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**Bilingual Emotional Word Processing:  
A Behavioral and Event-Related Potential Study**

A Dissertation Presented

by

**Zhiru Jia**

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Abstract of the Dissertation

**Bilingual Emotional Word Processing: A Behavioral and Event-Related Potential Study**

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**Doctor of Philosophy**

in

**Biopsychology**

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The current studies examined healthy Chinese-English bilinguals in their responses to visual word stimuli. The words were of different emotional valences (positive, negative, neutral) or categories (math, object, measure) in Chinese (L1) and English (L2) during a multistimulus oddball paradigm. Six conditions, with four using emotionally-valenced words and two using categorical words, were designed for an event-related potential (ERP) and behavioral study. The words in each condition were grouped into one infrequent target stimulus type (with a probability of 1/6) and five frequent non-target stimulus types (with a probability of 1/6 each) in random order.

As hypothesized, an enhanced late P300 (400-700 ms post-stimulus) was elicited by targets relative to non-targets, by non-targets in the same language as targets relative to other non-targets, and by L1 relative to L2 words, with the maximal enhancement at central and parietal scalp locations. Language and emotion interacted on late P300 amplitude with a larger enhancement elicited by L1 relative to L2 negative words than by L1 relative to L2 positive words and by L1 relative to L2 neutral words. A greater emotional arousal was found associated with word stimuli in L1 than in L2. Also as hypothesized, the reaction time data showed faster responses to L1

relative to L2 words, to non-targets relative to targets, and to neutral relative to negative or positive words. In addition, an unexpected enhancement was observed for an early ERP component (250-350 ms post-stimulus) to words in L2 relative to in L1 and to positive or negative relative to neutral words, with the maximal enhancement at frontal and central scalp locations.

The current studies further extended findings that P300 is an index of similarity between target and non-target stimuli. In particular, non-target words in the same language as target words, while exhibiting P300s that were similar to but smaller in amplitude than those elicited by target words, elicited larger P300s than non-target words that were in a different language from target words. The current studies also suggested that the early ERP component (250-350 ms post-stimulus) may be strongly correlated with language acquisition and proficiency in L1 and L2 among Chinese-English bilinguals. The implications of findings from the current studies on theories of bilingualism and emotion are discussed.

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# Introduction

## *Motivation for Studying Emotion and Bilingualism*

The past two decades have seen a great surge of interest in studying the relationship between language and emotions. This surge spreads across such diverse fields as cognitive linguistics (Athanasidou & Tabakowska, 1998; Harkins & Wierzbicka, 2001; Kövecses, 1990, 2000; Wierzbicka, 1999), linguistic anthropology (Besnier, 1990; Lutz 1988; Lutz & Abu-Lughod, 1990), pragmatics (Arndt & Janney, 1991), communication sciences (Fussell, 2002; Plana, 1999), and cognitive, cultural, social, and discursive psychology (Edwards, 1997; Russell, 1991). However diverse their perspectives, all of these disciplines only study the relationship between language and emotions from a monolingual perspective. None considers the implications of bilingualism nor language variation on emotions. This absence results from the Chomskian view of language which continues to dominate traditional linguistics and cognitive psychology. The view rejects both language variation and bilingualism as uninteresting phenomena that have little if anything to contribute to the theories of language and mind. This attitude has translated into two common scholarly practices. First, researchers recruiting participants for language studies often try to avoid bilinguals, whose perceptions, intuitions, and performances might exhibit ‘impure’ knowledge of the language in question and thus skew the results. Secondly, when bilingual informants and participants do take part in language studies, their multiple linguistic competencies are often obscured in the reporting, as a fact irrelevant to their ‘native speakerness’ (Pavlenko, 2006).

In terms of methodology, this monolingual bias obscures the fact that the implicitly ‘monolingual’ cross-linguistic research is conducted by bilingual researchers, with participants who may be proficient in more than one language – all of which could potentially influence the results. In terms of scope, the monolingual bias overlooks the fact that most of the world’s

population is bilingual, and that even those who view themselves as monolingual often have a long history of foreign language exposure. Yet theories of the relationship between language and emotions continue to privilege the one speaker–one language viewpoint, exhibiting an implicit assumption that whatever applies to monolinguals will also apply to bilinguals.

As the traditional approach to both linguistic and neurological inquiry about the human mind has been based on a monolingual ideal speaker, the resulting theories cannot be truly representative of what is a "messy, heteroglossic, and multilingual" reality (Pavlenko, 2006). Language competence even in first language (L1) is not the homogeneous and relatively unchangeable property that many researchers seem to presuppose (e.g., MacWhinney, 1997). Many factors point to an opposing reality; that is, bilingual speakers have a uniquely formed linguistic and emotional system that rather than being composed of two monolingual systems, is in fact a compound and dynamic system of multicompetence as theorized by Cook (1991) and Grosjean (1998). The study of bilingualism is thought to be a necessary component in the study of emotions in the fields of linguistics, psychology, and anthropology.

The fields of second language acquisition (SLA) and bilingualism can be greatly enriched by the study of emotions. As Pavlenko (2006) points out, bilinguals in monolingual societies have been avoided or treated as problematic, and bilingualism in multilingual societies has been ignored since it is the norm. Other work from the field of psychology shows a long history of looking at correlations between pathological identity formation and discriminating use of first language (L1) and second languages (L2) by subjects. Affective constructs such as anxiety, motivation, self-esteem, risk-taking, and tolerance of ambiguity that are frequently cited in the literature on language learning and acquisition may be relevant to classroom learners in a monolingual society, but they are not representative of the diverse emotional factors that play a role in bilingualism in the greater contexts of language learning and use. The area of neurophysiological responses is related to emotions when different languages are used by



bilingual speakers. There is evidence that L1 is more closely attached to the limbic system of the brain which processes emotions, and other evidence points to the idea that emotional memories are more strongly associated with L1.

The wonder of emotion has been attracting the awareness of more and more researchers from a variety of fields, including neurobiology, psychology, anthropology, and cognitive linguistics. Emotion, defined as the affective aspect of consciousness, was described by Oatley and Johnson-Laird (1998) as being at the center of human mental and social life which may involve both cultural similarity and diversity (Wierbicka, 1999). Human interest in emotion can be dated back in history to ancient Greece. Heraclitus (500 BC) defined the emotional state as a mixture of body parameters such as temperature (hot/cold) and sweat amount (wet/dry) and a normal or non-emotional state as being dry and cold. Democritus (460 BC) characterized happiness (positive emotion) as a state of mental and physical equilibrium and defined thoughts (cognitions) as being the result of a distributed interaction of some localized body components. Hippocrates (460 BC) believed that the brain was at least partly responsible for conscious life including emotions and the emotional states were characterized by brain temperature, moisture and aridity. Plato (427-347 BC) proposed a three-state theory in which pleasure and pain were states that depart from the neutral state.

Most basic emotion sets include fear, anger, joy, sadness, and disgust and some also include surprise, shame, and interest. Each basic emotion reflects a unique motivational and behavioral tendency. The basic emotions are important as they represent distinct modes of action tendencies and are physiologically distinguishable (Ekman, Levenson, and Friesen, 1983).

Emotional processing was first defined as a promising explanatory concept with particular relevance and application to the anxiety disorders (Rachman, 1980). The term was used to refer to the way in which an individual processes stressful life events. Rachman's definition of emotional processing emphasizes negative affects - how disturbing events and reactions were processed

rather than how neutral or positive events were processed. For negative emotional states such as anxiety, grief and anger, it is clear what needs to be changed or absorbed. For positive emotional states, it seems that enhancement or promotion is more preferred than absorption or interference.

Different methodologies have been used in exploring the nature of emotion. A common method in experimental and cognitive psychology was to first induce the desired affective state and then give the subject specific tasks and measure their performance. Performance such as recall and retention of items can be measured and speed, accuracy, and content of the recalled material under different affective conditions can be used to draw conclusions about the impact of affective states on cognition.

Researchers focusing on physiological theories use a variety of measures, including heart rate, and activity of facial musculature. In some cases blood samples are drawn to test for the presence of particular metabolites associated with specific emotional states. A variety of techniques have been used in studying the neural correlates of affect, including imaging techniques such as PET scan, fMRI and Event-Related Potentials (ERP). These non-invasive techniques are promising because they make it easy to study the human brain in vivo.

It is becoming increasingly important for researchers to understand how emotion is conceptualized and verbalized in different cultures. This can not only facilitate intercultural communication and understanding but also improve the ways in which multilingual people living in the mainstream culture deal with a wide range of social contexts. Moreover, the fact that more than half of the world's population is bilingual and multilingual (Romaine, 1995) suggests that more effort needs to be made in studying how becoming bilingual or multilingual can transform an individual's emotional concepts and scripts between languages.

Psycholinguistic studies have suggested that languages learned after puberty may differ from previously learned language(s). Languages learned early in life seem to have a stronger emotional resonance than languages learned later, which seem to have a weaker emotional hold on the

individual (Amati-Mehler et al., 1993; Javier, 1989; Santiago-Rivera & Altarriba, 2002). Bond and Lai (1986) and Javier and Marcos (1989) showed that bilinguals may code switch to their second language to distance themselves from what they say. They argued that language was strongly linked to emotion, affect, and identity. A sudden stop of the use of a child's native language (L1) by parents might lead to great emotional and psychological difficulties both for the parents and for the child. Studies on emotion vocabulary in the first and second languages of bilinguals who learned their second language beyond early childhood showed a greater emotional resonance in the native/first learned language (Gonzalez-Reigosa, 1976; Javier, 1989). Some researchers (Harris et al., 2003) measured fluctuations in reactivity to emotional words in the L1 and the L2 of bilinguals. Their results suggest that the L1 vocabulary may have more emotional connotations, given the proliferation of neural connections in early and middle childhood. Anooshian and Hertel (1994) showed that Spanish-English and English-Spanish bilinguals, who acquired their second language after the age of eight, recall emotional words more frequently than neutral words following their presentation in the L1. Altarriba and Santiago-Rivera (1994) found that late bilinguals in therapy prefer the native language to express their personal involvement.

Some questions on bilingualism and emotion include whether bilinguals are more emotional about one language than others, or whether they see one language as particularly suitable for expressing their emotion, such as anger, irritation, or enjoyment. Answers to these questions allow us to create a big picture of bilinguals' own perceptions of the relationship between their languages and emotion.

### ***Alphabetic versus Ideographic/Logographic Language Processing***

A writing system is a type of symbolic system used to represent elements or statements expressible in language. Writing systems fall into two major categories: ideographic and phonologic. In ideographic languages, the characters reflect the meaning of a thing or an idea rather than the pronunciation of a word. Examples of ideographic language are written Chinese,

Japanese, Korean, Vietnamese, etc. Phonological languages can be further divided into syllable-based languages where each unit reflects one syllable, and alphabetic languages where units correspond roughly to one phoneme. In an alphabetic language, symbols represent vowels and consonants for the pronunciation of words, and syllables and words are formed by a phonetic combination of symbols. Examples of alphabetic languages are English, Greek, Russian, German, Thai, Arabic, Hebrew, etc. (Coulmas, 1996).

Phonologic languages are often easier to handle than ideographic languages in the speech recognition framework, as in many cases rule-based unit-to-phoneme tools can be used to generate the pronunciation dictionary needed to guide recognition, while this is usually not possible for ideographic languages. Among the languages using alphabetic languages, the unit-to-phoneme relationship varies considerably. It ranges from a nearly one-to-one relationship such as for some Slavic languages up to languages like English that require complex rules and have many exceptions (Waibel et al., 2000).

The great benefit conferred by writing systems is their ability to maintain a persistent record of information expressed in a language, which can be retrieved independently of the initial act of formulation. All writing systems require: (a) a set of defined base elements or symbols, individually termed characters or units, and collectively called a script; (b) a set of rules and conventions understood and shared by a community, which arbitrarily assign meaning to the base elements, their ordering, and relations to one another; (c) a spoken language whose constructions are represented and able to be recalled by the interpretation of these elements and rules; (d) some physical means of distinctly representing the symbols by application to a permanent or semi-permanent medium, so that they may be interpreted (usually visually, but tactile systems have also been devised). Most writing systems can be broadly divided into three categories: logographic, syllabic and alphabetic (or segmental); however, all three may be found in any given writing system in varying proportions, often making it difficult to categorise a system uniquely. A

logogram is a single written character which represents a complete grammatical word. Most Chinese characters are classified as logograms (Sampson, 1985; Daniels, 1996; Rogers, 2005).

As each character represents a single word, many logograms are required to write all the words of language. The vast array of logograms and the memorization of what they mean are the major disadvantage of the logographic systems over alphabetic systems. However, since the meaning is inherent to the symbol, the same logographic system can theoretically be used to represent different languages. In practice, this is only true for closely related languages, like the Chinese languages, as syntactical constraints reduce the portability of a given logographic system. Japanese uses Chinese logograms extensively in its writing systems, with most of the symbols carrying the same or similar meanings. However, the semantics, and especially the grammar, are different enough that a long Chinese text is not readily understandable to a Japanese reader without any knowledge of basic Chinese grammar, though short and concise phrases such as those on signs and newspaper headlines are much easier to comprehend. Logograms are sometimes called ideograms, a word that refers to symbols which graphically represent abstract ideas, but linguists avoid this use, as Chinese characters are often semantic–phonetic compounds, symbols which include an element that represents the meaning and an element that represents the pronunciation. Some nonlinguists distinguish between lexigraphy and ideography, where symbols in lexigraphies represent words, and symbols in ideographies represent words. The most important modern logographic writing system is the Chinese one, whose characters are used, with varying degrees of modification, in Chinese, Japanese, Korean, Vietnamese, and other east Asian languages (DeFrancis, 1990).

An alphabet is a small set of letters — basic written symbols — each of which roughly represents or represented historically a phoneme of a spoken language. The word alphabet is derived from alpha and beta, the first two symbols of the Greek alphabet. Perfectly phonemic alphabets are very easy to use and learn, and languages that have them (for example Serbian or

Finnish) have much lower barriers to literacy than languages such as English, which has a very complex and irregular spelling system. As languages often evolve independently of their writing systems, and writing systems have been borrowed for languages they were not designed for, the degree to which letters of an alphabet correspond to phonemes of a language varies greatly from one language to another and even within a single language.

From a psycholinguistic perspective, Perfetti and Zhang (1995) asserted that the reader of an alphabetic system can do better at recovering the phonological form but less well at recovering the semantic category of the word. Further studies (Hardin, O'Connell, and Kowal, 1998) investigated the effect of writing systems (logographic vs. alphabetic) on the temporal organization of reading aloud. They instructed native speakers of Chinese and German to read a semantically identical passage from texts written in their own language. The Chinese version consisted of 132 characters (132 syllables), the German of 80 words (also 132 syllables). In accord with Perfetti and Zhang's assertion, Chinese readers articulated significantly more slowly; they also used significantly more pauses. Moreover, German readers used a set pattern of pause positions, whereas Chinese did not.

However, at the single word level, the processing of Chinese, an ideographic script, does not activate brain areas that are distinct from those activated by English, an alphabetic script. Chee et al. (1999b) compared blood oxygen level-dependent functional MRI images of Chinese-English bilingual subjects performing cued word generation in each language. They found no significant differences in peak-location or hemispheric asymmetry of activations in the prefrontal language areas. On the other hand, Neville et al. (1998) found that processing of American sign language, as a manual alphabetic language, was associated with right hemisphere activations, in addition to classical left hemisphere activations. In contrast, English, also as an alphabetic language, did not produce right hemisphere activations. The additional activations by American sign language were attributed to the temporal coincidence of language information and visuospatial decoding.

