal cortex while target objects that were unconventional or exhibited non-typical motion would lead to later activation of the flexible comprehension stream. Because the N400 in EEG indexes the difficulty in mapping incoming stimuli onto representations in semantic memory, the N400 amplitude would increase for both unconventional movie endings relative to their corresponding usual endings. However, because action-object associations are also stored in semantic representations, we expected that the unconventional endings with typical motions would be easier to map and thus evoke an attenuated N400 relative to the unconventional endings with non-typical motion. Further, as the late positivity has been shown to index the integration effort for flexible comprehension, late positivity effects would be observed for both unconventional endings relative to their usual counterparts. However, because the typical motion of a target object might facilitate access to stored semantic representations rather than initiate activity for flexible integration, we expected that the amplitude of the late positivity would be decreased for unconventional/typical motion movie endings relative to unconventional/non-typical motion movie endings. In identifying sources of activation with the spatial data from EEG/MEG modeling, we hypothesized that the pattern of motion would dissociate the brain regions for access to semantic representations and for flexible integration. As fMRI BOLD activity in the fronto-temporal system has been suggested to underlie comprehension based on strong, semantic associations (Van Petten & Luka, 2005), we predicted that action-object associations present in the unconventional/typical motion condition would evoke increased activation in the temporal and inferior frontal cortices compared to the unconventional/non-typical motion condition. In

contrast, as the fronto-parietal system has been implicated in flexible comprehension (Vincent et al., 2008), we expected that the absence of such associations in the unconventional/non-typical motion movies would result in increased activation of the DLPFC and parietal cortex relative to unconventional/typical motion movies. Altogether, by manipulating conventionality and target object motion, we predicted a complementation of the electrophysiological and spatial localization data to dissociate the semantic access and flexible integration processing streams.

From these hypotheses, we suggest the possibility that these two neurocognitive streams for real-world comprehension are mutually dependent and, therefore, cues activating the semantic access processing stream might draw resources away from flexible integration. In a situation where an unconventional object must be used to achieve a goal, attempts by the temporal cortex to map all stimulus features onto a stored semantic representation will flounder and the evaluation of the stimulus only on its goal-relevant features by the DLPFC will not be engaged. Any disability in the activation of the DLPFC or hyperactivation of temporal cortex, as evidenced in schizophrenia, could further exacerbate a lack of activation of the flexible integration processing stream. Therefore, by conducting this study in healthy participants and eventually schizophrenia patients, we might be able to better explain and even assess difficulties in real-world comprehension and in flexible behavior.

## Methods

### *Participants*

Thirteen native English-speaking volunteers (11 men, 2 women; mean age = 23.46 years) with normal or corrected-to-normal vision served as participants. Despite recruiting 13 participants, EEG modeling could not be completed for 5 participants and MEG modeling could not be completed for 4 participants due to technical complications in data acquisition.

### *Materials*

One hundred and fifty color, silent movie clips were filmed using a digital Canon GL1 video camera and edited using Adobe Premier 7.0 software. In all the clips, two or more events from a common goal-directed real-life activity (e.g. cooking, gardening) with one to three actors constituted a 6-s context, which was followed by a 2-s final scene in which a single actor manipulated a target object. The context and final scene for each movie was separated by a cut, and spliced together with no blank frames in between. The scene change at the cut was made to appear as natural and undisruptive as possible by shooting consecutive events throughout the movie from different angles (e.g. a 30° change in perspective, or changing from a long-distance shot to a close-up shot). All target objects (e.g. a knife) were clearly visible and were engaged into action (e.g. cutting) in the center of the frame at the onset of the final scene. The target object did not appear in the clip before the final scene. ERP recordings were time-locked to the onset of the final scenes.

The movie clips were constructed in pairs such that the same context could be used with one usual final scene and one unconventional final scene. For the unconventional final scenes, the target object was not commonly associated with the activity in the context nor did it have an affordance for the central action constrained by the context. This assertion was confirmed by a pre-test study: a separate group of 14 healthy participants (7 men, 7 women; mean age = 18.57 years) watched 82 movies for which cloze probability data had not been collected in Sitnikova et al. (2008). The participants watched only the context of each video, and were asked to describe the event (action and engaged objects) to come next. The pre-test demonstrated that the target objects used in the usual movie endings all had greater than 60% cloze probability while all unconventional movie endings had “0” cloze probability. Further, any of the actions described by

the participants for the expected target object could not be afforded to the unconventional objects. Filler movies were characterized by target objects that were unconventional, yet had affordances to serve the action constrained by the preceding context.

Another pre-test was used to assign the movies to typical motion or non-typical motion categories. Participants watched the full 8-s of the 150 movies containing the unconventional or filler endings, and were prompted to describe the action, objects, and goal in the final scene. For the movies with unconventional endings, description of the target object's action with a specific verb (e.g. ironing) classified the movie into the typical motion condition. Description of the action with a non-specific verb (e.g. moving, putting, or placing) classified a movie into the non-typical motion condition.

The movie clips were counterbalanced such that each target object for a usual final scene also served as a target object in an unconventional or filler final scene. The clips were arranged into two lists of 150 movies, each containing 30 movies of each condition (Figure 1). Clips were assigned to each of the two lists such that no context or final scene was included twice in one list. However, between both sets, each target object appeared in both usual and unconventional movies.

### *Behavioral Procedure*

Participants were first seated in the MEG magnetically-shielded room (Cohen & Halgren, 2009) approximately 160cm from the projection screen, elevated 76cm from the floor. During stimulus presentation, the participants viewed movies in a 12cm x 8cm frame against a black background and in the center of the screen (2.15° visual angle). Half of the participants viewed List 1 and the other half viewed List 2. The movie clips in each list were split into 6 presentation blocks, each consisting of 25 movies in pseudorandom order. Ten additional clips were used in a

practice session. The silent movies were shown at a rate of 30 frames per second, and each movie was 8-s in duration with a 6-s context and 2-s final scene.

Participants were instructed to keep their eyes in the center of the screen through each set of movies. Participants were informed that a yellow frame would appear when the final scene of each movie began, and were instructed to respond with a button box to report whether they could make sense (right index finger) or could not make sense (right middle finger) of the goal in the final scene. The participants were encouraged to be flexible, pressing with their right index finger if any thought came to mind for how the final scene could make sense. In each trial, the participants first viewed the 8-s movie. Following 100ms after the offset of each video clip, the participants were prompted for their response by a “?” with a 900ms duration. After a 1000ms inter-stimulus interval, a 1000ms fixation cross appeared. Participants were instructed to avoid blinking from the onset of the final scene until this fixation cross. The screen returned to a black background for 1000ms before the next movie trial began.

#### *Data Acquisition* (adapted from Sharon et al. 2007)

##### MEG/EEG –

The MEG data was recorded with a Vectorview (NeuromagElektta Oy, Helsinki, Finland) MEG 306-sensor array organized in 102 triplets, each with one magnetometer and two orthogonal planar gradiometers. EEG was simultaneously recorded with a 70 –electrode (Ag/AgCl) EasyCap EEG cap (Figure 2). Eye movement was monitored by bipolar electrode pairs for horizontal and vertical electrooculogram (EOG) recordings. Vertical EOG electrodes were placed above and below the left eye, and horizontal EOG electrodes were placed lateral to each eye. Scalp electrodes were referenced to a left mastoid electrode. Four head position indicator (HPI) coils were positioned on the EEG cap, two symmetrical anterior coils and two



slightly asymmetrical posterior coils. The 3D locations of the three cardinal landmarks (nasion, left and right periauriculars), HPI coils, EEG electrodes, and 100 additional points over the scalp were digitized with a Fastrak system (Polhemus, Colchester, VT) for registration of MEG/EEG data onto a structural MRI. Before entering the magnetically shielded room, the subject was magnetically neutralized using a degaussing coil. After each movie block, recording was stopped and an additional HPI reading was taken. The MEG/EEG data was gathered and saved at a sampling rate of 600Hz and a recording passband of 0.1-200Hz.

#### Structural MRI –

Data were collected with a 3-T TIM Trio scanner (Siemens Medical Solutions, Erlangen Germany) across three scans, each lasting approximately six minutes. Each participant had one standard structural magnetization-prepared gradient echo (MPRAGE) scan (651Hz/pixel, flip angle=7°, TR/TE/TI = 2.53s/1.1s/1 s, 2x GRAPPA acceleration) and two multi-echo multi flip angle (5° and 30°) fast low angle shot (FLASH) scans (651 Hz/pixel, TR=20ms, TE=(1.85+n2.0m ms,  $n = 0, \dots, 7$ , 3x GRAPPA acceleration). One-hundred and seventy-six contiguous 1-mm-thick sagittal slices were captured at a 1mm<sup>3</sup> isotropic resolution. The T1 scans differentiated cortex from subcortical structures in MEG and FLASH scans differentiated skull and skin layering in EEG.

#### *Data Analysis*

MEG and EEG data were analyzed with MNE software (<http://www.nmr.mgh.harvard.edu/martinos/userInfo/data/sofMNE.php>). MPRAGE sequence data was used to create MRI reconstructions in FreeSurfer. Using MRILab, head-dense registration of MRI data was achieved with fiducial landmarks, digitized HPI coils, EEG electrode locations, and additional scalp surface points. These data were analyzed to create a

COR transform. The FLASH scans were used to create a BEM mesh in Seglab. The BEM mesh, the COR transform, and average MEG or EEG (filtered at 15Hz) were integrated into a forward solution. The forward solution and a covariance matrix, derived from the MEG data, were put into an inverse operator to generate the inverse solution and subsequent activation maps.