Chinese as an ideographic language requires one to memorize the phonology and meaning of each character to vocalize and comprehend. Thus it is hypothesized that Chinese requires processing resources distinct from English at syntactic level. Because sentence processing is more complex than single word processing, Chee et al. (1999b) argued that intrahemispheric and interhemispheric differences in activation between Chinese and English in sentence level studies that are not observed with single word studies may be partly a result of differences in syntactic processing. They believe that it is preferable to probe for language specific processing requirements at single word level before seeking these at the sentence level since words are building blocks of sentences. Their conclusion is that cued word generation, even with orthographically distinct languages such as Chinese and English, can result in the activation of common cortical areas within the left hemisphere.

Another line of research regarding processing of ideographic and alphabetic languages employs the Stroop interference in which subjects are instructed to name color words printed in incongruent color inks. Morikawa (1981) found a significantly different degree of interference depending on the type of characters used in the Stroop task in Japanese speakers. The Kanji character of Japanese language is the ideographic characters originated from Chinese language, in which ideographic language refers to a type of languages whose original characters are pictorial symbols. The Kana character is its modified version in which each letter stands for a syllable. Thus Kana consists of phonographic characters which represent the Japanese phonemic system as English alphabets represent its phonemic system. In accordance with this distinction, Morikawa conducted an experiment in which his participants demonstrated the Stroop effect in both Kanji and Kana conditions. He observed that Japanese speakers showed significantly greater interference in the Kanji condition than in the Kana condition. Also, the reversed Stroop effect was observed only when the participants read Kanji words printed in incongruent colors. Morikawa assumed that ideographic and phonographic characters were processed differently in

the human cognitive system, probably in different hemispheres, and this resulted in greater interference in the ideographic condition.

Biederman and Tsao (1979) compared the degree of the Stroop interference between English and Chinese speakers and found that the Stroop interference was greater in the Chinese version of the Stroop tasks than the English version. They believed that the hemispheric difference of language processing contributed to the Stroop interference in Chinese speakers and asserted that Chinese, which is classified as an ideographic language, is dependent on the right hemisphere of the brain, whereas English, which is a phonographic or alphabetic language, is processed in the left hemisphere, and thus greater interference was observed in Chinese speakers.

Smith and Kirsner (1982) argued for no effect of hemispheric difference. They pointed out that, in Biederman and Tsao's experiment, Chinese speakers were slower in naming color in other conditions as well as interference conditions than English speakers. Therefore, they argued that the greater interference in the Chinese version—that is, more time differences between control conditions and interference conditions in Chinese version than in English version—was not due to ideographic form of Chinese language. Also, the results of their own experiments suggested no difference between Chinese and English conditions (Smith & Kirsner, 1982). Moreover, Smith and Kirsner reasoned that, because the process of picture identification was thought to be dominant in the right hemisphere over the left hemisphere, if the right-hemisphere advantage of Chinese words contributed to the greater interference, the word-picture interference (interference observed when naming a picture that is accompanied by an incongruent word, such as a picture of desk with a word chair) should be also greater in Chinese than in English. Yet they observed no result that would support this hypothesis. Therefore, the assumption that ideographic language was more competitive with color recognition in the right hemisphere was questioned.

More recent studies on the Stroop interference have been conducted and suggested both influence and non-influence of hemispheric differences (MacLeod, 1992). Thus, the question of



whether the hemispheric differences between ideographic and phonographic language processes have influence on the Stroop effect is unsolved. The overall pattern, however, is that ideographic word recognition is superior in the right hemisphere, while phonographic word recognition is superior in the left hemisphere (Sasanuma, Itoh, Mori & Kobayashi, 1977; Hatta, 1977; Hatta, 1978). Furthermore, the right hemisphere has an advantage for color recognition (Sasanuma, 1974; Davidoff, 1976; Pennal, 1977). On the other hand, speakers of ideographic languages display greater interference in the left visual field than in the right visual field (Tsao et al., 1981), indicating influence of hemispheric difference on the Stroop tasks. Even if it is possible that the perceptions of ideographic and phonographic characters are processed differently in different hemispheres, this does not directly affect the results of the Stroop tasks. Hence, the Stroop task is affected neither by the hemispheric differences nor by the ideographic-phonographic distinction.

### ***Electroencephalography (EEG) and Event-Related Potentials (ERPs)***

Electroencephalography (EEG) is an imaging technique that measures brain function by recording and analyzing the scalp electrical activity generated by brain structures. It is a noninvasive procedure that can be applied repeatedly in patients, normal adults, and children, with virtually no risks or limitations. Local current flows are produced when brain cells (neurons) are activated. However, only electrical activity generated by large populations of neurons concurrently active can be recorded on the head surface. The small electrical signals detected by the scalp electrodes are amplified thousands of times, then displayed on paper or stored to computer memory. The scalp electrical activity distribution can also be represented with color maps in 2D and 3D to enhance visualization. Because the EEG procedure is noninvasive and relatively painless, it is widely used to study the brain organization of cognitive processes such as perception, memory, attention, language, and emotion in normal adults and children.

ERPs (event-related potentials) are small voltage fluctuations resulting from evoked neural

activity. These electrical changes are extracted from scalp recordings by computer averaging epochs (recording periods) of EEG time-locked to repeated occurrences of sensory, cognitive, or motor events. The spontaneous background EEG fluctuations, which are random relative to when the stimuli occurred, are averaged out, leaving the event-related brain potentials. These electrical signals reflect only that activity which is consistently associated with the stimulus processing in a time-locked way. The ERP thus reflects, with high temporal resolution, the patterns of neuronal activity evoked by a stimulus. Due to their high temporal resolution, ERPs provide unique and important timing information about brain processing. Mental operations, such as those involved in perception, selective attention, language processing, and memory, proceed over time ranges in the order of tens of milliseconds. Most other functional imaging techniques (such as fMRI and PET) require integrating the evoked brain activity over many seconds and are thus unable to capture the time course (or sequence) of these operations. ERP recordings, however, provide a millisecond-by-millisecond reflection of evoked brain activity. For this reason, ERPs is an ideal methodology for studying the timing aspects of both normal and abnormal cognitive processes. On the other hand, ERP data provide less accurate spatial information than positron emission tomography (PET) or functional magnetic resonance imaging (fMRI), which lack fine temporal resolution. As a result, ERPs represent the natural complement of PET and fMRI to study human cognition. Whereas PET and fMRI can localize regions of activation during a given mental task, ERPs can help define the time course of these activations.

### ***The P300 ERP Component***

The P300 ERP component is a positive wave peaking between 300 and 600 ms post-stimulus employed considerably in studying normal cognitive functions as well as in assessing a variety of mental disorders. Discovered in 1965 by Sam Sutton and his colleagues, this ERP component is thought to provide much fundamental information on the neural basis of normal and dysfunctional cognition (Bashore & van der Molen, 1991, Sutton et al., 1965). Despite many

studies, the usefulness of P300 as a practical assessment tool has been limited because its neural generators are still unclear. Several subcomponents are thought to contribute to the overall P300 generation. The central/parietal maximum “target” P300, or sometimes called P3b, is typically elicited using the traditional two-stimulus oddball paradigm, wherein two types of auditory, visual or somatosensory stimuli are presented in random order, with one (non-target) occurring more frequently than the other (target). The frontal/central maximum P3a is elicited when an infrequent tone is presented with physically different frequent tones without a task (Squires et al., 1975; Snyder and Hillyard, 1976). Appropriately presented visual stimuli without a task also can produce a P3a-like potential (Mertens and Polich, 1997; Jeon and Polich, 2001). The frontal/central maximum “novelty” P300 is elicited using the modified three-stimulus oddball paradigm with novel non-target stimuli inserted as distracters into the sequence of target and standard non-target stimuli. Recent studies confirmed that “novelty” P300 and P3a potentials are the same component (Simon et al., 2001; Spencer et al., 1999). The central/parietal maximum “no-go” P300 is elicited by infrequent non-target stimuli that are not novel but easily recognized in the three-stimulus oddball paradigm, wherein subjects do not respond to the infrequent non-targets (Katayama & Polich, 1996, Falkenstein et al., 1995; Pfefferbaum & Ford, 1988, Pfefferbaum et al., 1985, Courchesne, 1978; Courchesne et al., 1978).

Donchin et al. (1986) describes P300 amplitude as an index of brain activities "required in the maintenance of working memory" when the mental representation of the stimulus context is updated. This theory is based on the orienting response model that was derived from habituation and dishabituation effects (Sokolov, 1977). Following initial sensory stimulus processing, the brain compares the current stimulus of the oddball sequence to the previous stimulus in working memory. If it detects no change in stimulus attributes, the brain maintains the old "schema" or neural model of the stimulus environment while recording the sensory evoked potentials. If the brain detects the processing of a new stimulus, it engages attentional mechanisms to "update" the

neural representation of the stimulus context while the P300 (P3b) is elicited to index the ensuing memory storage operations. This view is supported by findings that larger P300 amplitudes are related to memory for previous stimulus presentations (Fabiani et al., 1990; Johnson, 1995; Paller et al., 1988a).

P300 latency is thought to index stimulus evaluation time (e.g., Coles, Smid, Scheffers, & Otten, 1995) and measure stimulus classification speed unrelated to response selection processes (Kutas et al., 1977; McCarthy and Donchin, 1981). Its timing is generally related to but independent of response time (Duncan-Johnson, 1981; Pfefferbaum et al., 1986; Verleger, 1997). Because P300 latency is an index of the processing time prior to response generation, it serves as a temporal measure of the neural activity underlying the processes of attention allocation and immediate memory. Neuropsychological tests that assess how rapidly normal subjects allocate attentional resources for memory processing reveal that cognitive efficiency is negatively correlated with P300 latency. Shorter P300 latencies are associated with higher cognitive performance on the tests (e.g., Emmerson et al., 1990; Stelmack, & Campbell, 1998; Polich et al., 1983, 1990b; Polich & Martin, 1992; Houlihan et al., 1998; Reinvang, 1999; Stelmack & Houlihan, 1994). Goodin, Squires, and Starr (1978) found P300 to be the most sensitive ERP component to aging in normal subjects when comparing long-latency auditory evoked potentials from two groups of patients, with and without dementia, and those from a population of normal subjects ranging in age from 15 to 76 years. P300 was also found to be the only ERP component differentiating between the demented patients and the normal subjects or non-demented patients. More recent studies have provided evidence supporting that long-latency P300 latency increases with normal aging (Polich, 1996; Squires & Olo, 1999; Fjell and Walhovd, 2001), and peak timing increases as mental capability is compromised by dementia (Polich et al., 1986, 1990a; O'Donnell et al., 1992; Potter and Barrett, 1999; Polich and Corey-Bloom, 2005).

It is generally accepted that changes in P300 amplitude, latency, and scalp topography have

been associated with a number of psychometric and cognitive variables. The major factors affecting P300 measures include information content, stimulus-probability structure, stimulus properties, and task relevance/difficulty, defined as the amount of attention required by the stimulus (Donchin & Coles, 1988; Oken, 1989; Sommer et al., 1998; Verleger, 1988). Stimuli with high emotional value, informative feedback stimuli, and target stimuli usually elicit larger P300s than stimuli that do not have these properties (Johnson, 1988a, Picton, 1992, and Pritchard, 1981). In addition, P300 is sensitive to the general and specific arousal effects that contribute to attention activation and information processing (Pribram and McGuinness, 1975; Kok, 1990).

The between-subject correlation coefficient for P300 amplitude calculated from tests and retests ranges from 0.50 to 0.80 and for peak latency from 0.40 to 0.70 (Polich, 1986a; Fabiani et al., 1987; Segalowitz and Barnes, 1993). This test–retest variability results partially from “ultradian rhythms effects” on ERP measures (Lin and Polich, 1999; Ravden and Polich, 1999). Despite this variation, P300 measures are still considered to be as sensitive as most standard biomedical clinical assays that can measure individual cognitive capability in both normal and patient populations, and are relatively inexpensive to record (Polich and Herbst, 2000).

The precise neural origins and associated neuropsychological meaning of the P300 are as yet unknown, despite considerable progress made in the last two decades. Given the P300 association with attentional and memory operations which have neural origins in the hippocampal areas, the first human studies (Halgren et al., 1980; McCarthy et al., 1989) used depth electrodes implanted in epileptic patients to help identify sources of epileptic foci, with results suggesting that at least some portion of the P300 (P3b) is generated in the hippocampal areas of the medial temporal lobe. Subsequent studies using scalp recordings on individuals after temporal lobectomy (Johnson, 1988a; Smith & Halgren, 1989), monkeys after experimental excisions (Paller et al., 1988b, 1992), and patients with severe medial temporal lobe damage (Onofrj et al., 1992; Rugg et al., 1991) revealed that the hippocampal formation does not contribute directly to the generation

of P300 (Molnar, 1994). With a positive correlation found between P300 amplitude from each modality and the proportional size of the hippocampal formation relative to the temporal lobe (Polich & Squire, 1993), it is suggested that larger hippocampal size is associated with larger P300 amplitudes. Further studies of lesion patients have found that the temporal-parietal lobe junction is involved in either transmission or generation processes subsequent to hippocampal activity and contributes to component recordings at the scalp (Johnson, 1993; Knight et al., 1989; Yamaguchi & Knight, 1992; Verleger et al., 1994). All these findings suggest that although relative absence of the hippocampus does not eliminate the P300, its presence and/or connection with temporal-parietal lobe function does influence P300 generation (Polich, 2004).

The interruption of the attention required for the primary discrimination task by an infrequent non-target stimulus event generates the P3a subcomponent. The non-target does not have to be perceptually novel (Comerchero & Polich, 1999). The ERP data from humans with frontal lobe lesions (Knight, 1990, 1997; Knight et al., 1995) have shown a frontal-central scalp distribution for P3a elicited by the novel distracter stimulus and a parietal maximum distribution for P3b by the target stimulus for the controls, versus a decrease of the P3a subcomponent by the distracter stimulus and the usual parietal maximum for the P3b by the target stimulus for the frontal lesion patients. Thus frontal lobe activity is necessary for P3a generation and contributes to the larger role in attention control.

In addition to frontal lobe activity, ERP studies on patients with focal hippocampal lesions (Knight, 1996) found that hippocampal formation has also been associated with P3a generation. P3a amplitude elicited by novel auditory distracter stimuli for the control group reveals the typical frontal-central maximum scalp topography, whereas the P3a for the patient group is virtually eliminated over frontal electrode sites. In comparison, P3b amplitude elicited by the target stimulus is generally similar between the groups at the parietal site, as observed previously. Thus, frontal lobe activities as well as hippocampal processes driven by novelty information

processing contribute to the P3a generation (Polich, 2004).

The frontal lobe activity that reflects the attentional focus required by task performance is thought to be initiated by the discrimination between target and standard stimuli in an oddball paradigm (Pardo et al., 1991; Posner, 1992; Posner & Petersen, 1990). Additional ERP and fMRI findings demonstrate that frontal lobe activity is required for the detection of rare or alerting stimuli (McCarthy et al., 1997; Potts et al., 1996; Verbaten et al., 1997). P3a is thought to reflect the neural changes in the anterior cingulate in response to incoming stimuli replacing the contents of working memory, and causing communication of this representational change to be transmitted to the infero-temporal lobe for stimulus maintenance (Desimone et al., 1995). P3b is related to memory storage processes that are initiated at the hippocampal formation when the updated output is transmitted to parietal cortex (Squire & Kandell, 1999; Knight, 1996). Despite little knowledge about the exact pathways (Halgren et al., 1995ab), it is suggested that these events are caused by the neural processes in the hippocampal formation, even though it is not necessary for P300 generation (Johnson, 1988a; Polich & Squire, 1993). In summary, P3a is elicited by a demanding stimulus drawing frontal lobe attention, and P3b is generated when subsequent memory updating following stimulus evaluation processes causes allocation of attentional resources to establish connection with storage areas in associational cortex (Polich, 2004).