## Results

### *Behavioral Data*

The number of comprehended movies were averaged across participants ( $n = 13$ ) in each of the five movie conditions and means are shown in Table 1. As expected, responses of comprehension were significantly higher to usual movies than to unconventional movies for the typical motion condition,  $t(24) = 16.04$ ,  $p < .0001$ , and non-typical motion condition,  $t(24) = 18.94$ ,  $p < .0001$ . Responses to usual movies with typical and non-typical target object motion were not statistically different,  $t(24) = .1640$ ,  $p = .8711$ . Similarly, no difference was found in the comparison of typical and non-typical motion unconventional movies,  $t(24) = .6300$ ,  $p = .5346$ . Interestingly, the average number of comprehension responses to the filler condition was intermediate relative to conventionality, observed to be lower than both usual conditions and higher than both unconventional conditions.

### *EEG: Event-related potentials*

When averaging across the thirty videos for each condition, significant effects were observed concerning the N400 and late positivity. ERP averages ( $n = 10$ ) were generated for the left frontal AF3 electrode to examine N400 effects and for the central Cz electrode to examine late positivity effects. First, with regard to the N400, a negative deflection of the average ERP was observed to span 200ms-500ms. Based on this range, the early negativity was examined

according to each variable. For instance, a conventionality effect was observed with greater negativity to unconventional movies than to conventional movies in the typical motion conditions, and this effect was present, albeit less prominent, for non-typical motion conditions (Figure 3A). In a complementary analysis, the effect of motion was examined. While no difference was observed between typical and non-typical motion movies for the conventional conditions as expected, increased negativity was found for typical motion movies relative to non-typical motion movies in the unconventional conditions (Figure 3B).

Moreover, with a peak in negativity observed at 475ms, a  $2 \times 2 \times 5$  repeated measures ANOVA was conducted on data from 9 participants to analyze the effects of conventionality (usual or unconventional), target object motion (typical or non-typical), and midline electrode position (Afz, Fz, Cz, Pz, or Poz) on the voltage recordings at this time point. The negative deflection of the ERP waveform grew stronger when more anterior, as a significant main effect was found for electrode position,  $F(4,5) = 6.786$ ,  $p = .030$ . When controlling for the conventionality effect by subtracting voltage recordings of usual movies from unconventional movies at each electrode site, the anterior progression of increasing negativity was still observed. However, main effects for conventionality,  $F(1,8) = 1.137$ ,  $p = .317$ , and motion,  $F(1,8) = 1.525$ ,  $p = .252$  were not significant. In addition, no significant interactions between the three variables were found.

For the late positivity effects, the range of greatest positive deflection was observed from 700ms-1000ms and ERP recordings were examined with respect to the variables of conventionality and motion. For the effect of conventionality, greater positivity was observed for unconventional movies compared to conventional movies in the typical motion conditions, and this effect was even more prominent in the non-typical motion conditions (Figure 4A). With

regard to a motion effect, the type of motion was not a factor for differentiating movies in the conventional conditions yet much greater positivity was observed to non-typical motion movies relative to typical motion movies in the unconventional conditions (Figure 4B).

With a peak amplitude for the late positivity approximated at 900ms, a repeated measures ANOVA on the same 9 subjects as above revealed main effects for all three variables.

Unconventional movies significantly increased late positivity compared to usual movies (Figure 5A),  $F(1,8) = 13.088$ ,  $p = .007$ . Movies with non-typical motions of target objects demonstrated greater positive deflection of the ERP waveform relative to movies with typical motions of target objects (Figure 5B),  $F(1,8) = 8.181$ ,  $p = .021$ . With the greatest deflections observed at the Cz and Pz electrodes, the positivity also varied significantly with electrode position,  $F(4,5) = 6.703$ ,  $p = .030$ . Comparable to the negativity, this large central-posterior positivity was still apparent when accounting for conventionality. An interaction between conventionality of movies and electrode position was also found, as significantly greater positivity was observed at the five electrode positions when participants were viewing unconventional movies compared to usual movies (Figure 5C),  $F(4,5) = 8.057$ ,  $p = .021$ . From the large positivity previously observed at the Cz and Pz electrodes, planned comparisons of usual and unconventional conditions at these electrode sites revealed significantly greater positivity to unconventional movies at Cz,  $t(34) = 2.689$ ,  $p = .0110$ , and Pz,  $t(34) = 3.148$ ,  $p = .0034$ .

#### *MEG and EEG statistical parametric maps*

From an examination of MEG models ( $n = 9$ ), significant differences in spatial activation were observed between the typical motion and non-typical motion conditions. These differences were observed during distinct epochs post-stimulus presentation (Figure 6). Both the unconventional, typical and non-typical motion conditions were analyzed relative to their

corresponding usual conditions and significant differences in activation ( $p < .01$ ) were found.

The unconventional/typical motion movies evoked posterior ventral and lateral temporal activity during the 200ms-500ms epoch, while early activation for unconventional/non-typical motion movies was observed in the anterior ventral temporal cortex. During the 700ms-1000ms epoch, activity increases were localized to the inferior frontal cortex and posterior temporal cortex for unconventional/typical motion movies. In contrast, enhanced activity was found within the dorsolateral prefrontal cortex and anterior ventral temporal cortex for the unconventional/non-typical motion movies.

Statistical parametric maps of EEG ( $n = 8$ ) also provided further insight into differences in spatial activation between unconventional typical motion and non-typical motion conditions (Figure 7). Examined relative to their respective usual conditions for each subject, both unconventional conditions elicited distinct, significant activation patterns ( $p < .0001$ ). In the epoch of 200ms-500ms, activity in response to typical motion movies was found primarily in the posterior temporal cortex. This finding contrasted with early activity for the non-typical motion movies observed in temporal-parietal cortex. Progressing to 700ms-1000ms, the typical motion movies revealed increased activity in the posterior temporal and inferior frontal cortices, while the non-typical motion condition elicited much greater activity in the superior frontal cortex (specifically in the dorsolateral prefrontal cortex).

### *ROI Analysis of MEG*

To further examine the extent of the dichotomy between unconventional typical motion and non-typical motion movies, the activation was analyzed in two regions of interest (ROI). For access of semantic representations, the posterior temporal cortex (PTC) was selected and, for flexible integration, the dorsolateral prefrontal cortex (DLPFC) was selected. As aforementioned,

the activity in the statistical parametric maps accounted for the conventionality effect, whereby the activation in response to usual/typical motion or non-typical motion movies was subtracted from the activation of respective unconventional movies. The regions were then mapped onto each participant's MEG model, and activity within the region was measured every 50ms. The average activity at each 50msec time point was first plotted for both the PTC and the DLPFC (Figure 8A and 8B). Upon visual inspection of the time-course plots, there was higher activation in the PTC to typical motion movies during the 200ms-500ms epoch and higher activation in the DLPFC to non-typical motion movies during the 700ms-1000ms epoch. Activity was then averaged across the time points within the early and late epoch for each participant ( $n = 8$ ). For each epoch, a 2-way ANOVA was conducted to identify any effects of target object motion (typical or non-typical motion) or region of interest (PTC or DLPFC).

In the first time window of 200-500ms, a significant interaction was observed between motion and ROI,  $F(1,20) = 8.520$ ,  $p = .0084$  (see Figure 9A). Activation to unconventional movies was shown to be significantly greater for typical motion than non-typical motion movies when the source was localized to the PTC. In the DLPFC, heightened activation was observed for non-typical motion movies relative to typical motion movies during this epoch. Planned comparisons within each region of interest revealed differences near significance:  $t(10) = 2.223$ ,  $p = .0505$  for the PTC and  $t(10) = 1.947$ ,  $p = .0801$  for the DLPFC. Later in the time course from 700ms to 1000ms, another interaction was observed between motion and ROI,  $F(1,24) = 6.272$ ,  $p = .0195$  (see Figure 9B). In this case, the activation in response to non-typical motion movies compared to typical motion movies was significantly greater in the DLPFC. A main effect of motion was also observed during this epoch, whereby activation to non-typical motion movies was significantly greater than activation to typical motion movies across the ROIs. This was

confirmed by planned comparisons within each ROI:  $t(12) = 5.114$ ,  $p = .0003$  for the DLPFC and  $t(12) = 2.300$ ,  $p = .0402$  for the PTC.

## Discussion

The current study presents a multi-modal analysis of neurocognitive mechanisms during comprehension of goal-directed behaviors. Establishing an extensive network with other cortical structures, the prefrontal cortex has been observed to activate when selection of a stimulus must be based on goal-relevance, rather than familiarity, for comprehension (Miller & Cohen, 2001). With stored semantic representations closely tied to the inferior and posterior temporal cortex, it has been further suggested that two processing streams, a fronto-temporal system for understanding familiar stimuli and a fronto-parietal system for understanding goal-related stimuli, might be differentially activated according to situational demands (Vincent et al., 2008). Therefore, in this study, video clips ended with either a usual or unconventional final scene, in which the target object featured typical motion or non-typical motion.

With previous observations in EEG (Sitnikova et al., 2008), it was hypothesized that unconventional and non-typical motion target objects would increase the N400 and late positivity amplitudes due to greater demands for mapping stimuli onto semantic representations and more effortful integration. We also expected an interaction between conventionality and motion for ERPs, suggesting that typical motion movies would have significantly lower N400 and late positivity amplitudes in the usual condition and that non-typical motion movies would have significantly larger N400 and late positivity amplitudes for unconventional condition. Spatially, the use of MEG and EEG in the current study aimed to dissociate areas of activation from previous fMRI observations of goal-directed comprehension. We hypothesized that unconventional movies would lead to greater overall activation relative to usual movies. Further,

by an interaction between conventionality and motion, activation to unconventional movies would be greatest in the non-typical motion case, where a stimulus that was both unexpected and less familiar would have to be integrated. In terms of localization, we predicted that usual and typical motion movies would readily activate posterior temporal cortex for access to stored semantic representations, while unconventional and non-typical motion movies would be more likely to activate the dorsolateral prefrontal cortex for flexible integration.

From the results, the average number of comprehension responses provided the behavioral evidence for the validity of movies assignments as well as insight into parameters for flexible comprehension. As expected, participants averaged a near perfect report of comprehension for the 30 usual movies in each of the typical and non-typical motion conditions. While the scores were significantly lower for both unconventional conditions, the presence of any responses of comprehension suggests that people can be encouraged toward flexibility. As aforementioned, the target objects in unconventional movies do not possess the physical features necessary to complete the goal suggested by the context. Therefore, while the target objects in unconventional movies were seemingly incongruous, participants were flexible (on average) and were able to experience thoughts that led to a response of comprehension. Moreover, the intermediate number of comprehension responses for the filler condition was also noteworthy. The filler condition movies were designed with an unconventional target object that possessed the physical features necessary to accomplish the constrained goal. When participants were encouraged to be flexible, an average of responses for comprehension to these filler movies was only slightly below the averages for the usual conditions. This finding supports that, despite the unconventionality of the target object in the filler condition, participants were evaluating the



target stimulus based on task-relevant properties, a capability tied uniquely to the prefrontal cortex (Miller & Cohen, 2001).

Recordings of ERPs support the hypothesis that specific attributes of an incoming stimulus can facilitate its flexible integration in a real-world situation. With respect to the N400, the trend of greater negativity at more anterior electrodes demonstrated a significant main effect. This finding replicates previous observations, where negativities elicited by pictures and visual scenes are typically distributed over more anterior electrode positions (Barrett & Rugg, 1990; West & Holcomb, 2002; Sitnikova et al., 2010). However, the lack of main effects for conventionality and motion for the N400 did not agree with our hypotheses. We expected that target objects classified as usual or by a typical motion would exhibit a smaller N400 response than unconventional target objects or those with non-typical motion. A possible explanation for the absence of these main effects may stem from the flexibility demands in this paradigm. Because participants were encouraged to be flexible for the characterization of electrophysiological and cortical attributes of flexible integration, N400 modulation might have been less sensitive to single factors of conventionality and motion because participants are more prepared to consider alternatives when heading into the task. It is clear, however, that the late positivity reflects efforts to flexibly integrate stimuli. For instance, increased amplitude of the late positivity for unconventional movie endings demonstrates the need for greater resources for integration, as suggested by Sitnikova et al. (2008). The positivity differences at the centro-parietal electrodes being the largest when comparing unconventional to usual movies also replicates previous ERP findings during tasks requiring flexibility in response to incoming stimuli (Kiefer, 1998). Further, as predicted, the non-typical motion movies had significantly larger positivity amplitudes than typical motion movies. The absence of a typical motion

provided one less feature for mapping onto semantic representations and, likely contributed to later increases in positivity for integration. Therefore, these ERP results suggest that stimuli which are unconventional or exhibit non-typical motion are more likely be comprehended by flexible integration as opposed to semantic access.

An examination of the statistical parametric maps for MEG and EEG revealed condition-specific differences in activation patterns throughout the time-course. During the early epoch of MEG, unconventional movies with typical motion activated posterior temporal cortex, which has been previously linked to memory representations of mechanical and biological motion involved in object use (Xu et al., 2005; Hermsdörfer et al., 2007). In contrast, unconventional movies with non-typical motion activated more anterior temporal cortex, which has been implicated in higher-level amodal representations of real-world stimuli (Binney et al., 2010). We suspect that this initial difference in temporal cortex activity might influence separate neurocognitive processing streams because of observations of activity later in the time-course. The posterior temporal activity of unconventional/typical motion movies was followed by increased temporal and inferior frontal activity (a fronto-temporal system), which has been suggested to underlie comprehension based on strong, semantic associations (Van Petten & Luka, 2005). The initial posterior temporal activity, therefore, might limit subsequent activity to repeated mapping attempts of the object-action association onto stored semantic representations. Conversely, for the unconventional/non-typical motion movies, anterior temporal cortex activity was followed by increased activity in the dorsolateral prefrontal and posterior parietal cortices. Because the anterior temporal cortex has been tied to irregular associations (Patterson et al., 2007; Binney, 2010), it may permit subsequent activation in the regions of the fronto-parietal system implicated in flexible cognition (Vincent et al., 2008).

The EEG modeling results further support dichotomous efforts toward the two processing streams. Early in the time course for unconventional conditions, posterior temporal activity was observed for typical motion movies while more temporal-parietal activity was found for non-typical motion movies. Previous studies have suggested that inferior, posterior temporal cortex activity reflects a response to semantically congruous stimuli, while more dorsal temporal-parietal regions are activated for semantically incongruous stimuli (Menon et al., 1997; Takazawa, 2002). With a characteristic motion of the target object, typical motion movies contain a trigger for action-object associations stored in semantic memory. The strength of the typical motion might suggest potential congruity of the unconventional stimulus, leading to the activity in the posterior temporal cortex. In contrast, non-typical motion movies do not contain this salient feature. Therefore, the unconventional objects in non-typical motion movies are more likely to be seen as semantic anomalies, leading to the more temporal-parietal activation. Further, this early dichotomy in activation appears to affect processing later in the time-course. Reflecting the efforts directed toward access of stored representations, early posterior temporal activity increased and there was additional inferior frontal activity for the unconventional/typical motion movies. This activation likely reflects continual attempts to map the target stimulus onto known semantic associations. On the other hand, reflecting the efforts directed toward more flexible cognitive processes, the early temporal-parietal activity was followed by increases in prefrontal, frontal and parietal activity. As activation in these areas has been associated with the fronto-parietal system (Vincent et al., 2008), the non-typical motion characteristic of movies seems to more readily enable efforts toward flexible comprehension. Therefore, the presence or absence of salient features of the target object appears to impact whether brain resources are directed toward accessing semantic representations or engaging flexible integration.

The ROI analysis of the MEG not only agreed with the trends observed in the statistical parametric maps of MEG and EEG, but also presents a strong case for a trade-off in localized activation for real-world comprehension. The observation of an interaction between motion and ROI during the early epoch of 200-500ms, in which responses were significantly higher to typical motion movies than to non-typical motion movies in the PTC, suggests that the presence of typical motion rapidly activates the semantic access processing stream. Moreover, the heightened activation to non-typical motion movies in the DLPFC compared to the PTC in this early epoch suggests that non-typical motion of a stimulus might facilitate its passage from attempts with stored representations onto flexible integration efforts. This effect of non-typical motion was realized in the 700ms-1000ms time window. As greater activation was observed to non-typical motion movies relative to typical motion movies in the DLPFC, the interaction of motion and ROI during this later epoch supports the notion that non-typical motion of a stimulus facilitates flexible integration. The main effect of motion during this later epoch also agrees with electrophysiological data, as significantly greater positivity was observed at 900ms for non-typical motion movies. These results suggest that an unconventional stimulus with a task-irrelevant yet highly salient feature is likely to engage early activation of semantic access processing in the PTC and draw resources away from DLPFC. In contrast, a stimulus without such task-irrelevant, salient features is less likely to activate the processing stream for semantic access, thereby, facilitating flexible integration by making resources available for DLPFC activity.

In all, this study corroborates previous ERP and spatial findings associated with processes of semantic access and flexible comprehension. Building on the identification of these neurocognitive processes, this study characterizes a trade-off in spatiotemporal activity for

semantic access and flexible integration through ERPs as well as through MEG and EEG activation models. In future studies, we aim to conduct an ROI analysis on the activation observed in EEG modeling for comparison with the ROI analysis of MEG. Because of the complementary nature of EEG and MEG, a comparison of the EEG activity in the DLPFC and PTC regions might provide greater clarity with regard to a trade-off in activation between the ROIs and, consequently, the two processing streams. Furthermore, a combined EEG/MEG approach would likely enable better localization of activity for goal-directed comprehension. If smaller areas of activation were observed by this combined approach, an ROI analysis of the observed foci during specific epochs of the time-course might further characterize links between multiple cortical structures for semantic access and flexible integration.

Moreover, because flexible comprehension difficulties in schizophrenia have been linked to decreased activation of the DLPFC (Sitnikova et al., 2010), the application of the current paradigm to schizophrenia patients is encouraging for assessment and potential improvement of the impairment. For instance, if patients' increased reliance on formed associations (shown by hyperactivation of temporal cortex) is linked with reduced DLPFC activation, the difficulties in comprehension could be interpreted as an imbalance between the semantic access and flexible integration processing streams. Further, the ability of healthy controls to report comprehension to unconventional movies suggests unique approaches for potential therapies. As shown by the behavioral data, participants reported a high level of comprehension to filler movies, in which the target object was unconventional yet contained the physical characteristics for achieving the goal. Because this rule-based evaluation of a stimulus has been shown to initiate prefrontal activity, a learning-based approach whereby the critical feature of a target object could be presented as a verbal prime before the final scene might help engage the DLPFC in patients. If

increased comprehension of these filler movies was achieved in patients, flexibility might be gradually improved by removing the prime or adding in more salient, irrelevant features (as in the case of unconventional/typical motion movies). Therefore, future applications of the current paradigm aim to provide further insight into dissociable neurocognitive mechanisms for real-world comprehension as well as clinical implications for schizophrenia.