The interaction between frontal lobe and hippocampal/temporal-parietal function initiates the neuroelectric events that underlie P300 generation (Kirino et al., 2000; Knight, 1996). ERP and fMRI studies using oddball paradigms provide evidence supporting this frontal-to-temporal and parietal lobe activation pattern (He et al., 2001; Kiehl et al., 2001; Mecklinger et al., 1998; Opitz et al., 1999; Spencer et al., 1999). The fMRI studies of gray matter volumes reveal that individual variation in P3a amplitude elicited by distracter stimuli is correlated with the size of frontal lobe area, whereas P3b amplitude elicited by target stimuli is correlated with the size of parietal area (Ford et al., 1994). This finding seems to support individual variability in P3a and P3b

subcomponents as observed in simple oddball tasks (Polich, 1988; Squires et al., 1975).

It is hypothesized that the neural processes in the frontal lobe in response to the incoming stimulus during auditory discrimination are passed along between the cerebral hemispheres across the corpus callosum (Barcelo et al., 2000; Baudena et al., 1995; Satomi et al., 1995). The initial neural activation seems to originate from right frontal cortex (Polich et al., 1997) with larger P300 amplitude over the right compared to left frontal/central areas (Alexander et al., 1995, 1996; Mertens & Polich, 1997). This hypothesis is supported by evidence that larger callosal fiber tracts are associated with greater P300 amplitudes and shorter latencies (Alexander & Polich, 1995, 1997; Polich & Hoffman, 1998) caused most likely by increased inter-hemispheric communication (Witelson, 1992; Driesen & Raz, 1995). Thus, the P3a and P3b are distinct ERP components generated by the interaction between frontal lobe attentional control over the contents of working memory and the subsequent long-term storage operations (Polich, 2004).

### ***The Oddball Paradigm***

The commonly used “oddball” paradigm involves detection of an infrequent target stimulus within a series of rapidly presented “standard” stimuli. This detection evokes widespread neural activity that is reflected in both electrophysiological and hemodynamic measures. A typical auditory oddball task might involve the detection of a high-pitched tone in a sequence of low-pitched tones. Auditory oddball tasks sometimes also include a low probability task-irrelevant stimuli, such as novel, non-repeating random noises, which are thought to elicit automatic attentional orienting responses (Friedman, Simpson, & Hamberger, 1993). A typical visual oddball task might assign a 95% chance for a square to be presented and a 5% chance for a circle. Typically, the task during an oddball paradigm is to press a button in response to target stimuli and ignore non-target stimuli or to mentally count the occurrence of target stimuli. In oddball tasks that require a response to a particular infrequent stimulus type, an enhanced P300 is usually elicited by the infrequent target stimuli relative to the frequent non-target stimuli (See Figure 1).



This is thought to reflect cognitive processes necessary for updating working memory representations of task-relevant stimuli (Donchin & Coles, 1988).

### **INSERT FIGURE 1 HERE**

The oddball task and its variants have been used in thousands of published electrophysiological studies (Herrmann & Knight, 2001; Picton, 1992), and recent studies have adopted the oddball design within event-related functional magnetic resonance imaging (fMRI) (Huettel and McCarthy, 2004). This popularity is a direct result of its success in evoking robust and reliable phenomena that have been used as markers of cognitive function (Polich, 1999). Modifications of the traditional oddball paradigms include three-stimulus oddball paradigms (Courchesne, Hillyard, & Galambos, 1975), single-stimulus (Polich, Eischen, & Collins, 1994), and passive tasks (Squires & Ollo, 1999). In a visual oddball task, Courchesne et al. (1975) used rarely interposed numeral 4s and novels in a sequence of frequently flashed background numeral 2s. Subjects were instructed to count the number of presentations of the numeral 4 and ignore intrusive and task-irrelevant novel stimuli in this three-stimulus oddball task. The rare stimuli were of two types: simples, which were easily recognizable (e.g., geometric figures), and novels, which were completely unrecognizable (i.e., complex, colorful patterns). It was found that the simples and the counted 4s evoked posteriorly distributed P300 waves (latency 380-430 msec) while the irrelevant novels evoked large, frontally distributed P300 waves (latency 360-380 msec). These large, frontal P300 waves to novels were also found to be preceded by large N200 waves (latency 278 msec). These findings indicate that "the P300" wave is not a unitary phenomenon but should be considered in terms of a family of waves, differing in their brain generators and in their psychological correlates.

Comparing a single-stimulus task with two-stimulus auditory oddball task, Polich et al. (1994) found that P300 amplitude and latency were highly similar for both tasks across all conditions. Both target and standard tones were presented in the classical oddball paradigm while only a

target tone was presented in the single-stimulus paradigm. Two experiment conditions were designed with the first one having three different target stimulus probabilities (0.20, 0.50, and 0.80) and the second one having two inter-stimulus interval (2 seconds and 6 seconds) and two target stimulus probabilities (0.20 and 0.80). Both conditions produced highly similar P300 amplitude and latency results across probability levels for each paradigm. In another auditory oddball task, Squires and Ollo (1999) used rare auditory stimuli that were discrepant from the frequent stimuli both in frequency and intensity. In one condition, subjects were instructed not to attend. In the other condition, subjects were instructed to count the rare stimuli. The ERPs elicited under both non-attend and attend conditions were compared with ERPs elicited in a standard oddball paradigm. The results revealed that the ERPs elicited by the discrepant oddball stimuli under non-attend conditions were similar in scalp distribution to the ERPs elicited by the same stimuli in attend and standard conditions.

Watson, Azizian, Berry, and Squires (2005) used a multi-stimulus visual oddball paradigm to study the ERP correlates of processing non-target stimuli that are conceptually, but not perceptually, similar to a target. Pictures of five objects (globe, hanger, dart, racquet, and harp) and their corresponding names were used as stimuli with either the word “globe” or the picture of globe being the target stimuli. All stimuli were presented with equal probability (.10). Participants were instructed to mentally count number of target presentations. Large P300s were elicited by the target word “globe” and the non-target picture of the globe, though the P300 to the picture was smaller in amplitude. But when the target was the picture of the globe, large P300 was elicited only by the target but not by the related non-target word “globe”. In another recent study (Azizian, Freitas, Parvaz, and Squires, 2006), a multi-stimulus visual oddball paradigm was used to investigate ERP correlates relating perceptual similarity to action control. Five geometric shapes were used as stimuli with target types randomly counterbalanced across participants. Four stimulus types with one as target were presented with equal probability (.10), and frequent non-

targets were presented with a .60 probability, thus allowing comparison between target and three non-target stimulus types of equal probability. The stimulus types were defined as targets, similar non-targets with missing parts, dissimilar non-targets, dissimilar non-targets with missing parts, and frequent non-targets. The task was to press one button for targets and the other button for non-targets with assignment of hand use counterbalanced across subjects. The results showed an enhanced N200 elicited by similar non-targets relative to any other stimuli at fronto-central scalp sites and an enhanced P300 elicited by targets relative to non-targets with maximal at centro-parietal scalp sites.

There is great interest in determining what factors modulate the neural responses to target and non-target stimuli in an oddball task. Global target probability (Duncan-Johnson & Donchin, 1977), the inter-stimulus interval (Polich, 1990), and the order of non-target and target stimuli (Polich & Bondurant, 1997) have been found to modulate the P300 ERP component. However, these manipulations also change the absolute time between targets, referred to as target-to-target interval, or target interval. It is unclear which brain structures might be modulated by target intervals because of the difficulty inferring the location of ERP neural generators in general (Baillet & Garnero, 1997; Pascual-Marqui, Michel, & Lehmann, 1994) and the P300 in particular (Halgren et al., 1995a; Halgren et al., 1995b; Halgren, Marinkovic, & Chauvel, 1998). The measurement of brain hemodynamics using fMRI provides a way to identify which structures are influenced by oddball target interval manipulations. Several fMRI auditory oddball studies showed that hemodynamic activity is elicited in numerous, widespread cortical and subcortical brain structures during target detection and novelty processing. One of the studies (Kiehl et al., 2005) showed that activation elicited by target and novel stimuli was extremely reliable in the vast majority of these regions.

Another recent fMRI study (Stevens, Calhoun, and Kiehl, 2005) examined the influence of the length of target-to-target intervals on hemodynamic activity elicited by target and novel stimuli

by re-analysis of a large fMRI data set (Kiehl et al., 2005). The task was a three-stimulus auditory oddball task previously used in both ERP and fMRI studies (Kiehl et al., 2001; Kiehl et al., 2005). The standard stimulus was a 1000-Hz tone with a probability of .80, the target stimulus was a 1500 Hz tone with a probability of .10, and the novel stimuli were non-repeating random digital noises (e.g., tone sweeps, whistles) with a probability of .10. Participants were instructed to respond as quickly and as accurately as possible with their right index finger when a target tone occurred and not to respond to other stimuli. Stimuli were presented for 200 ms with a 2000-ms stimulus onset asynchrony (SOA). Target intervals ranged from 8 to 68 seconds and novel intervals ranged from 8 to 62 seconds with 15 separate target intervals and 17 novel intervals in total. The study found a positive relationship between target interval and hemodynamic activity in the anterior cingulate and in bilateral lateral prefrontal cortex, temporal-parietal junction, post-central gyri, thalamus, and cerebellum, suggesting updating of the working memory template for the target stimuli. No such effect of novel interval was found suggesting that neuronal modulation may only occur for task-relevant stimuli, possibly in the service of strategic resource allocation processes.

### ***Neural Representation of Emotion***

The experience of human emotions is thought to be linked to brain areas responsible for attention and motivation. Earlier work by Broca (1878), Papez (1937), and MacLean (1952) suggested that emotion-related structures exist in the center of the brain called the limbic system. The major structures of the limbic system are the hypothalamus, cingulate cortex, and hippocampi. More recent studies (see Dalgleish, 2004 for a review), by employing fMRI, lesion, and single-cell recording techniques to identify neural substrates of emotional processing, have found that some of these limbic structures are not as directly related to emotion as others, while some non-limbic structures are more involved in emotional processing. These non-limbic structures include amygdala, prefrontal cortex, anterior cingulated cortex, ventral striatum, and

insular cortex. The amygdalae, located anterior to the hippocampus structures near the temporal poles, are thought to be involved in detecting and learning what parts of human surroundings are important and have emotional significance. It is widely believed that the amygdala plays an important role in processing emotional stimuli, and perhaps threatening stimuli in particular. The prefrontal cortex, located at the very front of the brain, behind the forehead and above the eyes, is thought to play a critical role in the regulation of emotion and behavior by anticipating the consequences of human actions. The anterior cingulate cortex (ACC), located in the middle of the brain and just behind the prefrontal cortex, is thought to play a central role in attention and initiation of motivated behavior. The ventral striatum is a group of sub-cortical structures thought to be involved in the experience of goal-oriented positive emotion. Individuals with addictions experience increased activity in this area when they encounter the object of their addiction. The insular cortex is thought to play a critical role in the bodily experience of emotion, as it is connected to other brain structures that regulate the body's autonomic functions (heart rate, breathing, digestion, etc.). This region also processes taste information and is thought to play an important role in experiencing the emotion of disgust.

The hemispheric asymmetry hypothesis in the experience of human emotion has long been a controversy with early theories highlighting the importance of right hemisphere function while more recent studies pointing towards differential involvement of left and right frontal cortical regions in regulating positive and negative emotion respectively. Recent functional MRI data (Lawrence & Murphy 2001) revealed activation of medial and dorso-medial frontal cortical regions (particularly in the left hemisphere) for positive emotions such as happiness and pleasantness, and bilateral activation of ventral, ventro-lateral and medial prefrontal cortex for negative emotions such as sadness, anger, fear, guilt, disgust, anxiety, and unpleasantness. Statistical meta-analysis of 106 PET and fMRI studies showed greater left-sided activity for positive/approach emotions and symmetrical activity for negative/withdrawal emotions (Murphy,

Nimmo-Smith & Lawrence, 2003).

Many recent studies (Dolan, 2002; Adolphs, 2003) investigating the neural representation of emotion have found differences in brain responses to stimuli that vary in emotional valence. Such differences have been interpreted as evidence for special brain structures responsible for the processing of emotional information. A complex interconnected network of brain structures has been found to be responsible for emotional processing, including higher order sensory cortices, the amygdala, paralimbic and higher cortical areas such as somatosensory cortex, anterior cingulate, and medial prefrontal cortex. Perceptual representations of emotionally relevant stimuli are thought to be formed at higher order sensory cortices. Sensory representations are thought to be classified in terms of their emotional significance at the amygdala, orbitofrontal cortex, and ventral striatum structures. Conscious representations of emotional states are thought to be generated at paralimbic and higher cortical areas and used in the strategic control of behavior in complex social situations, and in the planning of future goals and actions.

One group of studies have used emotional faces as salient stimuli to investigate neural substrates of emotional processing. These studies have found that brain areas generally involved in the processing of emotional information are also activated during the processing of facial emotion. The initial perceptual analysis of faces takes place in inferior occipital cortex ('occipital face area'; see Rossion et al., 2003) and in the middle fusiform gyrus for structural properties of faces which determine face identity (Hoffman & Haxby, 2000; Haxby, Hoffman, & Gobbini, 2000; Gobbini & Haxby, 2007). The superior temporal sulcus is involved in the processing of dynamic aspects of faces, such as facial expression, eye and mouth movements (Allison, Puce, & McCarthy, 2000; Puce, Epling, Thompson, & Carrick, 2007). A rapid evaluation of the emotional and motivational significance of facial expression appears to be mediated by the amygdala and orbitofrontal cortex, while structures such as the anterior cingulate, prefrontal cortex and somatosensory areas are linked to the conscious representation of emotional facial expression for

the strategic control of thought and action, as well as to the production of concomitant feeling states (Adolphs, 2003).

Another group of studies, though not as many as the first group using emotional faces, have employed emotional words as visual stimuli to probe the underlying neural structures responsible for the processing of emotional information. The consistent finding is that emotional word stimuli activate the posterior cingulate cortex, a region that is thought to have memory-related functions. One fMRI study (Maddock, Garrett, & Buonocore, 2003) using pleasant, unpleasant and neutral words in a valence evaluation task has found that pleasant and unpleasant words when compared with neutral words activate the subgenual cingulate cortex, anteromedial orbital and left inferior and middle frontal cortices. Unpleasant words only activate right amygdala and auditory cortex while pleasant words only activate left frontal pole. A PET study (Beauregard, et al., 1997) reveals that the occipital regions are involved in visual-perceptual analysis of words, and the left temporal lobe represents the neural substrate for the orthographic lexicon, while limbic brain structures of the frontal lobes carry out further processing of emotionally relevant material. Viewing of random-letter strings or abstract, concrete, or emotional words (words with positive or negative emotional salience) by subjects produces a cognitively complex mental state in which anticipation, emotional responses, visual perceptual analysis, and activation of orthographic representations are all occurring. With baseline conditions being either passive viewing of plus signs or an anticipatory state (viewing plus signs after being warned to expect words or random letters to appear imminently), all words, and to a lesser extent the random letters, produced robust activation of cerebral blood flow in bilateral occipital regions as well as the left posterior temporal lobe. In particular, emotional words produced activation in orbital and midline frontal structures.

Earlier research has shown a valence dependent encoding asymmetry of emotional words (e.g., Pratto & John, 1991; White, 1996; Stenberg, Wiking & Dahl, 1998). A recent study (Dahl 2001)

has found affective asymmetry in response latencies when processing emotional words. Significantly prolonged response latencies have been found for negative words relative to positive ones in the subsequent detection task when using an affective orienting task but not when using a non-affective orienting task. The results support the Mobilization-Minimization hypothesis (Taylor, 1991) that negative events and stimuli occupy more cognitive resources.

As most of these recent studies have used fMRI measures, which are based on relatively slow hemodynamic brain responses to emotional stimuli, information about the time course of emotional processing has been relatively scarce. Event-related brain potential (ERP) or magnetoencephalographic (MEG) measures, on the other hand, represent a useful tool to study the time course and the functional properties of emotional processing stages, such as their automaticity, specificity, and sensitivity to attentional states. They provide more detailed temporal information and present a more comprehensive picture of the functional properties of the emotional brain. Thus, ERPs and MEGs complement fMRI measures by providing insights into temporal parameters of emotional processing.

A recent ERP study (Holt et al., 2005) provides further evidence supporting earlier findings that processing negative words requires more cognitive resources than positive words, or the so-called “negativity bias”. The stimuli used are unpleasant, pleasant and neutral words in two-sentence descriptions of social situations with the first one being neutral and affectively ambiguous in content, while the second one maintaining the ambiguity or providing a resolution via one word either negatively or positively valenced. The study consists of two experiments with the first one requiring subjects to perform an "active" explicit affective judgment task, while the second requiring subjects to make only occasional congruency judgments in a "passive" reading task. ERP data show that unpleasant words when compared with pleasant ones within sentences, regardless of task, elicit a larger late P300, an index of attentional and contextual updating, with a latency window between 500 and 700 ms, consistent with the “negativity bias”. Furthermore, this



“negativity bias” operates during the online comprehension of verbal descriptions of social situations. An N400 effect, an index of semantic integration, has also been found in response to unpleasant words versus neutral words in the implicit passive reading task. The study suggests that negative words within sentences describing social situations are more difficult to integrate semantically than neutral words.

More recent research (Cunningham et al., 2005) reveals the frontal ERP asymmetries associated with emotionally-valenced words and processing goals. Subjects have been asked to make good vs. bad (evaluative) and abstract vs. concrete (non-evaluative) judgments of socially relevant concepts (e.g., “murder,” “welfare”), and then rate all concepts for goodness and badness. A late P300 component has been found beginning at about 475 ms post stimulus with maximal amplitudes over anterior sites. A higher amplitude and shorter latency for late P300 has been observed on the right for concepts later rated bad, and on the left for concepts later rated good. Moreover, larger degree of lateralization for the amplitude but not the latency has been observed with participants making evaluative judgments than making non-evaluative judgments. The results support early findings that discrete regions of prefrontal cortex (PFC) are specialized for the evaluative processing of positive and negative stimuli.

An early encoding of the emotional valence, supported by recent ERP studies exploring the time signatures of the processes evoked by emotional stimuli, is found typically within the first 100–300 ms from stimulus onset. Pioneer work by Pizzagalli, Regard, and Lehmann (1999) who recorded the ERPs during hemifield presentation of ‘disliked’ and ‘liked’ faces showed modulation by the emotional stimuli happened as early as 80–116 ms after stimulus onset when stimuli were presented to the right hemisphere and 140–160 ms when stimuli were presented to the left hemisphere. More recent ERP studies confirm the early modulatory effects of emotional stimuli using either emotional faces (Campanella et al., 2002; Eger et al., 2003; Eimer & Holmes, 2002; Esslen et al., 2004; Sato et al., 2001) or emotional words (Ortigue et al., 2004) as stimuli.

These studies reveal consistently an early encoding of the emotional value of the stimuli before perceptual or categorical encoding of the stimuli themselves. Using emotional faces, Eimer and Holmes (2002) reported a fronto-parietal positivity elicited by fearful faces within 120 ms after stimulus presentation, while typical structural face-specific encoding is linked to the N170 component. Using emotional words, Ortigue et al. (2004) reported activity at the bilateral lateral-occipital location related to emotional words in the 100–140 ms post-stimulus period, while semantic encoding of words is typically identified by the N400 component. These results indicate that the networks (for different modalities) involved in encoding the emotional value of stimuli are dissociated from the networks responsible for the higher-level categorization of these stimuli. Hence a crude emotional classification seems to begin very early on after stimulus onset providing support for a “fast” route theory (Taylor & Fragopanagos 2005).

### ***Neural Representation of Language***

The human brain contains billions of neural cells, or neurons, with one neuron influencing tens of thousands of other neurons while in turn being influenced by other neural cells irrespective of their distance. The higher cerebral areas are thought to control learned vocalizations such as human language whereas lower cerebral areas control innate vocal utterances such as human crying. Hippocrates, in the 5th century BC, initiated the concept of contralateral control of function through findings on temporary loss of the ability to speak after convulsive crises that resulted in a paralysis of the tongue and of the right side of the body. The right hemisphere lesions provoked spasms in the left side of the body and, conversely, left hemisphere lesions provoked spasms in the right side of the body. Broca (1878) found that the left hemisphere controlled both language acquisition and the dominant use of the right hand or right manual preference, identifying the left frontal lobe (the Broca’s area) as accounting for articulated language. Carl Wernicke (1874) identified another language center located in the left temporal lobe as accounting for comprehension of phonemes and words. Wernicke ascribed the motor

functions to the frontal brain, the cerebral structures anterior to the Rolandic fissure, and the sensory functions to the temporo-occipital brain. He viewed language as being organized in various interconnected centers via specific communication pathways (Gray, 1994).

The most widely used method of assessing the cerebral organization of language is by observing patients with language disorders caused by localized cerebral lesions. Most typical language disorders (or aphasia syndromes) are related to the site and extent of the left cortical lesion. Studies of patients with focal lesions in the right hemisphere have led to better understanding of the role played by the so-called non-dominant cerebral hemisphere in the organization of communication. Furthermore, the right hemisphere is thought to be involved in the comprehension of high-frequency words, words that can easily be visualized, and concrete words as well. Some researchers have proposed that the left hemisphere controls the most automatic aspects of language, whereas the right hemisphere, which activates diffusely, processes language non-automatically (Fabbro, 1999).

Using positron emission tomography (PET) technique, Pettito et al. (2000) reported cerebral blood flow activity in profoundly deaf signers processing specific aspects of sign language in key brain sites widely assumed to be unimodal speech or sound processing areas. The areas were the left inferior frontal cortex when signers produced meaningful signs, and the planum temporale bilaterally when they viewed signs or meaningless parts of signs (sign-phonetic and syllabic units). Contrary to the traditional view about the planum temporale (PT) being exclusively dedicated to processing speech sounds, the study revealed that PT may actually be specialized for processing more abstract properties essential to all languages that can engage multiple modalities.

Gil-da-Costa et al. (2006) recently analysed the brain activity of Rhesus monkeys listening and recognising other monkeys' calls. They found that the brain areas activated in monkeys were equivalent to those used for language in humans. Also using the PET technique, they injected radioactive isotopes (which are biologically safe and similar to the ones used in many exams

performed in humans) into the bloodstream of the monkeys and then took several PET images to trace the isotopes within the body. The logic is that when a task is performed and a specific brain region is activated, blood (and isotopes) rushes into this area in bigger quantities, identifying in this way the region involved in the task. Several images were taken from rhesus monkeys while listening to coos and screams of other monkeys as well as to non-biological sounds as controls such as musical instruments and computer-synthesized noise. All these sounds were matched to have the same frequency, rate, scale, and duration as the sounds from the macaques, to assure that the results observed were a response to the calls' meaning and not just to a particular noise. The monkeys' brain areas equivalent to the Perisylvian region in humans, were found to be significantly activated while listening to other monkeys' calls than to control sounds. This suggests that the most recent ancestor of human and non-human primates, that lived 25-30 million years ago, already had the neural substrate that later led, through different evolutionary processes, to the appearance of language in humans and the basic specific-meaning sounds found in monkeys.

One of the most important adaptations during human evolution is the ability to acquire language and create new interactions and ideas to bridge time and space. Differences in sucking and heartbeats rates among four-week-old human babies when presented with audiotape in different consonant sounds show that they can respond to about 40 consonants. This seemingly innate ability is supported by the observation that babies from English-speaking parents react to consonants in Japanese that not exist in the English language (Kasper 1997). The ability of a six-year-old child to react to sounds to which he/she has not been exposed is severely reduced as brain development rate decreases at this point. After that age, it is thought much more difficult to learn a second language. Two main language centers identified in the human brain, i.e., Broca's area, in the frontal lobe and Wernicke's area, in the posterior, are both found within a larger surface called the Perisylvian region. This region is believed to be associated with language

comprehension and production. The PET findings (Gil-da-Costa et al., 2006) support the hypothesis that the neural basis for language already existed in a common ancestor, thus ending the long debate about the origin of brain areas responsible for human language. Researchers earlier had different opinions regarding whether these mechanisms appeared independently in humans or were already present in a common ancestor of human and non-human primates. Though not having the language capability, monkeys do have an extended amount of sounds with specific functions such as alerting to the presence of predators and marking various social interactions or emotional states. The brain areas in monkeys were found similar to the Perisylvian area, although until now their functional significance was unknown, as was their link to the equivalent human region.

It has been previously revealed that listening to sounds by other monkeys also activated brain areas associated with the visual and emotional memories of objects in humans. The most recent PET results further suggest that not only a common neural basis exists in monkeys and humans for understanding socially relevant information from sounds within the species, but also a much broader neurological network exists in both human Perisylvian area which seems to be the language center and in equivalent monkeys' brain areas that are involved in the extraction of meaning from socially relevant situation.

### ***Second Language Acquisition/Neural Representation of Language in Bilinguals***

Whereas first language acquisition seems natural, second language acquisition is a process that involves perception, attention, memory, emotion from a neuropsychological perspective. Studies show that bilinguals may store their first language and the second language in separate memory systems. The first language is mainly stored by implicit strategies and the second language stored to a wider extent by explicit strategies (Paradis, 1994). Most neuropsychologists in the late 1970's and early 1980's believed that the following variables might contribute to the functional organization of languages in the bilingual brain: age, proficiency, literacy, reading effects, type of

script, language specific factors, social acculturation, teaching method, cognitive style and nonverbal, interactional elements in communication. Their major questions were whether the left and right hemispheres organize language differently in bilinguals from monolinguals and whether there is no significant hemispheric difference in bilinguals' first (L1) and second (L2) languages processing (Vaid and Genesee, 1980; Vaid, 1981; Galloway, 1982).

The age hypothesis claims a logical difference in L2 acquisition between early bilinguals (bilingual from infancy or childhood) and late bilinguals (bilingual after puberty) because cognitive growth and brain maturation are at different stages of development for older and younger people. Vaid (1981) proposed that the pattern of hemispheric processing in bilinguals is more similar to monolinguals if L2 acquisition occurs early and more dissimilar if L2 acquisition occurs later. The proficiency hypothesis claims that right hemisphere may be more involved during the initial stages of L2 acquisition than it is after the greater degree of fluency has been attained (Obler, 1981). This hypothesis predicts that (1) there should be no laterality differences between L1 and L2 in proficient bilinguals and (2) L1 should appear more lateralized to the left hemisphere than L2 during the early stages of L2 acquisition. Despite preliminary studies that provided some insights into the proficiency hypothesis, later studies found no supporting evidence. Proficient bilinguals (early or late) show no significant laterality differences between L1 and L2. However, if limited primarily to reading, the left hemisphere may appear more involved in the L2 acquisition and if it is a new and foreign writing system, the right hemisphere may be more involved in processing the orthography (Galloway, 1982).

A couple of studies show that the L2 is more left-lateralized than the L1 if the L2 is acquired in a formal classroom setting emphasizing reading skills rather than speaking and auditory comprehension. Wechsler (1976) hypothesized that reading and writing may contribute to the language dominance of the LH. He further predicted that bilinguals would suffer more and longer impairments to write-only languages (e.g., Latin) than to vernacular languages after left-sided

brain damage but less and shorter impairments to write-only languages than to vernacular languages after right-sided brain damage. In addition, a language in which a patient was illiterate would be more impaired (or recover later) than languages that the patient could read after right-sided damage. Conversely, languages that the patient could not read would be less impaired (or recover earlier) than languages that the patient could read after left-sided lesions.

It is generally accepted that the right hemisphere shows performance superiority in processing novel visual shapes and design (Gordon & Carmon, 1976). Visual tests and reaction time studies indicated a shift from right to left hemisphere performance superiority with increased familiarity with the L1 orthography. A study by Vaid (1981) using a visual Stroop paradigm supports initial right hemisphere superiority in dealing with non-native, unknown alphabets. Vaid also concluded that the more phonetic a language script is the more its processing tends to be left lateralized. In contrast, the ideographic scripts may rely more on right hemisphere processing. For example, Chinese characters have less symbol-sound correspondence than phonic scripts such as German and tend to be processed in the right hemisphere. Language scripts with a close letter-sound correspondence may involve less visual processing and more auditory processing in the anterior portion of the left hemisphere. On the other hand, language scripts with a weak sound-symbol relationship may involve less auditory and more visual processing in the posterior visual areas of the left hemisphere.

A number of techniques aimed at investigating the cerebral organization of language have been devised so as to present no danger to the subject's health. These techniques include dichotic listening, finger tapping, tachistoscopic viewing, electroencephalographic techniques (EEG), mapping EEG, event-related potentials (ERPs), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). They can be used not only in the study of aphasics but also of normal adult subjects.

Numerous studies have described the functions of some left cortical areas with regard to

language organization. On the other hand, the role played by the main subcortical structures remains to be further investigated. Subcortical structures lie at the base of the two cerebral hemispheres in the middle of the brain. They are localized under the cerebral cortex and can be divided into two groups: the basal ganglia and the thalamus. Studies show that the basal ganglia and the thalamus of the left hemisphere are involved in language organization (Alexander, 1989; Nadeau & Crosson, 1997). Neuro-imaging studies suggest that even people who have been fluent speakers of a second language since childhood still use a little extra brainpower to speak their non-native tongue. The site of the extra brainpower lies in the putamen (Klein et al., 1995), the deep brain region not previously thought to play a special role in the memory of learned language. The results by Klein et al. (1995) came as a surprise because the putamen had not previously been linked to language learning. It is part of the basal ganglia sitting underneath the frontal lobe, and its main role was thought to be the production of rote movements. Klein et al. (1995) used native English speakers as subjects who had learned French at 7 years old and spoke both languages fluently and daily. They imaged the subjects' brains with positron emission tomography (PET) to measure cerebral blood flow (an indicator of brain activation) while they were repeating a French or English word or speaking its synonym in the same language, and translating words from English to French and vice versa. Then they compared the brain activation patterns generated in bilingual individuals speaking French with those generated while they were speaking English. The results showed equivalent activation in all brain areas except for the left putamen area, which lit up only when the subjects responded in French. However, it is not clear whether this is specific to English speakers who have learned French. Further studies are expected to study native French speakers who learned English at an early age and to check the effects on the brain of learning other languages that are even more different from English, such as Chinese.

Throughout the 1980s and 1990s, refined neuroimaging studies showed that the neural



representation of second languages differed from first languages. But this general observation was improved by later studies. Dahan et al. (1997) reported that the neural representation of a second language is identical to that of a first language if the individual is truly bilingual. However, if the mastery of the second language is not as strong as the first, then the functional neuroanatomy is different. They further found that it was the mastery of the language rather than the age at which the second language was acquired that proved the most important in leading to shared neural representation for both languages. Other researchers (Petitto et al., 2000) reported similar findings with individuals who are congenitally deaf but proficient in sign language. They found the brain areas involved in signing are the same as those of hearing speakers using a spoken language.