## References

- American Psychiatric Association, 1994. *Diagnostic and Statistical Manual of Mental Disorders* (4<sup>th</sup> ed.). Washington, DC: Author.
- Barrett, S.E. & Rugg, M.D. (1990). Event-related potentials and the semantic matching of pictures. *Brain and Cognition*, 14, 201–212.
- Binney, R.J., Embleton, K.V., Jefferies, E., Parker, J.M., Lambon Ralph, M.A. (2010). The ventral and inferolateral aspects of the anterior temporal lobe are crucial in semantic memory: Evidence from a novel direct comparison of distortion-corrected fMRI, rTMS, and semantic dementia. *Cerebral Cortex*, In Press.
- Bunge, S.A., Hazeltine, E., Scanlon, M.D., Rosen, A.C., & Garbieli, J.D.E. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *Neuroimage*, 17, 1562-1571.
- Cohen, D. & Halgren, E. (2009). Magnetoencephalography. *Encyclopedia of Neuroscience*. L. R. Squire. Oxford, Academic Press. 5: 615-622.
- Fletcher, P.C., Shallice, T., & Dolan, R.J. (1998a). The functional roles of prefrontal cortex in episodic memory. *Brain*, 121, 1239-1248.
- Fletcher, P.C., Shallice, T., Frith, C.D., Frackowiak, R.S.J., & Dolan, R.J. (1998b). The functional roles of prefrontal cortex in episodic retrieval. *Brain*, 121, 1239-1248.
- Friederici, A.D., Pfeifer, E., & Hahne, A. (1993). Event-related brain potentials during natural speech processing: effects of semantic, morphological and syntactic violations. *Cognitive Brain Research*, 1, 183–192.
- Funahashi, S. (2001). Neuronal mechanisms of executive control by the prefrontal cortex. *Neuroscience Research*, 39, 147-165.
- Ganis, G. & Kutas, M. (2003). An electrophysiological study of scene effects on object identification. *Cognitive Brain Research*, 16, 123–144.
- Ganis, G., Kutas, M., & Sereno, M.I. (1996). The search for “common sense”: An electrophysiological study of the comprehension of words and pictures in reading. *Journal of Cognitive Neuroscience*, 8, 89-106.
- Grose-Fifer, J. & Deacon, D. (2004). Priming by natural category membership in the left and right cerebral hemispheres. *Neuropsychologia*, 42, 1948–1960.
- Hagoort, P. & Brown, C.M. (2000). ERP effects of listening to speech: semantic ERP effects. *Neuropsychologia*, 38, 1518–1530.

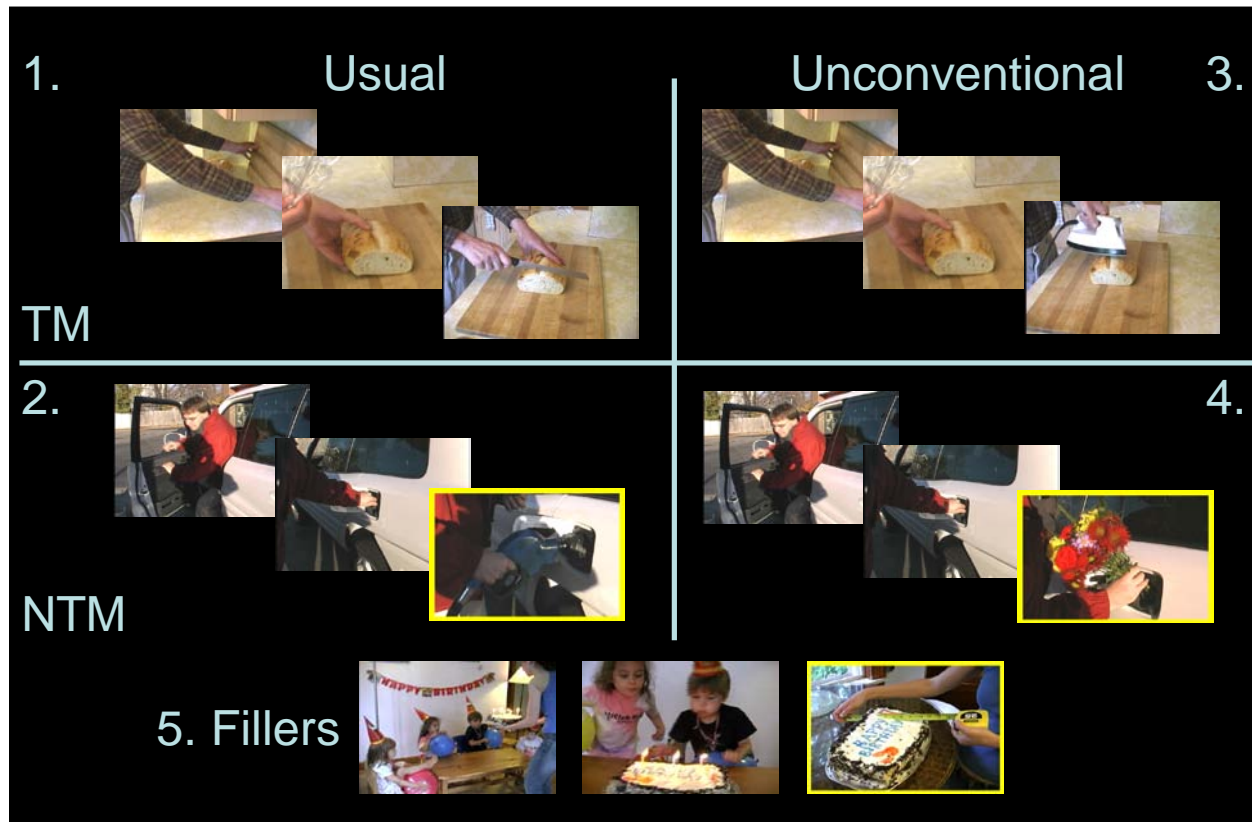
- Hermisdörfer, J., Terlinden, G., Mühlau, M., Goldenberg, G., & Wohlschläger, A.M. (2007). Neural representations of pantomimed and actual tool use: Evidence from an event-related fMRI study. *Neuroimage*, 36, 109-118.
- Holcomb, P.J. & McPherson, W.B. (1994). Event-related brain potentials reflect semantic priming in an object decision task. *Brain and Cognition*, 24, 259–276.
- Holcomb, P.J., Kounios, J., Anderson, J.E., & West, W.C. (1999). Dual-coding, context availability, and concreteness effects in sentence comprehension: an electrophysiological investigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25, 721–742.
- Jiang, Y. & Kanwisher, N. (2003). Common neural substrates for response selection across modalities and mapping paradigms. *Journal of Cognitive Neuroscience*, 15, 1080-1094.
- Kiefer, M., Marzinzik, F., Weisbrod, M., Scherg, M., & Spitzer, M. (1998). The time course of brain activations during response inhibition: Evidence from event-related potentials in a go/no go task. *NeuroReport*, 18, 765-770.
- Kuperberg, G.R., Caplan, D., Sitnikova, T., Eddy, M., & Holcomb, P.J. (2006). Neural correlates of processing syntactic, thematic and semantic relationships in sentences. *Language and Cognitive Processes*, 21, 489–530.
- Kuperberg, G.R., Kreher, D.A., Sitnikova, T., Caplan, D.N., & Holcomb, P.J. (2007). The role of animacy and thematic relationships in processing active English sentences: evidence from event-related potentials. *Brain and Language*, 100, 223–237.
- Kuperberg, G.R., Sitnikova, T., Caplan, D., & Holcomb, P.J. (2003). Electrophysiological distinctions in processing conceptual relationships within simple sentences. *Cognitive Brain Research*, 17, 117–129.
- Kutas, M. (1993). In the company of other words: electrophysiological evidence for single-word and sentence context effects. *Language and Cognitive Processes*, 8, 533–572.
- Kutas, M. Hillyard, S.A. (1980a). Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biological Psychology*, 11, 99–116.
- Kutas, M. & Hillyard, S.A. (1980b). Reading senseless sentences: brain potentials reflect semantic incongruity. *Science*, 207, 203–205.
- Menon, V., Ford, J.M., Lim, K.O., Glover, G.H., & Pfefferbaum, A. (1997). Combined event-related fMRI and EEG evidence for temporal–parietal cortex activation during target detection. *NeuroReport*, 8, 3029-3037.
- Miller, E.K. & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24, 167-202.