A functional magnetic resonance imaging (fMRI) study of multiple-language representation in the human brain shows that within the frontal-lobe language-sensitive regions (Broca's area), second languages acquired in adulthood are spatially separated from native languages. However, when acquired during the early language acquisition stage of development, native and second languages tend to be represented in common frontal cortical areas. Furthermore, the temporal-lobe language sensitive regions (Wernicke's area) show little or no separation of activity regardless of age of language acquisition (Kim et al., 1997). Kim et al. imaged 6 subjects who acquired two languages simultaneously early in their development (early subjects) and 6 subjects who acquired their second languages in adulthood (late subjects). The sentence-generation task was performed silently (internal speech) to minimize head movement and was similar to tasks previously employed in neuro-imaging language studies. The subject was instructed to "describe" events that occurred during a specified period of the previous day (morning, afternoon, night); this task was practiced before the imaging sessions. Immediately before each run, the subject was instructed which language he/she was to imagine speaking, and graphical cues signalling morning, afternoon, and night were displayed in various orders for 10 seconds

during the 30-second task period. These graphics provided common non-linguistic cues for the task and the unpredictable order of presentation presumably reduced the tendency to rehearse mentally before the cue. The languages were alternated during the imaging session to prevent habituation and a potentially time-dependent bias.

For all six late-bilingual subjects, distinct areas of activation were observed for the native and second languages in Broca's area. Two distinct but adjacent centers of activation separated by a range between 4.5mm to 9.0mm were evident within the inferior frontal gyrus. This suggests that two specific regions served each of the two languages. In the posterior language area, the same tasks yielded centroids of activity with a centre-to-centre spacing between 1.1 mm and 2.8mm, less than the width of a voxel, suggesting that similar or identical cortical regions served both languages in this posterior area.

An fMRI study (Wang et al., 2001) of cortical changes resulting from Chinese Mandarin tone training showed that for native Chinese Mandarin speakers, significant activation was found only in the language-specific regions, i.e. Broca's and Wernicke's areas. For the non-native speakers, however, bilateral activation was generally observed for both pre- and post-training images, and additional areas were activated after training, especially in the right hemisphere in the region equivalent to Broca's area. Wang et al. (2001) also found that native Chinese speakers predominantly process Mandarin tones in the left hemisphere while American listeners engage both hemispheres equally for Mandarin tone perception.

Nakada et al. (2001) investigated brain activation associated with reading among Japanese-English and English-Japanese bilinguals and monolinguals and found that the neuroanatomical substrates underlying the cognitive processing of reading are differentially determined based on the language system. Ten normal Japanese volunteers (five highly literate in both Japanese and English) and ten American native English speakers (five highly literate in both English and Japanese) participated in the study which used blood oxygenation level dependent (BOLD)

contrasting functional magnetic resonance imaging (fMRI) on a high-field (3.0T) system specifically optimized for fMRI. The activation patterns in Japanese subjects reading Japanese (L1) were substantially different from the patterns obtained in American subjects reading English text (L1). The activation patterns during reading in L2 were virtually identical to the patterns seen when reading L1 in both Japanese and English natives highly literate in both language systems. The study further indicates that the cognitive processes for reading in the second language involve the same cortical structures employed for the first language, supporting the hypothesis that the second language represents the cognitive extension of the first language.

A study using event-related brain potentials and functional magnetic resonance imaging (fMRI) showed that words from the non-target language are rejected at an early stage before semantic analysis in bilinguals (Rodríguez-Fornells et al., 2002). Bilingual Spanish/Catalan and monolingual Spanish subjects were instructed to press a button when presented with words in one language, while ignoring words in the other language and pseudo-words. The brain potentials of bilingual subjects in response to words of the non-target language were not sensitive to word frequency, indicating that the meaning of non-target words was not accessed in bilinguals. The fMRI activation patterns of bilinguals included a number of areas previously implicated in phonological and pseudo-word processing, suggesting that bilinguals use an indirect phonological access route to the lexicon of the target language to avoid interference.

Another study (Hernandez et al., 2001) investigated the nature of cognitive control in within- and between-language switching in bilingual participants. To examine the neural substrate of language switching, the researchers used functional magnetic resonance imaging (fMRI) as subjects named pictures in one language only or switched between languages. Participants were also asked to name (only in English) a separate set of pictures as either the actions or the objects depicted or to switch between these two types of responses on each subsequent picture. Picture naming compared to rest revealed activation in the dorsolateral prefrontal cortex, which extended

down into Broca's area in the left hemisphere. There were no differences in the activation pattern for the two languages. English and Spanish activated overlapping areas of the brain. Similarly, there was no difference in activation for naming actions or objects in English. However, there was increased intensity of activation in the dorsolateral prefrontal cortex for switching between languages relative to no switching, an effect which was not observed for naming of actions or objects in English. The study suggested that the dorsolateral prefrontal cortex serves to attenuate interference that results from having to actively enhance and suppress two languages in alternation. These results are consistent with the view that switching between languages involves increased general executive processing. Finally, the results are consistent with the view that different languages are represented in overlapping areas of the brain in early bilinguals.

A recent functional MRI study (Gandour et al., 2007) investigated the neural substrates underlying the perception of two sentence-level prosodic phenomena that occur in both Mandarin Chinese (L1) and English (L2). Late-onset, medium-proficiency Chinese-English bilinguals were asked to selectively attend to either the sentence focus (sentence-initial vs. sentence-final position of contrastive stress) or sentence type (declarative vs. interrogative modality) in paired three-word sentences in both L1 and L2 and then make speeded-response discrimination judgments. L1 and L2 elicited highly overlapping activations in frontal, temporal, and parietal lobes. Furthermore, region of interest analyses revealed that for both languages the sentence focus task elicited a leftward asymmetry in the supramarginal gyrus; both tasks elicited a rightward asymmetry in the mid-portion of the middle frontal gyrus. A direct comparison between L1 and L2 did not show any difference in brain activation in the sentence type task. In the sentence focus task, however, greater activation for L2 than L1 occurred in the bilateral anterior insula and superior frontal sulcus. The sentence focus task also elicited a leftward asymmetry in the posterior middle temporal gyrus for L1 only. Differential activation patterns are attributed primarily to disparities between L1 and L2 in the phonetic manifestation of sentence focus. Such

phonetic divergences lead to increased computational demands for processing L2. These findings support the view that L1 and L2 are mediated by a unitary neural system despite late age of acquisition, although additional neural resources may be required in task-specific circumstances for unequal bilinguals.

### *ERP Correlates of Second Language Acquisition*

Event related brain potentials (ERPs) have been found to contain components that reflect semantic processing since the early 1980's. The N400 component, first discovered in 1980, is related to semantic priming or activation (Kutas & Hillyard, 1984). A number of paradigms have been used to elicit N400 such as a word-series paradigm (Harbin et al., 1984), paired-word paradigm (MarCarthy et al., 1985; Holcomb, 1988), pseudo-oddball word paradigm (Miyamoto et al., 1998) and categorization paradigm (Polich, 1986a).

Most cognitive neuroscience studies on second language processing have been focused on whether processing of native and foreign language processing is based on the same neural substrate. These studies used either PET or fMRI as dependent measures. Whereas some studies report that both languages utilize common neuroanatomical regions (Chee et al., 1999a, 1999b; Klein et al., 1995; Cappa et al., 1998), others observed clear differences (Dehaene & Cohen., 1997; Kim et al., 1997). A comparison of these different studies suggests that the proficiency level in L2 might be the most important variable. For low-proficient subjects, different brain areas are recruited for processing L1 and L2, whereas high-proficient L2 subjects recruit identical neural substrate. This is even true if age of acquisition is controlled for (Cappa et al., 1998).

The ERP study by Ardal et al. (1990), on semantic processes during reading in highly fluent bilingual subjects as well as in monolinguals, showed that all subjects displayed an N400 component, but the N400 latency was earlier in monolinguals and delayed by 40 ms in bilinguals' second language relative to their first language. The study by Weber-Fox and Neville (1996) of

Chinese-English bilinguals showed similar results with all subjects displaying an N400 effect. The peak latency for N400 was delayed for late bilingual subjects who acquired L2 (English) after the age of 11.

Hahne and Friederici (2001) studied semantic and syntactic processes during auditory sentence comprehension in Japanese-German bilinguals who acquired L2 after the age of 18. The results showed an N400 effect for semantically incorrect sentences relative to correct sentences. In addition to N400, a late right anterior negativity was observed, which had not been reported for native listeners. The most remarkable differences were observed for sentences containing phrase structure violations. In contrast to native listeners, L2 learners showed neither a modulation of the early anterior negativity nor of the late positivity. Similar results were observed in another study (Nicoles et al., 2000) which compared first and second language processing in French native speakers learning German as a second language. The French-German bilinguals displayed an N400 followed by a late right-anterior negativity for semantic violations in L2. For phrase structure violations, there was no modulation in the early anterior negativity and only a tendency toward a P600 effect. By contrast, the French-German bilinguals showed an anterior negativity as well as a P600 for a similar syntactic violation in their L1.

Another ERP study by Hahne (2001) compared sentence comprehension of auditorily presented German sentences in 16 native German speakers (L1 group) and 16 native Russian speakers who learned German after the age of 12 (L2 group). The results showed an N400 effect in both L1 and L2 groups for semantic violations, but with reduced amplitude and longer peak latency in the L2 group. Sentences with a phrase structure violation elicited an early anterior negativity followed by a broad centro-parietal positivity in the L1 group. By contrast, there was not differential modulation of the early anterior negativity in the L2 group. A late positivity was also elicited in L2 group, but it was slightly delayed compared to that shown by L1 group.

Adult second language learning seems to be more difficult and less efficient than first

language acquisition during childhood. However, by using event-related brain potentials, Friederici et al. (2002) found that adults who learned a miniature artificial language display a similar real-time pattern of brain activation when processing this language as native speakers do when processing natural languages. Participants trained in the artificial language showed two event-related brain potential components taken to reflect early automatic and late controlled syntactic processes, whereas untrained participants did not. This result challenges the common view that late second language learners process language in a principally different way from native speakers. Their findings demonstrate that a small system of grammatical rules can be syntactically instantiated by the adult speaker in a way that strongly resembles native-speaker sentence processing.

### ***Processing of Emotion in Bilinguals from an ERP Perspective***

An ERP study by Kim (1993) measured brain wave activities from monolingual native English speakers and Korean-English bilinguals with varying degrees of English language proficiency in response to visual stimuli presented as emotionally-valenced words (positive, negative, neutral) in English. Her hypothesis was that emotion responsiveness would differ for words in the L1 and L2. She specifically used P300 amplitude as the dependent measure, assuming that this ERP component was sensitive to the incentive or emotional value of a stimulus. However, her ERP recordings showed no significant differences in P300 amplitude as a function of words' emotional valence or participants' English proficiency. As she explained, the emotional stimuli she used in her study only covered English words with moderately negative connotations such as "steal" and moderately positive connotations such as "truth," which had probably been insufficiently arousing. Prior studies showed that the P300 amplitude was sensitive to highly evocative stimuli such as pictures and slang expressions (Vanderploeg, Brown, & Marsh, 1987). Another reason for the insignificance in Kim's study might be the experimental design in which the emotional English word stimuli were presented as L1 to monolingual native English speakers but as L2 to

Korean-English bilinguals. Although Kim's ERP study did not show significant variation in emotional responsiveness between the L1 and L2, her study provided a good starting point for further ERP studies using between-subject experimental designs in which stimuli could be presented in both the L1 and L2 to the same group of bilingual subjects.

Recent research has begun to shed some light on why emotional resonance may differ between the L1 and L2, which are frequently learned in different contexts (Bond & Lai, 1986; Deiele & Pavlenko, 2002; Deiele & Regan, 2001; Durst, 2001; Pavlenko, 1999, 2002; Schrauf, 2000; Wierzbicka, 1999). An L1 is mostly learned in the context of family life with more emotional extremes. The family life usually provides an individual with the earliest encounters with the whole series of human emotions (Schrauf, 2000). An L2 is often the language of schooling, work, and professional achievement and thus comes with emotional control, autonomy, and achievement (Bond & Lai, 1986; Deiele & Pavlenko, 2002; Ervin, 1964). Bond and Lai (1986) reasoned that, because the L2 is usually mastered in more emotionally neutral settings than the L1, less arousal would be conditioned to L2 words. These researchers thus predicted that bilinguals would be more comfortable discussing embarrassing topics in their L2 during interviews. There has been some evidence supporting this hypothesis as bilinguals would speak at greater length about embarrassing topics (but not neutral topics) when instructed to respond in their L2.

Several researchers have used event-related brain potential (ERP) measures as indices of emotional processing (for a review, see Kayser et al., 1997). They analysed the ERP waveforms of a homogenous sample of young, right-handed women and found that positive and negative stimuli when compared with neutral stimuli produce enhanced amplitudes for several ERP components such as N2, N3, late P300, and slow wave (Johnston et al., 1986; Naumann et al., 1992; Palomba et al., 1997), and this enhancement was greatest over the right parietotemporal region (Cacioppo et al., 1993, 1996; Kayser et al., 1997). This lateralization of cortical activity



related to emotional processing has also been confirmed by functional imaging study (Lang et al., 1998).

### ***The Current Studies and Major Hypotheses***

The current studies, prompted by several gaps in human knowledge of emotion and bilingualism, compared bilinguals' responses to emotional and categorical word stimuli in their first language (L1) and second language (L2) during a multistimulus oddball paradigm. The first gap in the previous literature results from a lack of attention from researchers to the emotional correlates of language, especially from the bilingual perspective, where there may be a greater emotional arousal associated with the L1 than the L2. Secondly, there has been reluctance to study bilinguals who have highly variable language-learning experiences in their first and second language acquisition processes. The factors at play in second language acquisition (SLA) include age of acquisition, environment, and the meaning of learning languages for an individual. These factors and the subjective nature of emotional experience create challenges to studies on the difference in perceived emotionality associated with L1 words versus L2. Thirdly, it has been traditionally assumed that investigating personal emotional experiences, such as which language feels more emotional, lies outside the scope of scientific research. So far there has been little ERP research on emotional word processing in bilinguals or multilinguals. The current studies were expected to shed some light on the mechanisms of how bilinguals process emotionally valenced or categorical visual word stimuli in an L1 versus an L2 from an ERP perspective.

The current studies have been designed in two parts to use the modified oddball paradigm with the aim of answering important questions about emotional word processing among bilinguals. The first part makes use of ERP methodologies to investigate how bilinguals respond to emotionally-valenced or categorical word stimuli which are in both L1 and L2 and grouped into targets and non-targets, and how L1 and L2 are involved in emotional word processing at different scalp locations (anterior-posterior and left-right distributions). The second part employs

behavioral response latency as the dependent measure of the effects of target versus non-target, and emotional valence versus category in L1 and L2 words.

The unique contribution of the current studies lies in its original within-subject experimental design which groups emotional valences (negative, neutral, positive) or categories (math, object, measure), in two languages (L1 and L2), into six stimulus types within each of the six conditions (a total of 36 condition-type combinations) for each subject. Bilinguals make it feasible to compare two languages in a single subject. While previous studies have dealt with emotion and bilingualism separately, the current studies has uniquely combined emotion and bilingualism in a multi-stimulus oddball paradigm using both ERP and behavioral response latency measures to investigate the mechanism behind bilingual emotional word processing. In addition, two categorical conditions (V & VI) were used as the control for the four emotional conditions (I-IV).

The first goal of the current studies was to investigate how bilinguals respond to target/non-target word stimuli in L1 and L2, and what ERP components are involved in bilingual processing of emotional and categorical words. As would be expected in an oddball paradigm study, it was hypothesized that target words would elicit larger P300 than non-target words. In addition, based on ERP findings on P300 amplitude as a useful index of similarity between a target and nontarget stimuli (Azizian, et al., 2005; Azizian, Parvaz, & Squires, 2006; Azizian, Freitas, Parvaz, & Squires, 2006), and on findings that stimuli with high emotional value, informative feedback stimuli, and target stimuli usually elicit larger P300s than stimuli that do not have these properties (Johnson, 1988, Picton, 1992, and Pritchard, 1981), it was further hypothesized that when positive words are target stimuli, non-target positive words (in a different language) would elicit larger P300 than non-target negative words (L1 slightly larger than L2) that in turn elicit larger P300 than non-target neutral words (L1 slightly larger than L2), and when negative words are targets, non-target negative words (in a different language) would elicit larger P300 than non-target positive words (L1 slightly larger than L2) that in turn elicit larger P300 than non-target

neutral words (L1 slightly larger than L2).

Based on psycholinguistic findings that the emotional resonance may differ between two languages (Bond & Lai, 1986; Dewaele & Pavlenko, 2002; Dewaele & Regan, 2001; Durst, 2001; Pavlenko, 1999, 2002; Schrauf, 2000; Wierzbicka, 1999), it was also hypothesized that positive words in L1 would elicit larger P300 than in L2 when positive words are target stimuli, and negative words in L1 would elicit larger P300 than in L2 when negative words are targets. And the gap in P300 enhancement elicited by target negative stimuli in L1 when compared with in L2 would be larger than by target positive stimuli in L1 when compared with in L2. The current studies hypothesized that target categorical words (object) would elicit larger P300 than non-target categorical words (math & measure) and the difference in P300 between L1 and L2 is not as distinctive as in when emotionally-valenced words are targets. This is the typical oddball paradigm effect without any emotional effect.

The second goal was to investigate the difference in response latencies between target and non-target stimuli, between L1 and L2, and between stimuli of different emotional valence. Response latency or reaction time (RT) is the elapsed time between the receiving of stimuli and the subsequent reaction. There are three types of reaction time tasks (Luce, 1986; Welford, 1980). In simple reaction time tasks, subjects respond to only one stimulus type. In recognition reaction time tasks (or Go/NoGo tasks), subjects respond to one stimulus type (Go) but ignore the other stimulus type (NoGo). In choice reaction time tasks, subjects respond differentially to two stimulus types by pressing one key in response to one stimulus type and a different key to the other.

The current studies employed the choice reaction time task with subjects responding differentially to stimuli grouped into targets vs. non-targets, in L1 vs. in L2, and of different emotional valences or categorical differences. One of the most investigated factors affecting reaction time is 'arousal' or state of attention. Reaction time is fastest with an intermediate level of

arousal, and deteriorates when the subject is either too relaxed or too tense (Welford, 1980; Broadbent, 1971; Freeman, 1933). Since target visual stimuli might require more attention (or more ‘arousal’) from subjects than non-target, it was hypothesized that responses to non-targets are faster than to targets. In line with many studies concluding that a complex stimulus (or task complexity) elicits a slower reaction time (Brebner and Welford, 1980; Teichner and Krebs, 1974; Luce, 1986), it was further hypothesized that responses to stimuli in L1 are faster than in L2 as it might require more processing for language complexity (i.e. words in L2 are more complex than in L1 for bilinguals), and responses to emotionally-neutral words are faster than to positive or negative words as it might require more processing for emotion complexity (i.e. positive or negative words are more complex than neutral words in emotional valence).

## **Methods**

### *Participants*

Thirty-four right-handed Chinese-English bilingual students participated in the two-part study. Nine of them only participated in the ERP study and four others only in the behavioral study. Twenty-one students participated in both the ERP and behavioral studies. Most participants had finished high school in China and were enrolled at the time of this dissertation in either undergraduate or graduate programs at Stony Brook University. They had similar Chinese (L1) and English (L2) language exposure and cultural background, except for three who had acquired English as L2 in their early childhood (one participant was born in the US and the other two immigrated to the US at about 8 years old). All participants were right-handed with normal or corrected-to-normal vision and had no history of mental or neurological disorders. They provided written informed consent prior to the experiment. They received subject-pool credits, if they were from the subject pool of the Department of Psychology, or they were paid, if not from the pool. The funding for participant recruitment was provided by the Department of Psychology at Stony

Brook University.

For ERP study, data from eight participants were discarded due to insufficiency in artifact-free trials (<15) and data from two additional participants were discarded due to excessive movement artifact. Final ERP data analysis included 20 participants (12 women and 8 men with a mean age of 23 years old and standard deviation of 6.5 years, a mean age starting English acquisition at 11 years old and standard deviation of 3.1 years, and a mean stay in the US for 6.8 years and standard deviation of 5.8 years) but a separate analysis was performed on the three Chinese-English bilinguals (1 woman and 2 men with a mean age of 24 years old and standard deviation of 6.2 years) who acquired English (L2) at their early childhood. For the behavioral study, data from two participants were discarded due to failure of participants to follow instructions correctly. Final behavioral data analysis included 23 participants (15 women and 8 men with a mean age of 22 years old and standard deviation of 5.6 years, a mean age starting English acquisition at 10 years old and standard deviation of 3.6 years, and a mean stay in the US for 6.3 years and standard deviation of 5.0 years).

### ***Stimuli for both ERP and Behavioral Studies***

The stimuli were the same for both the ERP and behavioral studies. There were two sets of word stimuli. The first set consisted of 30 positively valenced English (L2) words and their Chinese (L1) counterparts, 30 negatively valenced English (L2) words and their Chinese (L1) counterparts, and 30 neutrally valenced English (L2) words and their Chinese (L1) counterparts resulting in a total of 180 emotionally valenced words. The second set contains 30 English (L2) object words and their Chinese (L1) counterparts, 30 English (L2) math words and their Chinese (L1) counterparts, and 30 English (L2) measure words and their Chinese (L1) counterparts totaling 180 categorical words. The English (L2) word list was selected from the British National Corpus (BNC) with balanced word length, syllables, and word frequency. All English words ranged in length from 3 to 10 letters and 1 to 4 syllables. All Chinese words were equivalents of

the English words with balanced number of characters and word frequencies (Da, J., 2004). Six experimental conditions were performed with each containing 180 trials, four conditions (I-IV) focusing on emotional stimuli and two conditions (V&VI) on categorical stimuli. Each participant participated in all six conditions for a total of 1080 trials. The oddball paradigm was applied in each condition in such a way that the frequency of occurrence was about 1/6 for target word stimuli and 5/6 for non-target word stimuli (see Table 1 and Figure 2). The number of target stimuli was randomized between 26 and 30 to prevent participants from predicting based on prior experiments.

**INSERT TABLE 1 HERE**

**INSERT FIGURE 2 HERE**

## **Part 1: The ERP Study**

### *Procedure*

Participants were divided into four groups, with different orders of exposure to the conditions, the first participating in conditions I, II, III, IV, V and VI, the second in conditions V, VI, I, II, III and IV, the third in conditions II, I, IV, III, VI and V, and the fourth in conditions VI, V, II, I, IV and III. This was to counter balance the effects of exposure to emotional and categorical words, and between L1 and L2. Prior to each condition, the participants were asked to keep a silent mental count of target stimuli and ignore the non-target stimuli and to report the target count following each condition. Participants were allowed to rest between conditions.

Word stimuli in white color were presented on black background for 500 milliseconds with an inter-stimulus interval (ISI) of 1000 milliseconds. Participants were fitted with electrodes and positioned in a reclining chair in a sound-attenuating chamber. A 12-inch flat-panel LCD (resolution 800 x 600 pixels) was placed 2 feet from the face of the participant with the center of

the screen at eye level. Participants were instructed to sit as still as possible and minimize eye blinks by attending to a centered fixation point (a white cross with resolution 20 x 20 pixels in the middle of the screen) that was displayed for the duration of the experiment. Rapid and predictable stimulus onsets and offsets were coordinated by STIM software (NeuroScan, Inc., 1994).

Prior to each condition, the screen displayed the stimulus type to be the target for that condition, i.e., positive or negative words in English or Chinese, or object words in English or Chinese, etc. Participants were then presented with a randomized sequence of target and non-target stimuli (English or Chinese words) one at a time. Following the completion of each condition, participants were asked to report the number of targets and the report was compared with the actual count. Participants were debriefed and allowed to view their raw EEG data after they finished all six experiments.

### ***EEG/EOG Recording***

Recordings of the EEG and EOG were obtained using a 64-channel cap with electrodes positioned according to the International 10-20 system. Electrodes were placed on the outer canthus of each eye to record horizontal eye movements and above and below the left eye to record vertical eye movements. The EEG was digitized at a rate of 500 Hz and amplified with a gain of 1000 and a band-pass of 0.1 to 30 Hz. The amplifier was calibrated prior to each recording. Electrode impedances were at or below 10 k $\Omega$  for all electrodes. To eliminate artifacts, trials with EEG voltages exceeding  $\pm 75 \mu\text{V}$  were rejected from the average.

With the stimulus duration of 500 ms and an inter-stimulus interval of 1000 ms, ERP epochs were acquired from 100 ms before the onset of each stimulus and continuing for 900 ms after presentation. For each participant, individual ERP averages were created for each of the six stimulus types in each of the six conditions.

Data from nine electrodes were used to reduce the number of statistical comparisons made in

this study while allowing for analysis of differences in the anterior–posterior and left-right dimensions. The nine electrodes were F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4 (see Figure 3). Grand averages of waveforms at these nine electrodes were created across 20 participants for each experiment condition and each stimulus type.

### **INSERT FIGURE 3 HERE**

Based on examination of the grand-average waveforms, two time interval windows were chosen for analysis (see Figure 4). Peak 1 was the interval between 250 and 350 ms after stimuli onset. Peak 2 was between 400 and 600 ms after stimuli onset for those conditions with a Chinese target (II, IV, and VI) and between 500 and 700 ms after stimuli onset for those conditions with an English target (I, III, and V). Mean ERP amplitude during the latency windows were measured relative to the pre-stimulus baseline. All averaging and measurements were performed off-line. All analyses used an alpha level of .01.

### **INSERT FIGURE 4 HERE**

#### ***ERP Waveforms***

Figure 5 shows grand-average ERP waveforms for six stimulus types at 9 electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4) in emotional condition I with English positive words as target stimuli (thick in green) that compared with 5 other non-target stimuli (English negative and neutral words, Chinese positive, negative, and neutral words). The average was across 20 participants. At each of the seven electrode sites (F3, FZ, F4, C3, CZ, C4, PZ), English word stimuli elicited larger Peak 1 amplitudes than Chinese word stimuli in the latency window between 250 ms and 350 ms. The maximal gap in Peak 1 amplitudes between English and Chinese stimuli appeared at the FZ electrode site. There was little difference in Peak 1 amplitudes for stimuli in the same language (L1 or L2). Also at these seven electrode sites, an enhanced Peak 2 component was observed for target stimuli (thick in green) in the latency window between 500



ms and 700 ms as compared with non-target stimuli. The maximal gap in Peak 2 amplitudes between target and non-target stimuli appeared at CZ electrode site. At P3 and P4 electrode sites, English stimuli did not elicit larger Peak 1 amplitudes than Chinese stimuli, and target stimuli did not elicit larger Peak 2 amplitudes than non-targets.

#### **INSERT FIGURE 5 HERE**

Figure 6 shows grand-average ERP waveforms for six stimulus types at 9 electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4) in emotional condition II with Chinese positive words as target stimuli (thick in yellow) that compared with 5 other non-target stimuli (English positive, negative and neutral words, Chinese negative and neutral words). Six electrodes (F3, FZ, F4, C3, CZ, and C4) had enhanced Peak 1 amplitudes for English (L2) words as compared with Chinese (L1) words in the latency window between 250 ms and 350 ms. The maximal gap in Peak 1 amplitudes appeared at the FZ electrode site between English and Chinese stimuli. In addition, all nine electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4) had an enhanced Peak 2 component for target stimuli (thick in yellow) versus non-target stimuli in the latency window between 400 ms and 600 ms. The maximal gap in Peak 2 amplitudes between target and non-target stimuli appeared at CZ electrode site. There was little difference in Peak 1 amplitudes between English and Chinese stimuli at P3 and P4 electrode sites.

#### **INSERT FIGURE 6 HERE**

Figure 7 shows grand-average ERP waveforms for six stimulus types at 9 electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4) in emotional condition III with English negative words as target stimuli (thick in red) that compared with 5 other non-target stimuli (English positive and neutral words, Chinese positive, negative, and neutral words). At six electrodes (F3, FZ, F4, C3, CZ, and C4), English stimuli elicited larger Peak 1 amplitudes than Chinese stimuli in the latency window between 250 ms and 350 ms. In addition, Chinese negative stimuli elicited Peak 1 amplitudes lower than English stimuli but higher than Chinese positive and neutral stimuli. English neutral

stimuli elicited Peak 1 amplitudes higher than Chinese stimuli but lower than English negative and positive stimuli. Seven electrodes (F3, FZ, F4, C3, CZ, C4, and PZ) had an enhanced Peak 2 component for target stimuli (thick in red) versus non-target stimuli in the latency window between 500 ms and 700 ms. The maximal gap in Peak 2 amplitudes appeared at CZ electrode site between target and non-target stimuli. At P3 and P4 electrode sites, there was almost no difference in Peak 1 amplitudes between English and Chinese stimuli and in Peak 2 amplitudes between target and non-target stimuli.

### **INSERT FIGURE 7 HERE**

Figure 8 shows grand-average ERP waveforms for six stimulus types at 9 electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, P4) in emotional condition IV with Chinese negative words as target stimuli (thick in light blue) that compared with 5 other non-target stimuli (English positive, negative and neutral words, Chinese positive and neutral words). Seven electrodes (F3, FZ, F4, C3, CZ, C4, and PZ) had enhanced Peak 1 amplitudes in the latency window between 250 ms and 350 ms for English stimuli as compared with Chinese stimuli. At all nine electrode sites, an enhanced Peak 2 component was observed in the latency window between 400 ms and 600 ms for target stimuli (thick in light blue) as compared with non-target stimuli. There was little difference in Peak 1 amplitudes between English and Chinese stimuli at P3 and P4.

### **INSERT FIGURE 8 HERE**

Figure 9 shows grand-average ERP waveforms for six stimulus types at 9 electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4) in the categorical condition (V) with English object words as target stimuli (thick in red) that compared with 5 other non-target stimuli (English math and measure words, Chinese math, object, and measure words). At six electrodes (F3, FZ, F4, C3, CZ, and C4), English stimuli elicited larger Peak 1 amplitudes than Chinese stimuli in the latency window between 250 ms and 350 ms. Five electrodes (F4, C3, CZ, C4, and PZ) had an enhanced Peak 2 component for target stimuli (thick in red) versus non-target stimuli in the latency window

between 500 ms and 700 ms. The maximal gaps in Peak 2 amplitudes between target and non-target stimuli appeared at PZ and CZ electrode sites. There were almost no differences in Peak 1 amplitudes between English and Chinese stimuli at P3, PZ, and P4 electrode sites and in Peak 2 amplitudes between target and non-target stimuli at F3, FZ, P3, and P4 electrode sites.