- Nigam, A., Hoffman, J.E., & Simons, R.F. (1992). N400 to semantically anomalous pictures and words. *Journal of Cognitive Neuroscience*, 4, 15-22.
- Osterhout, L., Holcomb, P.J., & Swinney, D.A. (1994). Brain potentials elicited by garden-path sentences: evidence of the application of verb information during parsing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20, 786–803.
- Patterson, K., Nestor, P.J., & Rogers, T.T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience*, 8, 976-987.
- Ridderinkhof, K.R., van den Wildenberg, W.P.M., Segalowitz, S.J., & Carter, C.S. (2004). Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain and Cognition*, 56, 129-140.
- Rogers, R.L., Papanicolaou, A.C., Baumann, S.B., Saydjari, C., & Eisenberg, H.M. (1990). Neuromagnetic evidence of a dynamic excitation pattern generating the N100 auditory response. *Electroencephalography and Clinical Neurophysiology*, 77, 237-240.
- Rougier, N.P., Noelle, D.C., Braver, T.S., Cohen, J.D., & O'Reilly, R.C. (2005). Prefrontal cortex and flexible cognitive control: Rules without symbols. *PNAS*, 102, 7338-7343.
- Sharon, D., Hämäläinen, M.S., Tootell, R.B.H., Halgren, E., & Belliveau, J.W. (2007). The advantage of combining MEG and EEG: Comparison to fMRI in focally stimulated visual cortex. *Neuroimage*, 36, 1225-1235.
- Sitnikova, T., Holcomb, P.J., Kiyonaga, K.A., & Kuperberg, G.R. (2008). Two neurocognitive mechanisms of semantic integration during the comprehension of visual real-world events. *Journal of Cognitive Neuroscience*, 20, 2037–2057.
- Sitnikova, T., Kuperberg, G.R., & Holcomb, P.J. (2003). Semantic integration in videos of real-world events: an electrophysiological investigation. *Psychophysiology* 40, 160–164.
- Sitnikova, T., Perrone, C., Goff, D., & Kuperberg, G.R. (2010). Neurocognitive mechanisms of conceptual processing in healthy adults and patients with schizophrenia. *International Journal of Psychophysiology*, 75, 86-99.
- Sitnikova, T., West, W.C., Kuperberg, G.R., & Holcomb, P.J. (2006). The neural organization of semantic memory: electrophysiological activity suggests feature-based segregation. *Biological Psychology*, 71, 326–340.
- Stroop, J.R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology: General*, 121, 15-23.

- Takazawa, S., Takahashi, N., Nakagome, K., Kanno, O., Hagiwara, H., Itoh, K., & Koshida, I. (2002). Early components of event-related potentials related to semantic and syntactic processes in the Japanese language. *Brain Topography*, *14*, 169-177.
- Van Petten, C. & Luka, B.J. (2005) Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain and Language*, *97*, 279-293.
- Vincent, J.L., Kahn, I., Snyder, A.Z., Raichle, M.E., & Buckner, R.L. (2008). Evidence for the frontoparietal control system revealed by intrinsic functional connectivity. *Journal of Neurophysiology*, *100*, 3328-3342.
- West, W.C. & Holcomb, P.J. (2002). Event-related potentials during discourse-level semantic integration of complex pictures. *Cognitive Brain Research*, *13*, 363–375.
- Xu, J., Kemeny, S., Park, G., Frattali, C., & Braun, A. (2005). Language in context: emergent features of word, sentence, and narrative comprehension. *Neuroimage*, *25*, 1002-1015.

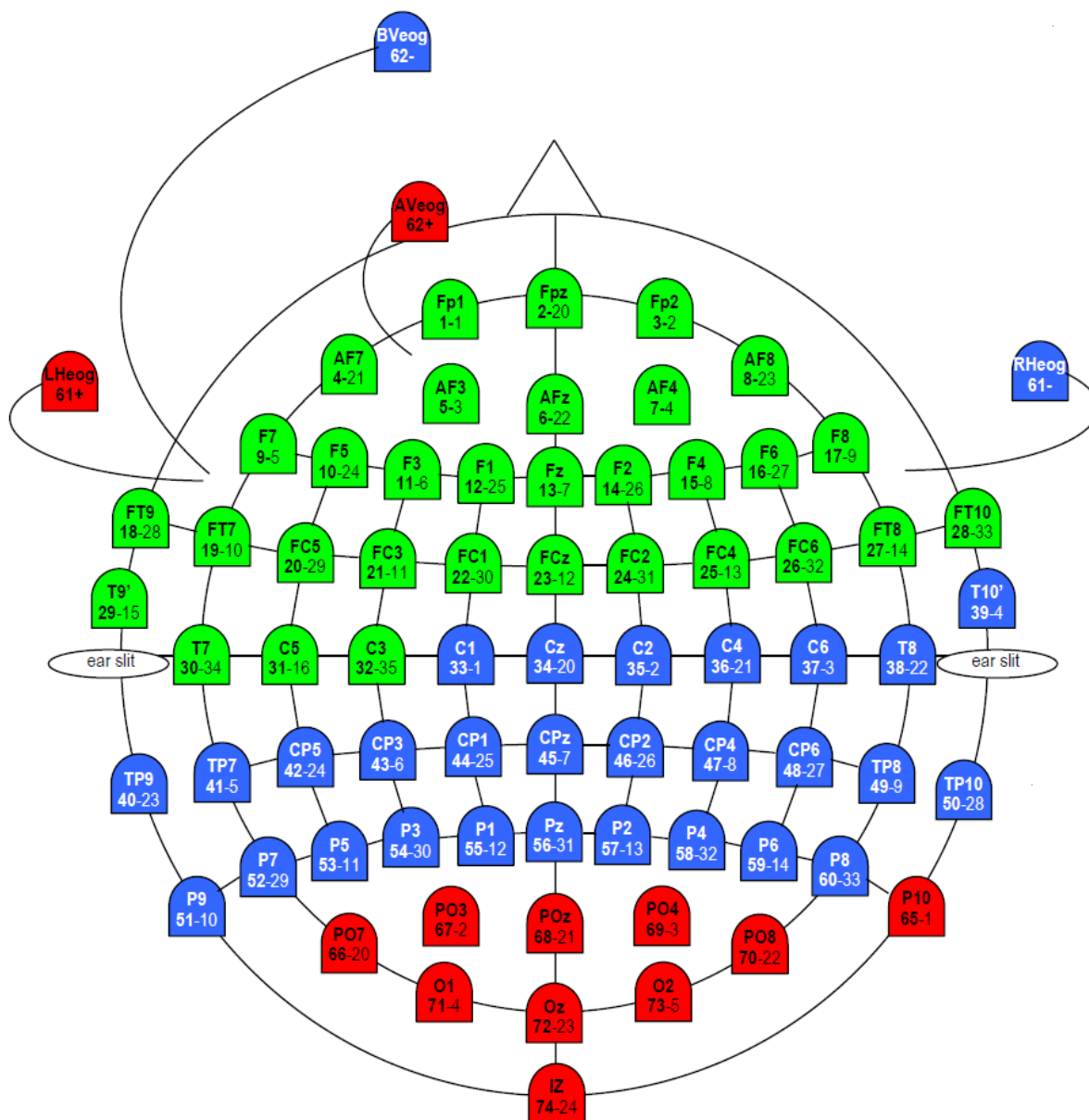
## Figures and Tables



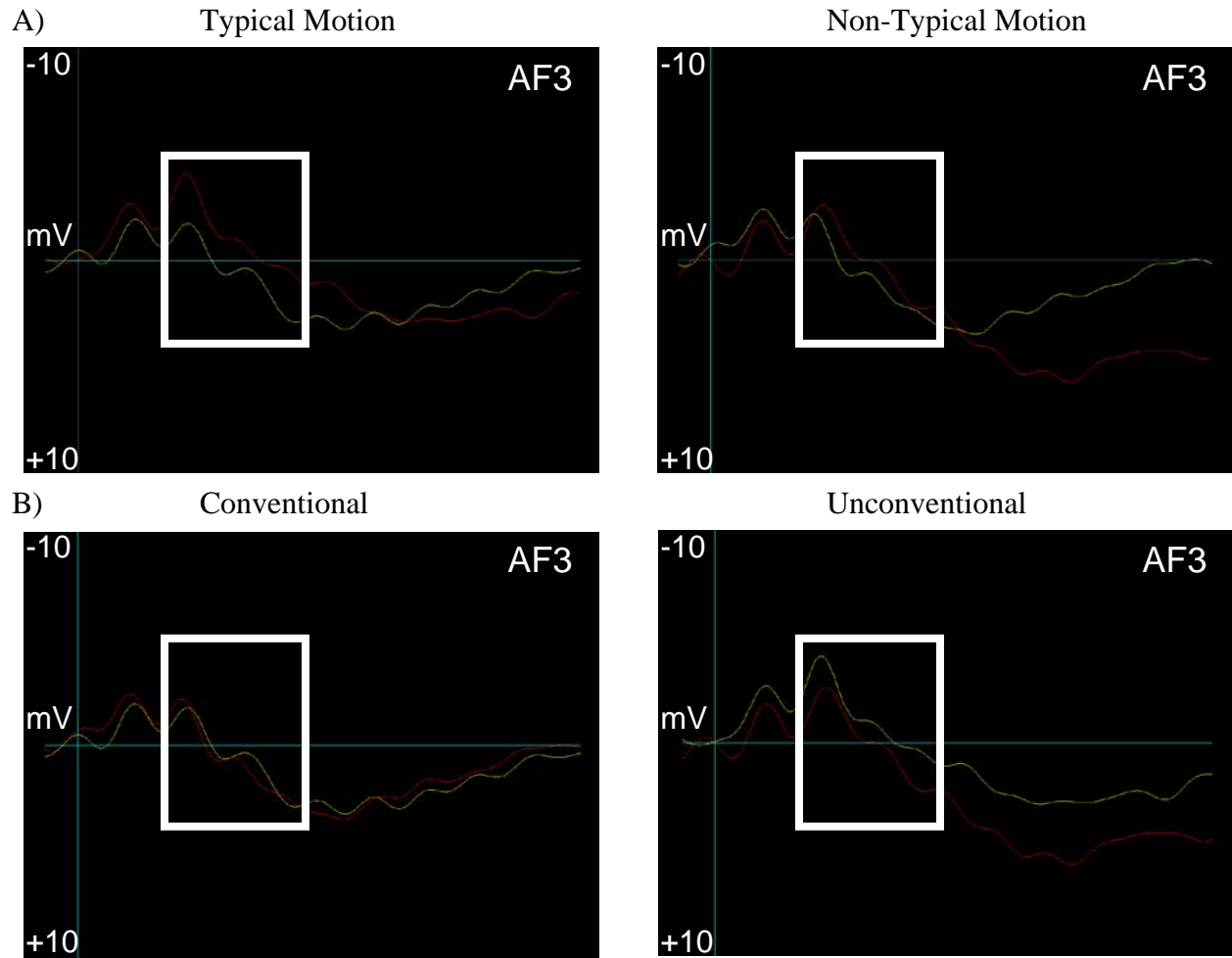
*Figure 1.* Conventionality x Motion Paradigm. Each context was paired one usual and one unconventional final scene, which was classified into typical or non-typical motion categories. There were 30 videos per condition.