**INSERT FIGURE 9 HERE**

Figure 10 shows grand-average ERP waveforms for six stimulus types at 9 electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, P4) in the categorical condition (VI) with Chinese object words as target stimuli (thick in light blue) that compared with 5 other non-target stimuli (English math, object and measure words, Chinese math and measure words). Seven electrodes (F3, FZ, F4, C3, CZ, C4, and PZ) had enhanced Peak 1 amplitudes in the latency window between 250 ms and 350 ms for English stimuli as compared with Chinese stimuli. There was little difference in Peak 1 amplitudes between English and Chinese stimuli at P3 and P4 electrode sites. At FZ, F4, C3, CZ, C4, P3, and PZ electrode sites, an enhanced Peak 2 component was observed in the latency window between 400 ms and 600 ms for target stimuli (thick in light blue) as compared with non-target stimuli. The maximal gaps in Peak 2 amplitudes between Chinese and English stimuli appeared at CZ electrode site. There was little difference in Peak 2 amplitudes between target and non-target stimuli at F3 and P4 electrode sites.

**INSERT FIGURE 10 HERE**

To show enhanced Peak 1 amplitudes in response to Chinese (L1) and English (L2) stimuli in general, four grand-average ERP waveforms were created across 20 participants at each of the nine electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4). The first one averaged three English (L2) stimulus types (positive, negative, and neutral) in four emotional conditions (I-IV). The second one averaged three Chinese (L1) stimulus types (positive, negative, and neutral) in four emotional conditions (I-IV). The third one averaged three English stimulus types (math, object, and measure) in two categorical conditions (V & VI). The fourth one averaged three Chinese

stimulus types (math, object, and measure) in two categorical conditions (V & VI). Figure 11 shows the four grand-average ERP waveforms at nine electrode sites with two for English stimuli and two for Chinese. English stimuli elicited larger Peak 1 amplitudes than Chinese stimuli at seven (F3, FZ, F4, C3, CZ, C4 and PZ) electrode sites and the maximal gap in Peak 1 amplitudes between English and Chinese stimuli appeared at the frontal and central locations (F3, FZ, F4, C3, CZ, C4). On the other hand, Chinese stimuli elicited larger Peak 2 amplitudes at five (C3, CZ, C4, P3, and PZ) electrode sites and the maximal gap in Peak 2 amplitudes between Chinese and English stimuli appeared at the CZ electrode site. It can also be seen that English stimuli in emotional conditions elicited higher Peak 1 amplitudes than English stimuli in categorical conditions (green vs. red) while Chinese stimuli in categorical conditions elicited higher Peak 1 amplitudes than Chinese stimuli in emotional conditions (yellow vs. light blue) at six electrode sites (F3, FZ, F4, C3, CZ, and C4). The gap in Peak 1 amplitudes between English and Chinese stimuli in emotional conditions (green vs. light blue) was larger than between English and Chinese stimuli in categorical conditions (red vs. yellow) at six electrode sites (F3, FZ, F4, C3, CZ, and C4).

### **INSERT FIGURE 11 HERE**

To show enhanced Peak 2 amplitudes for target stimuli in general, four grand-average ERP waveforms were created across 20 participants at each of the nine electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4). The first one averaged all target stimuli in four emotional conditions (I-IV). The second one averaged all non-target stimuli in four emotional conditions (I-IV). The third one averaged all target stimuli in two categorical conditions (V&VI). The fourth one averaged all non-target stimuli in two categorical conditions (V&VI). Figure 12 shows the four grand-average ERP waveforms at nine electrode sites with two for target stimuli and two for non-target. Target stimuli elicited larger Peak 2 amplitudes than non-target stimuli at all nine electrode sites (F3, FZ, F4, C3, CZ, C4, P3, PZ and P4). The maximal gap in Peak 2 amplitudes between target and non-

target stimuli appeared at the central and parietal locations (C3, CZ, C4, and PZ electrode sites). It can also be seen that target stimuli in emotional conditions elicited higher Peak 2 amplitudes than target stimuli in categorical conditions (green vs. red), and the gap in Peak 2 amplitudes between target and non-target stimuli in emotional conditions (green vs. light blue) was larger than between target and non-target stimuli in categorical conditions (red vs. yellow) at four electrode sites (C3, CZ, C4, and PZ).

**INSERT FIGURE 12 HERE**

To further illustrate enhanced Peak 2 amplitudes elicited by target stimuli, by non-target in the same language as target, and by non-target in different language as target, three grand-average ERP waveforms were created across 20 participants at each of the nine electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4). The first one averaged all target stimuli in six conditions I-VI. The second one averaged all non-target stimuli that were in the same language as target in six conditions I-VI. The third one averaged all non-target stimuli that were in different language from target in six conditions I-VI. Figure 13 shows the three grand-average ERP waveforms at nine electrode sites elicited by target stimuli (in green), non-target stimuli in the same language as target (in red), and non-target stimuli in different language from target (in blue). Target stimuli elicited enhanced Peak 2 amplitude relative to all non-targets in the latency window between 400 ms and 700 ms at all nine electrode sites. Non-target stimuli in the same language as target elicited significantly larger Peak 2 amplitude than non-targets in different language from target in the latency window between 400 ms and 600 ms, which is the latency window for Peak 2 when targets are in L1 in conditions II, IV and VI, at seven electrode sites (F3, FZ, F4, C3, CZ, C4, and PZ).

**INSERT FIGURE 13 HERE**

Figure 14 displays 64-channel ERP topographical distribution maps taken at latencies corresponding to the maximal amplitudes of Peak 1 and Peak 2 for Chinese (L1) and English (L2)

stimuli in emotional conditions (I-IV). The 2D mapping of Peak 1 and Peak 2 ERP components was taken at CZ electrode with waveforms averaged across Chinese (L1) and English (L2) stimuli in the four emotional conditions. Two grand-average ERP waveforms with one for L1 and the other for L2 were created. The latency for maximal Peak 1 ERP amplitude was 284 ms for Chinese (L1) and 272 ms for English (L2) and the latency for maximal Peak 2 ERP amplitude was 502 ms for Chinese (L1) and 632 ms for English (L2). The two maps on the left showed English (L2) stimuli elicited larger Peak 1 amplitude (in blue) in a wider brain area at frontal and central scalp locations than Chinese (L1) stimuli. The two maps on the right showed that Chinese (L1) stimuli elicited larger Peak 2 amplitude (in light blue) in a wider brain area at central and parietal locations than English (L2) stimuli. The two upper maps showed ERP amplitude enhancement in anterior locations by English (L2) stimuli, which was not observed in the lower two maps for Chinese (L1) stimuli.

**INSERT FIGURE 14 HERE**

***Statistical Analysis Results***

Six multiple comparison analyses (MCA) were performed on mean Peak 2 amplitudes at 9 channels (F3, FZ, F4, C3, CZ, C4, P3, PZ, P4) as the dependent variable and stimulus type as the classification variable in each of the six experimental conditions. The four in emotional conditions (I-IV) compared mean Peak 2 amplitude among six emotionally-valenced stimuli in L1 and L2 (i.e., English positive, negative, and neutral words, and Chinese positive, negative, and neutral words), and the two in categorical conditions (V & VI) compared mean Peak 2 amplitude among six categorical stimuli in L1 and L2 (i.e., English math, object, and measure words, and Chinese math, object, and measure words). Table 2 summarizes the grand-averages of mean Peak 2 amplitude with mean and standard deviation for each stimulus type in each condition and standard error for each condition.

## INSERT TABLE 2 HERE

As illustrated in Table 2, in condition I, target English (L2) positive stimuli elicited the largest mean Peak 2 amplitude, followed by non-target English (L2) neutral, Chinese (L1) neutral, English (L2) negative, Chinese (L1) negative and positive stimuli, showing a combination of emotional valence and language (L1/L2) as (a) positive (L2), neutral (L2), neutral (L1), negative (L2), negative (L1) and positive (L1). In condition II, target Chinese (L1) positive stimuli elicited the largest mean Peak 2 amplitude, followed by non-target Chinese (L1) negative and neutral, English (L2) neutral, negative and positive stimuli, showing a combination of emotional valence and language (L1/L2) as (b) positive (L1), negative (L1), neutral (L1), neutral (L2), negative (L2) and positive (L2). In condition III, target English (L2) negative stimuli elicited the largest mean Peak 2 amplitude, followed by non-target English (L2) positive and Chinese (L1) neutral and negative, and English (L2) neutral and Chinese (L1) positive stimuli, showing a combination of emotional valence and language (L1/L2) as (c) negative (L2), positive (L2), neutral (L1), negative (L1), neutral (L2) and positive (L1). In condition IV, target Chinese (L1) negative stimuli elicited the largest mean Peak 2 amplitude, followed by non-target Chinese (L1) positive and neutral, English (L2) neutral, negative and positive stimuli, showing a combination of emotional valence and language as (d) negative (L1), positive (L1), neutral (L1), neutral (L2), negative (L2) and positive (L2). In condition V, target English (L2) object stimuli elicited the largest mean Peak 2 amplitude, followed by non-target English (L2) measure, Chinese (L1) object, and English (L2) math, and Chinese (L1) measure and math stimuli And in condition VI, target Chinese (L1) object stimuli elicited the largest mean Peak 2 amplitude, followed by non-target Chinese (L1) measure and math, English (L2) measure, math and object stimuli.

### MCA on Peak 2

Figure 15 visualizes the results for four emotional conditions (I-IV) and two categorical conditions (V & VI) from Table 2. A comparison of conditions I & II with III & IV shows that

target stimuli in L1 elicited larger Peak 2 amplitude than target stimuli in L2. Non-target stimuli in L1 elicited larger mean Peak 2 amplitude non-target stimuli in L2 in conditions when target stimuli were in L1 (II & IV). In addition, aroused response to target positive stimuli in L1 (condition II) was accompanied by aroused responses to non-target stimuli in L1 but aroused responses to target positive stimuli in L2 (condition I) did not have the same effect. Neither did aroused responses to target negative stimuli (conditions III & IV) generate accompanying aroused responses to non-target stimuli in the same language. Non-target positive words elicited the smallest Peak 2 when target stimuli were in a different language in all emotional conditions (I-IV).

#### **INSERT FIGURE 15 HERE**

A comparison of conditions I & III with II & IV shows that Peak 2 enhancement elicited by negative target stimuli was larger than positive target stimuli when target was in L1 (II & IV) but smaller than positive target stimuli when target was in L2 (I & III). Aroused responses to target negative stimuli were accompanied by slightly aroused responses to non-target positive stimuli and this was true when target negative stimuli were in L1 or in L2.

A comparison of conditions V & VI with I & II once again shows that Peak 2 enhancement elicited by target in L1 was larger than by target in L2 and mean Peak 2 amplitude elicited to stimuli in L1 were larger than by L2 when target stimuli were in L1. Furthermore, target object word stimuli in L1 elicited Peak 2 amplitude similar to target positive word stimuli in L1. A comparison of conditions V & VI with III & IV shows that mean Peak 2 amplitudes elicited by target object stimuli in L1 were smaller than by target negative stimuli in L1. All six conditions showed a significant oddball effect (i.e., mean Peak 2 amplitudes elicited by target stimuli were significantly larger than by non-targets) at the .01 level. But each condition except for condition I revealed additional statistically significant differences in mean Peak 2 amplitude elicited by non-target stimuli.



MCA on mean Peak 2 amplitudes from condition II shows additional statistically significant language effects between mean Peak 2 amplitudes elicited by stimuli in L1 and in L2. In particular, non-target Chinese (L1) negative stimuli elicited significantly larger Peak 2 than all English stimuli and non-target Chinese (L1) neutral stimuli elicited enhanced Peak 2 when compared with English (L2) positive or negative stimuli. No significant difference was found between mean Peak 2 amplitudes elicited by non-target Chinese neutral and by non-target English neutral stimuli. In condition III, non-target English positive stimuli which were in the same language as target stimuli (English negative) elicited significantly larger mean Peak 2 amplitudes than non-target Chinese positive stimuli. No significant differences were found between other non-target stimuli. In condition IV with Chinese negative words as target stimuli, both non-target Chinese positive words and neutral words elicited significantly larger mean Peak 2 amplitudes than English positive words. No significant differences were found between other non-target stimuli.

MCA on mean Peak 2 amplitudes in condition V shows that non-target English measure words elicited significantly larger Peak 2 than non-target Chinese math words, and MCA from condition VI shows additional significant differences between non-target Chinese measure words and all non-target English words.

In addition to six MCAs on mean Peak 2 amplitude, four 5-way ( $2 \times 2 \times 3 \times 3 \times 3$ ) between-subject analyses of variance (ANOVAs) were conducted with mean Peak 1 and Peak 2 amplitudes at 9 channels (F3, FZ, F4, C3, CZ, C4, P3, PZ, P4) as the dependent variables. Two ANOVAs were for four emotional conditions (I-IV) with the independent variables being language (2), target (2), emotion (3), locality (3), and laterality (3). The other two ANOVAs were for two categorical conditions (V&VI) with the independent variables being language (2), target (2), category (3), locality (3), and laterality (3).

The language variable had two levels (Chinese - L1, English - L2). The target variable had two

levels (target, non-target). The emotional valence variable had three levels (positive, negative, neutral) and the category variable had three levels (object, math, measure). The locality variable had three levels (frontal – F3, FZ, F4, central – C3, CZ, C4, parietal – P3, PZ, P4), and laterality variable three levels (left – F3, C3, P3, midline – FZ, CZ, PZ, and right – F4, C4, P4). Table 3 summarizes significant main and interaction effects on mean Peak 1 and Peak 2 amplitudes with F statistics and p-values.

### **INSERT TABLE 3 HERE**

#### ANOVA on Peak 1 (250 – 350 ms post-stimulus in I-VI)

For Peak 1 mean ERP amplitude, six main effects were found to be statistically significant at the .01 level. The first one was the language effect found in emotional conditions (I-IV),  $F_{(1, 4230)} = 323.32, p < .001$ , and in categorical conditions (V & VI),  $F_{(1, 2088)} = 105.32, p < .001$ . The second one was the category effect in categorical conditions,  $F_{(2, 2088)} = 10.51, p < .001$ . The third one was the emotion effect in emotional conditions,  $F_{(2, 4230)} = 4.72, p < .01$ . The fourth one was the target effect in categorical conditions,  $F_{(1, 2088)} = 8.46, p < .01$ . The fifth was the locality effect in emotional conditions,  $F_{(2, 4230)} = 29.78, p < .001$ , and in categorical conditions,  $F_{(2, 2088)} = 22.17, p < .001$ . And the sixth one was the laterality effect in emotional conditions,  $F_{(2, 4230)} = 22.20, p < .001$ , and in categorical conditions,  $F_{(2, 2088)} = 11.84, p < .001$ .

Figure 16 summarizes five statistically significant main effects on mean Peak 1 amplitude of language, category, emotion, locality and laterality grouped in emotional and categorical conditions. Simple comparisons revealed that mean Peak 1 amplitudes for English (L2) stimuli ( $m = 3.81 \mu\text{V}$ ,  $SE = .09$  in emotional conditions and  $m = 3.83 \mu\text{V}$ ,  $SE = .10$  in categorical conditions) were significantly larger than for Chinese (L1) stimuli ( $m = 1.47 \mu\text{V}$ ,  $SE = .09$  in emotional conditions and  $m = 1.56 \mu\text{V}$ ,  $SE = .10$  in categorical conditions). Measure word stimuli in categorical conditions elicited significantly larger mean Peak 1 amplitude ( $m = 2.78 \mu\text{V}$ ,  $SE = .11$ ) than math ( $m = 2.20 \mu\text{V}$ ,  $SE = .11$ ) and object ( $m = 2.30 \mu\text{V}$ ,  $SE = .09$ ) stimuli. Negative

word stimuli in emotional conditions elicited significantly larger mean Peak 1 amplitude ( $m = 2.82 \mu\text{V}$ ,  $SE = .10$ ) than neutral stimuli ( $m = 2.31 \mu\text{V}$ ,  $SE = .09$ ). There was no statistically significant difference in mean Peak 1 amplitude between negative and positive stimuli.