*Table 1:* Average responses of comprehension in the behavioral task ( $n = 13$ ).

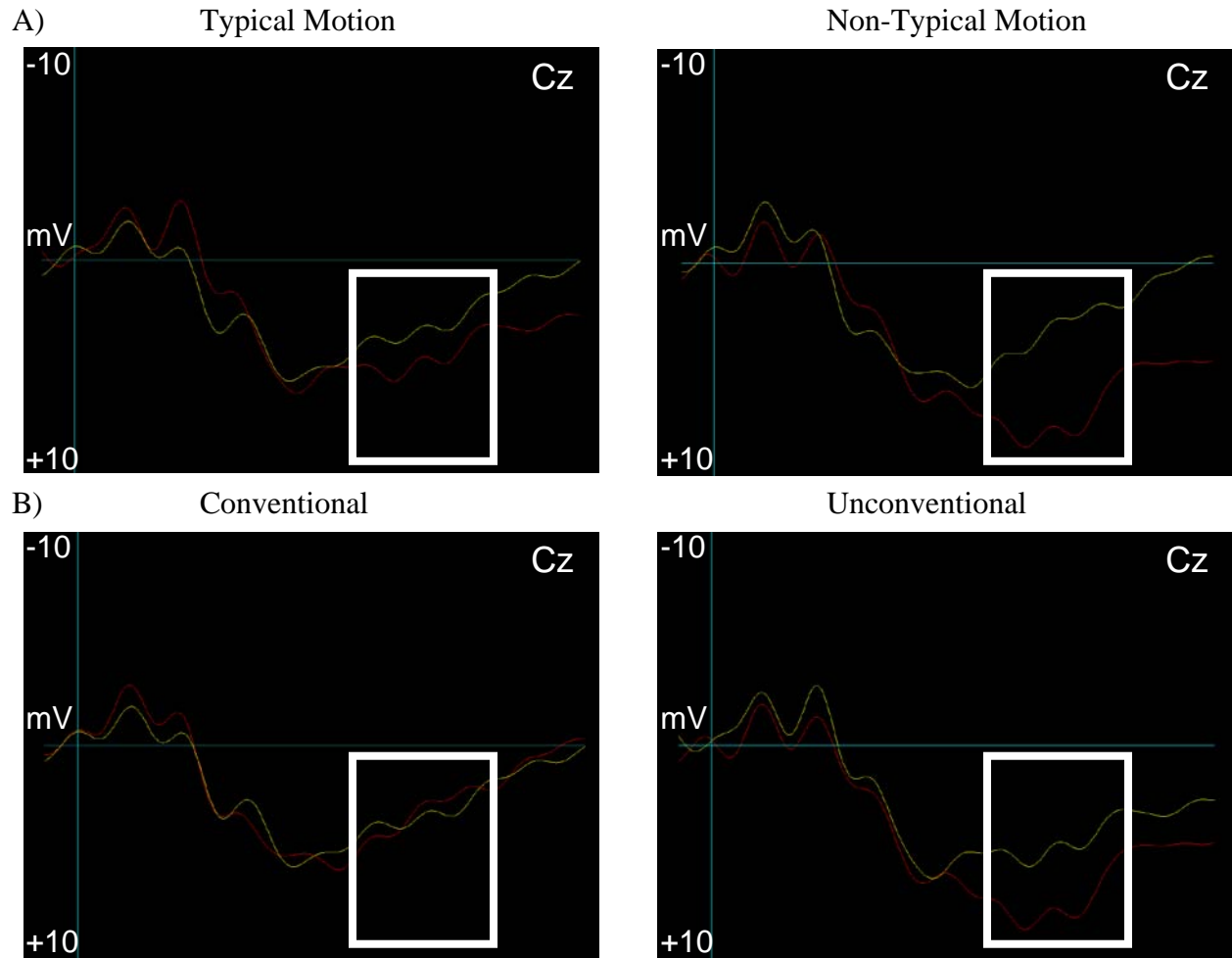
Condition	Conventional / Typical Motion	Conventional / Non-typical Motion	Unconventional / Typical Motion	Unconventional / Non-Typical Motion	Fillers
Mean Comprehension (out of 30)	29.62	29.54	6.92	5.77	24.31



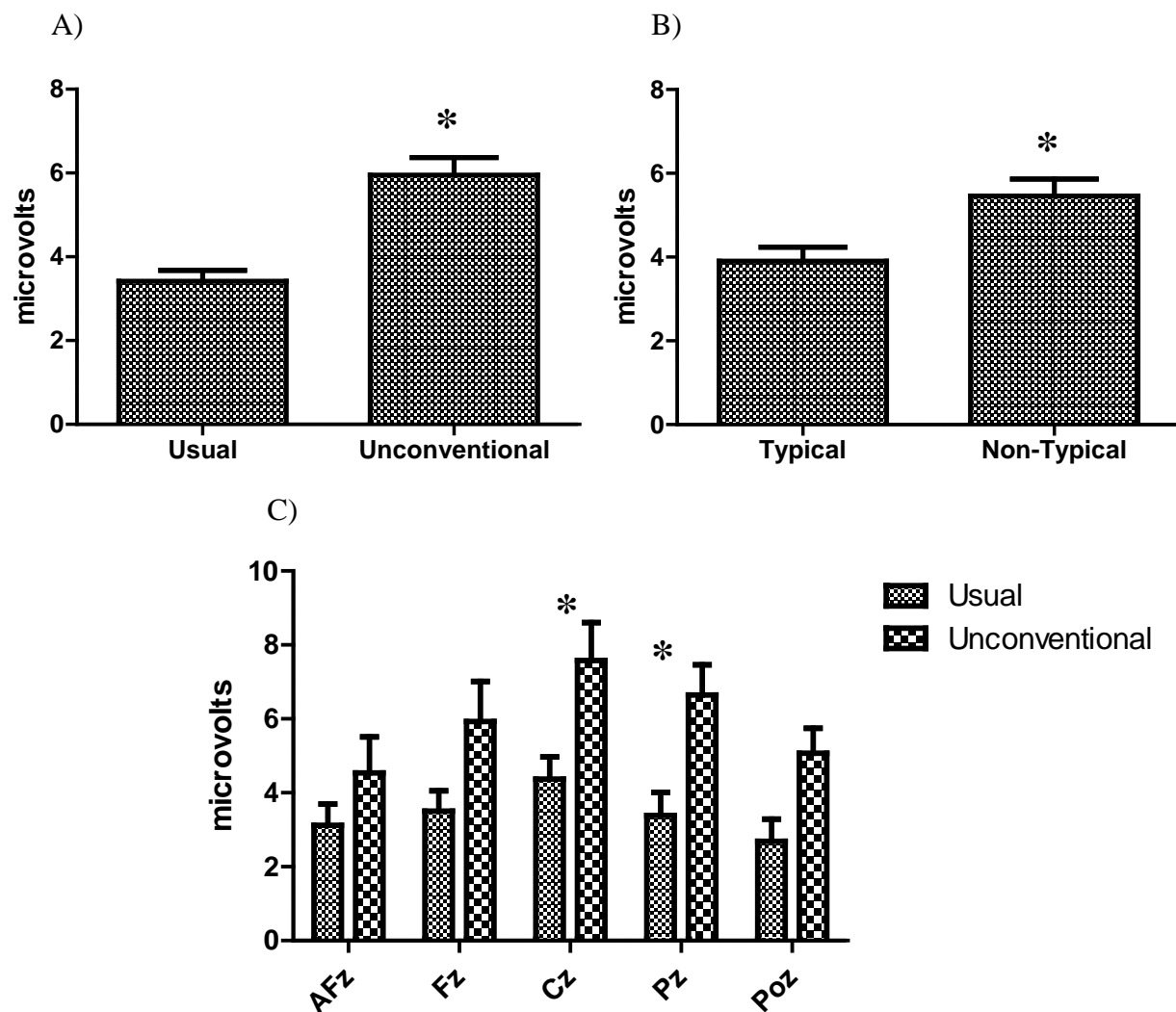
*Figure 2.* Electrode montage. Event-related potentials were measured from electrophysiological activity at 70 scalp electrode sites. Two vertical and two horizontal EOG electrodes, attached to the EEG cap, monitored eye movement.



*Figure 3.* Average ( $n = 10$ ) electrophysiological recordings for the 200ms-500ms time window (boxed region) at the left frontal electrode, AF3. A) The increase in negativity for unconventional movies (red) compared to conventional movies (yellow) was greater for the typical motion conditions (left) than for the non-typical motion conditions (right). B) While no difference was observed for type of motion in the conventional conditions (left), greater negativity was observed for typical motion movies (yellow) relative to non-typical motion movies (red) in the unconventional conditions (right).



*Figure 4.* Average ( $n = 10$ ) electrophysiological recordings for the 700ms-1000ms time window (boxed region) at the central electrode, Cz. A) The increase in positivity for unconventional movies (red) compared to conventional movies (yellow) in the typical motion conditions (left) was not as strong as in the non-typical motion conditions (right). B) While no difference was observed for type of motion in the conventional conditions (left), greater positivity was observed for non-typical motion movies (red) relative to typical motion movies (yellow) in the unconventional conditions (right).



*Figure 5.* Main Effects and Interactions of the Late Positivity. Increased positivity was evoked to video clips classified as A) unconventional or B) having non-typical motion. C) Electrode site was shown to interact with conventionality with significant increases in the positivity amplitude to unconventional movies compared to conventional movies at the Cz and Pz positions. Statistical significance was set at  $p < .05$ , indicated by an \*.

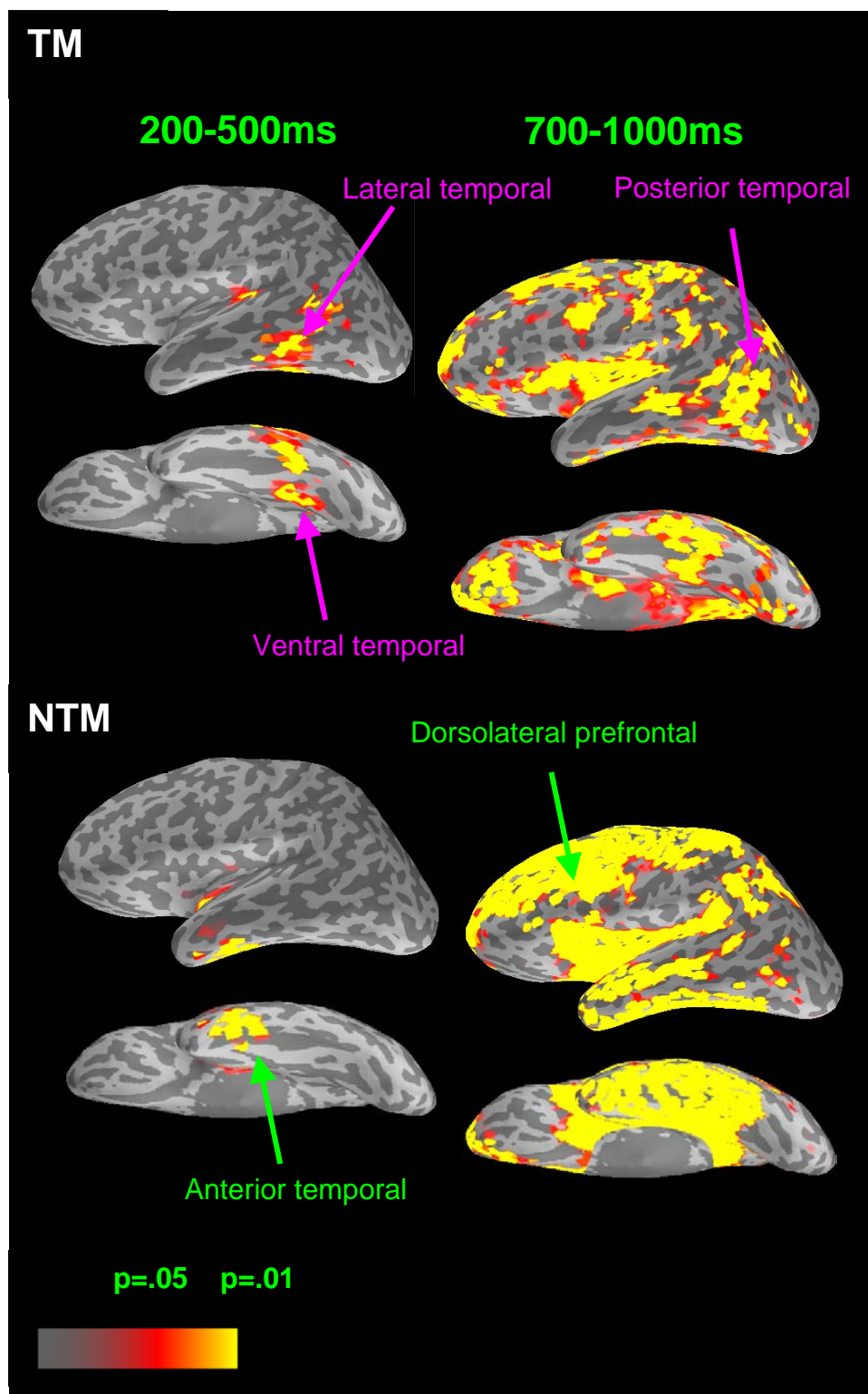
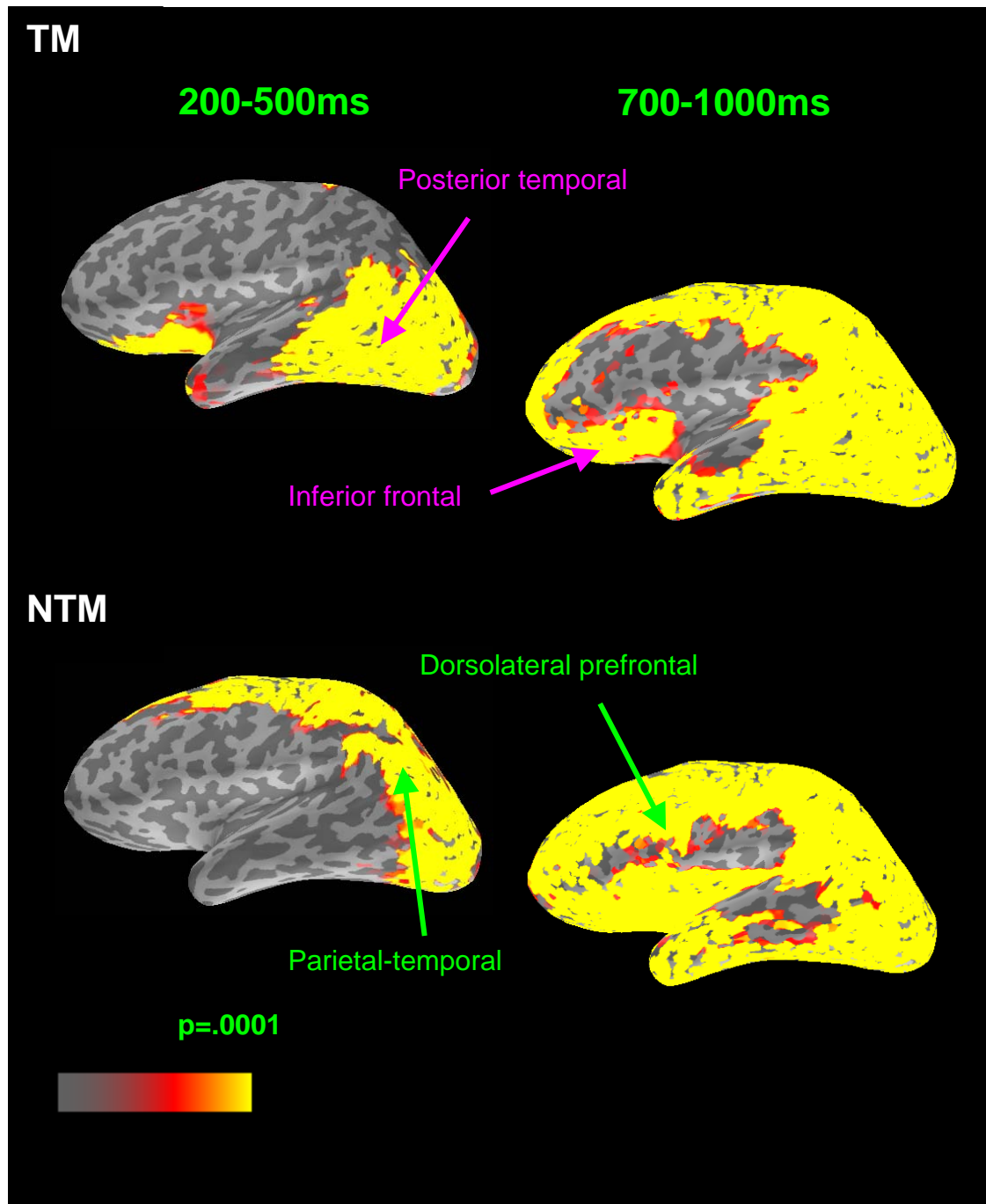
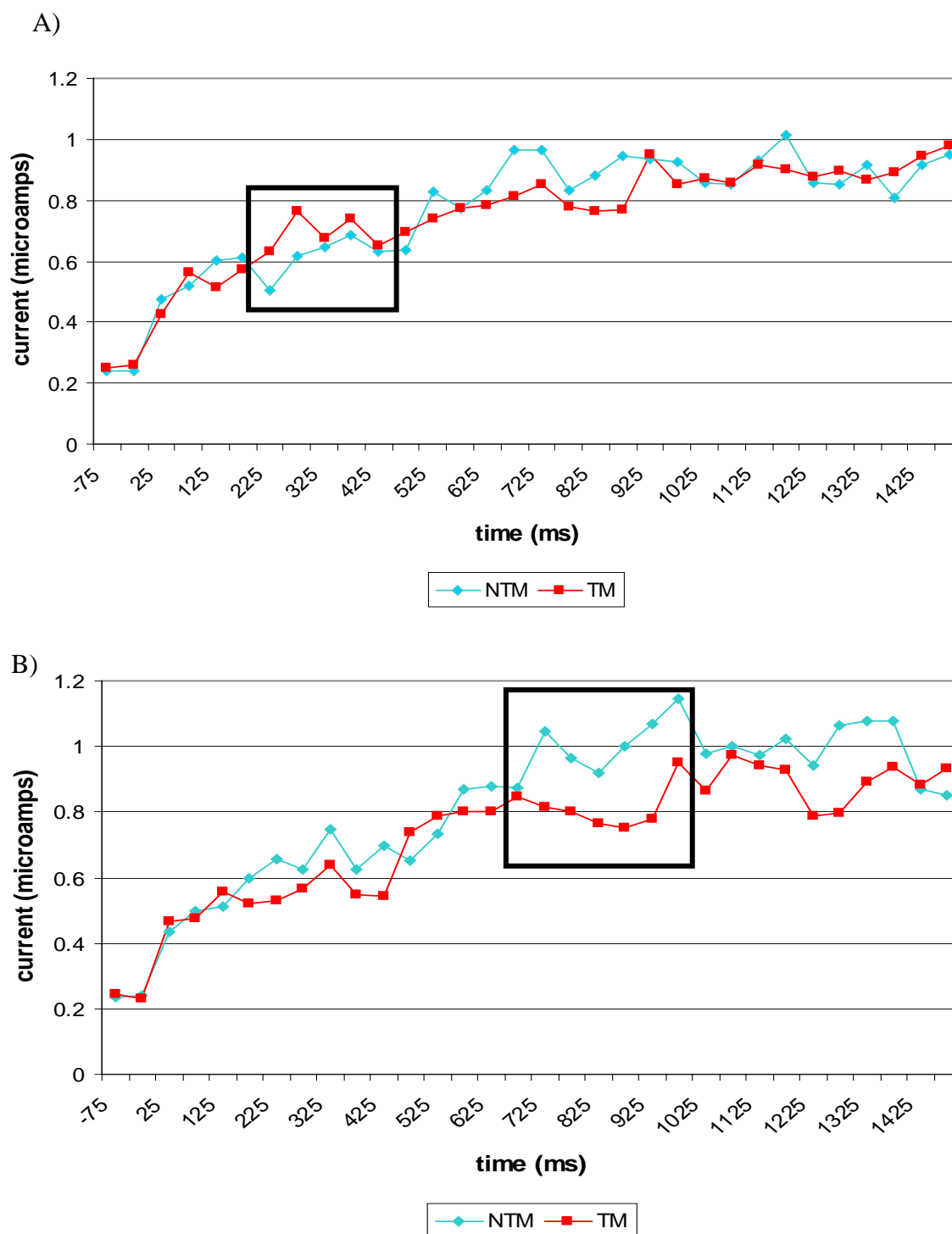


Figure 6. Grouped average ( $n = 9$ ) of MEG statistical parametric maps. Relative to their usual counterparts, unconventional typical motion (TM) movies demonstrated early activation in lateral and ventral temporal cortex while unconventional non-typical motion (NTM) movies exhibited anterior temporal activation. Later in the time course, activity to TM movies increased in posterior temporal cortex, while activity to NTM movies increased in the dorsolateral prefrontal cortex.

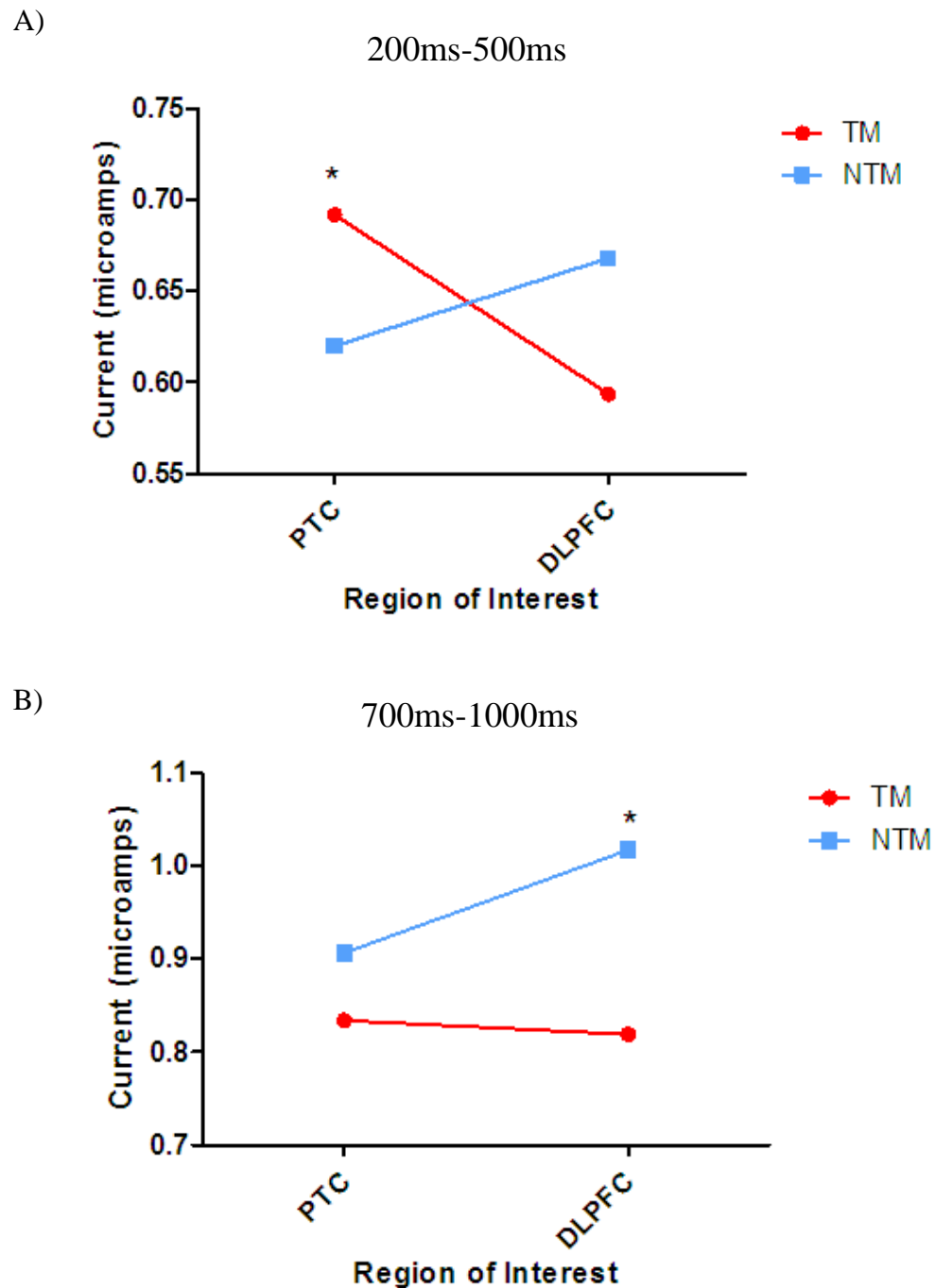




*Figure 7.* Grouped average ( $n = 8$ ) of EEG statistical parametric maps. Relative to their usual counterparts, unconventional typical motion (TM) movies demonstrated early activation in posterior temporal cortex while unconventional non-typical motion (NTM) movies exhibited more parietal-temporal activation. During the later epoch, activity to TM movies increased in posterior temporal and inferior frontal cortices, while activity to NTM movies largely increased in the frontal cortex and, more specifically, the dorsolateral



*Figure 8.* Time-course of average activation ( $n = 10$ ) within regions of interest in MEG models. Measurements of current within the A) posterior temporal cortex and B) dorsolateral prefrontal cortex demonstrate differential activation in response to typical and non-typical motion conditions when controlling for the conventionality effect. The boxed regions correspond to activation values for 200ms-500ms and 700ms-1000ms for (A) and (B), respectively, for identification of latencies in activity similar to ERP observations.



*Figure 9.* Quantified activation from regions of interest in response to typical and non-typical motion movies. A) Early activation in the 200ms-500ms epoch was significantly higher in the posterior temporal cortex (PTC) for typical motion movies compared to non-typical motion movies. B) Later activation in the 700ms-1000ms epoch was significantly higher in the dorsolateral prefrontal cortex for non-typical motion movies compared to typical motion movies. Statistical significance was set at  $p < .05$ , indicated by an \*.