Emotionally-neutral target stimuli in categorical conditions elicited significantly larger mean Peak 1 amplitude ( $m = 2.63 \mu\text{V}$ ,  $SE = .13$ ) than non-target stimuli ( $m = 2.32 \mu\text{V}$ ,  $SE = .28$ ). The mean Peak 1 amplitudes at frontal location ( $m = 1.89 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 1.55 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) were significantly smaller than at central ( $m = 2.95 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 2.71 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) and parietal ( $m = 3.08 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 2.92 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) locations. The mean Peak 1 amplitudes at right laterality location ( $m = 3.27 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 2.93 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) were significantly larger than at midline ( $m = 2.30 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 2.05 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) and left ( $m = 2.35 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 2.20 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) laterality locations.

### **INSERT FIGURE 16 HERE**

There were two statistically significant 2-way interaction effects on mean Peak 1 amplitude between language and locality ( $F_{(2, 4230)} = 62.54$ ,  $p < .001$  in emotional conditions and  $F_{(2, 2088)} = 11.74$ ,  $p < .001$  in categorical conditions) and between target and locality ( $F_{(2, 4230)} = 4.85$ ,  $p < .01$  in emotional conditions and  $F_{(2, 2088)} = 7.51$ ,  $p < .01$  in categorical conditions). There was no statistically significant main effect for target/non-target and no other statistically significant 2-way interaction effects or significant 3-way, 4-way or 5-way interaction effects at the .01 level. Figure 17 displays the statistically significant interaction effects between language and locality found both in emotional and in categorical conditions. The mean Peak 1 amplitudes for Chinese (L1) stimuli at frontal ( $m = 0.14 \mu\text{V}$ ,  $SE = .15$  in emotional conditions and  $m = 0.43 \mu\text{V}$ ,  $SE = .17$  in categorical conditions) and central ( $m = 1.36 \mu\text{V}$ ,  $SE = .15$  in emotional conditions and  $m =$

1.64  $\mu\text{V}$ ,  $\text{SE} = .17$  in categorical conditions) locations were significantly smaller than English stimuli at frontal ( $m = 3.64 \mu\text{V}$ ,  $\text{SE} = .15$  in emotional conditions and  $m = 2.66 \mu\text{V}$ ,  $\text{SE} = .17$  in categorical conditions) and central ( $m = 4.54 \mu\text{V}$ ,  $\text{SE} = .15$  in emotional conditions and  $m = 3.79 \mu\text{V}$ ,  $\text{SE} = .17$  in categorical conditions) locations but there was no statistically significant difference in mean Peak 1 amplitudes between L1 and L2 at parietal location.

### **INSERT FIGURE 17 HERE**

Figure 18 displays the statistically significant interaction effects between target and locality found in emotional and in categorical conditions. The mean Peak 1 amplitudes for target stimuli at frontal location ( $m = 2.38 \mu\text{V}$ ,  $\text{SE} = .22$  in emotional conditions and  $m = 2.35 \mu\text{V}$ ,  $\text{SE} = .28$  in categorical conditions) were significantly larger than non-target stimuli at frontal location ( $m = 1.57 \mu\text{V}$ ,  $\text{SE} = .10$  in emotional conditions and  $m = 1.28 \mu\text{V}$ ,  $\text{SE} = .13$  in categorical conditions) but there was no statistically significant difference in mean Peak 1 amplitudes between target and non-target at central and parietal locations.

### **INSERT FIGURE 18 HERE**

#### ANOVA on Peak 2 (500 – 700 ms in I, III, V and 400 – 600 ms in II, IV, VI)

For mean Peak 2 ERP amplitude, there were five statistically significant main effects at the .01 level. The first main effect was language in emotional conditions (I-IV),  $F_{(1, 4230)} = 29.72$ ,  $p < .001$ , and in categorical conditions (V & VI),  $F_{(1, 2088)} = 10.53$ ,  $p < .001$ . The second one was the category effect in categorical conditions,  $F_{(2, 2088)} = 8.36$ ,  $p < .001$ . The third one was the target effect in emotional conditions  $F_{(1, 4230)} = 530.24$ ,  $p < .001$ , and in categorical conditions,  $F_{(1, 2088)} = 136.41$ ,  $p < .001$ . The fourth was the locality effect in emotional conditions,  $F_{(2, 4230)} = 132.00$ ,  $p < .001$ , and in categorical conditions,  $F_{(2, 2088)} = 81.50$ ,  $p < .001$ . The fifth one was the laterality effect in emotional conditions,  $F_{(2, 4230)} = 27.49$ ,  $p < .001$ , and in categorical conditions,  $F_{(2, 2088)} = 11.98$ ,  $p < .001$ .

Figure 19 summarizes the four statistically significant main effects on mean Peak 2 amplitude of language, target/non-target, locality and laterality grouped in emotional and categorical conditions. Simple comparisons revealed that mean Peak 2 amplitudes for Chinese (L1) stimuli ( $m = 2.62 \mu\text{V}$ ,  $SE = .08$  in emotional conditions and  $m = 2.09 \mu\text{V}$ ,  $SE = .10$  in categorical conditions) were significantly larger than for English (L2) stimuli ( $m = 1.99 \mu\text{V}$ ,  $SE = .08$  in emotional conditions and  $m = 1.50 \mu\text{V}$ ,  $SE = .10$  in categorical conditions). Object word stimuli in categorical conditions elicited significantly larger mean Peak 2 amplitude ( $m = 2.30 \mu\text{V}$ ,  $SE = .12$ ) than measure stimuli ( $m = 1.59 \mu\text{V}$ ,  $SE = .12$ ) which in turn elicited significantly larger mean Peak 2 amplitude than math stimuli ( $m = 0.99 \mu\text{V}$ ,  $SE = .12$ ). Target stimuli elicited significantly larger mean Peak 2 amplitude ( $m = 4.07 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 3.67 \mu\text{V}$ ,  $SE = .17$  in categorical conditions) than non-target stimuli ( $m = 1.12 \mu\text{V}$ ,  $SE = .11$  in emotional conditions and  $m = 1.17 \mu\text{V}$ ,  $SE = .17$  in categorical conditions). The mean Peak 2 amplitudes at central location ( $m = 3.45 \mu\text{V}$ ,  $SE = .10$  in emotional conditions and  $m = 2.90 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) were significantly larger than at frontal ( $m = 2.25 \mu\text{V}$ ,  $SE = .10$  in emotional conditions and  $m = 1.80 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) and parietal ( $m = 1.21 \mu\text{V}$ ,  $SE = .10$  in emotional conditions and  $m = 0.69 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) locations. There was no statistically significant difference in mean Peak 2 amplitudes at frontal and parietal locations. The mean Peak 2 amplitudes at midline laterality location ( $m = 2.86 \mu\text{V}$ ,  $SE = .10$  in emotional conditions and  $m = 2.24 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) were significantly larger than at left ( $m = 2.11 \mu\text{V}$ ,  $SE = .10$  in emotional conditions and  $m = 1.67 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) and right ( $m = 1.93 \mu\text{V}$ ,  $SE = .10$  in emotional conditions and  $m = 1.47 \mu\text{V}$ ,  $SE = .12$  in categorical conditions) laterality locations.

### **INSERT FIGURE 19 HERE**

Five 2-way interaction effects and one 3-way interaction effect on mean Peak 2 amplitude were found to be statistically significant at the .01 level. The first 2-way interaction was between

language and emotion,  $F_{(2, 4230)} = 5.03, p < .01$ , in emotional conditions. The second one was between language and locality,  $F_{(2, 4230)} = 16.41, p < .001$ , in emotional conditions. The third one was between target and locality,  $F_{(2, 4230)} = 12.57, p < .001$ , in emotional conditions. The fourth one was between target and laterality,  $F_{(2, 4230)} = 9.32, p < .001$ , in emotional conditions. The fifth one was between locality and laterality,  $F_{(4, 4230)} = 14.22, p < .001$ , in emotional conditions, and  $F_{(4, 2088)} = 8.31, p < .001$ , in categorical conditions. The one statistically significant 3-way interaction effect on mean Peak 2 amplitude was among language, target, and locality,  $F_{(2, 4230)} = 13.18, p < .001$ , in emotional conditions.

Figure 20 summarizes the three 2-way interaction and one 3-way interaction effects on mean Peak 2 amplitude between target and locality, between language and locality, between target and laterality, and among language, target and locality in emotional conditions. The gap in mean Peak 2 amplitude between target and non-target stimuli was significantly larger at central locality location ( $m = 5.74 \mu\text{V}, SE = .20$  for target vs.  $m = 1.92 \mu\text{V}, SE = .09$  for non-target) than the gaps between target and non-target stimuli at frontal ( $m = 3.88 \mu\text{V}, SE = .20$  for target vs.  $m = 1.16 \mu\text{V}, SE = .09$  for non-target) and parietal ( $m = 2.60 \mu\text{V}, SE = .20$  for target vs.  $m = 0.28 \mu\text{V}, SE = .09$  for non-target) locality. The gap in mean Peak 2 amplitude between target and non-target stimuli was significantly larger at midline laterality location ( $m = 5.10 \mu\text{V}, SE = .20$  for target vs.  $m = 1.38 \mu\text{V}, SE = .09$  for non-target) than the gaps between target and non-target stimuli at left ( $m = 3.58 \mu\text{V}, SE = .20$  for target vs.  $m = 1.13 \mu\text{V}, SE = .09$  for non-target) and at right ( $m = 3.54 \mu\text{V}, SE = .20$  for target vs.  $m = 0.86 \mu\text{V}, SE = .09$  for non-target) laterality locations. The mean Peak 2 ERP amplitude for Chinese (L1) stimuli was significantly higher than English (L2) stimuli at central ( $m = 3.91 \mu\text{V}, SE = .13$  for L1 vs.  $m = 2.99 \mu\text{V}, SE = .13$  for L2) and at parietal ( $m = 1.80 \mu\text{V}, SE = .13$  for L1 vs.  $m = 0.61 \mu\text{V}, SE = .13$  for L2) locality locations but not at the frontal location ( $m = 2.15 \mu\text{V}, SE = .13$  for L1 vs.  $m = 2.35 \mu\text{V}, SE = .13$  for L2). There was no statistically significant difference in peak2 amplitude between Chinese and English stimuli at the

frontal location. For the 3-way interaction effect among language, target and locality in emotional conditions, non-target Chinese (L1) stimuli elicited significantly higher mean Peak 2 amplitude than non-target English (L2) stimuli at central location ( $m = 2.35 \mu\text{V}$ ,  $SE = .13$  for non-target L1 vs.  $m = 1.50 \mu\text{V}$ ,  $SE = .13$  for non-target L2) but not at frontal ( $m = 1.27 \mu\text{V}$ ,  $SE = .13$  for non-target L1 vs.  $m = 1.06 \mu\text{V}$ ,  $SE = .13$  for non-target L2) and parietal ( $m = 0.46 \mu\text{V}$ ,  $SE = .13$  for non-target L1 vs.  $m = 0.10 \mu\text{V}$ ,  $SE = .13$  for non-target L2) locations, and target Chinese (L1) stimuli elicited significantly larger mean Peak 2 amplitude than target English (L2) stimuli at parietal location ( $m = 3.81 \mu\text{V}$ ,  $SE = .28$  for target L1 vs.  $m = 1.39 \mu\text{V}$ ,  $SE = .26$  for target L2) but not at frontal ( $m = 3.48 \mu\text{V}$ ,  $SE = .28$  for target L1 vs.  $m = 4.28 \mu\text{V}$ ,  $SE = .26$  for target L2) and central ( $m = 6.25 \mu\text{V}$ ,  $SE = .28$  for target L1 vs.  $m = 5.23 \mu\text{V}$ ,  $SE = .26$  for target L2) locations. The mean Peak 2 amplitude for non-target L1 was not significantly different from for non-target L2 at frontal and at parietal locations. The mean Peak 2 amplitude for target L1 was not significantly different from for target L2 at frontal and central locations.

#### **INSERT FIGURE 20 HERE**

Figure 21 summarizes the 2-way interaction effect on mean Peak 2 amplitude between language and emotion in emotional conditions. The gap in mean peak2 ERP amplitude between Chinese (L1) negative stimuli ( $m = 3.18 \mu\text{V}$ ,  $SE = .13$ ) and English (L2) negative stimuli ( $m = 2.08 \mu\text{V}$ ,  $SE = .13$ ) was significantly larger than the gaps between Chinese (L1) neutral ( $m = 1.44 \mu\text{V}$ ,  $SE = .11$ ) and English (L2) neutral ( $m = 1.10 \mu\text{V}$ ,  $SE = .11$ ) and between Chinese (L1) positive ( $m = 2.65 \mu\text{V}$ ,  $SE = .13$ ) and English (L2) positive stimuli ( $m = 2.34 \mu\text{V}$ ,  $SE = .13$ ).

#### **INSERT FIGURE 21 HERE**

For the 2-way interaction effects on mean Peak 2 amplitude between locality and laterality found both in emotional and in categorical conditions, the results were that on the left, the mean Peak 2 amplitude at the central site (C3), with  $m = 3.19 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 2.71 \mu\text{V}$  and  $SE = .22$  for categorical conditions, was significantly larger than at the

frontal site (F3), with  $m = 2.22 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 1.76 \mu\text{V}$  and  $SE = .22$  for categorical conditions, which in turn was significantly larger than at the parietal site (P3), with  $m = 0.91 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 0.54 \mu\text{V}$  and  $SE = .22$  for categorical conditions. The same was true on the right, i.e., the mean Peak 2 amplitude at the central site (C4), with  $m = 3.30 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 2.77 \mu\text{V}$  and  $SE = .22$  for categorical conditions, was significantly larger than at the frontal site (F4), with  $m = 2.31 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 1.94 \mu\text{V}$  and  $SE = .22$  for categorical conditions, which in turn was significantly larger than at the parietal site (P4), with  $m = 0.18 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = -0.30 \mu\text{V}$  and  $SE = .22$  for categorical conditions. On the midline, the mean Peak 2 amplitude at the central site (CZ), with  $m = 3.85 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 3.21 \mu\text{V}$  and  $SE = .22$  for categorical conditions, was significantly larger than at either the frontal site (FZ), with  $m = 2.21 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 1.69 \mu\text{V}$  and  $SE = .22$  for categorical conditions, or the parietal site (PZ), with  $m = 2.53 \mu\text{V}$  and  $SE = .16$  for emotional conditions and  $m = 1.83 \mu\text{V}$  and  $SE = .22$  for categorical conditions. There was no statistically significant difference in mean Peak 2 amplitude between frontal (FZ) and parietal (PZ).

## **Part 2: Behavioral Study**

### *Procedure*

Participants were seated in a comfortable chair in a sound proof chamber. They were given a response pad placed in front of a computer display and told that the experiment is concerned with judgments of target and non-target stimuli, and that accuracy and reaction time were equally important. The task was for each participant to press the right button upon seeing target stimuli and the left button on seeing non-target stimuli. After assurances that the participant understood the task, the experimenter left the room and the trials began.



As in the previous experiment, participants were divided into four groups, with different orders of exposure to the conditions, the first participating in conditions I, II, III, IV, V and VI, the second in conditions V, VI, I, II, III and IV, the third in conditions II, I, IV, III, VI and V, and the fourth in conditions VI, V, II, I, IV and III. This was to balance the effects of running order between emotional valence and categorical words and between L1 and L2 on reaction time and accuracy. Participants were allowed to rest between conditions. Different from the previous experiment, the behavioral study used stimulus duration of 1000 milliseconds with an inter-stimulus interval (ISI) of 1000 milliseconds.

Similar to the previous experiment, participants were presented with a screen indicating the target stimuli prior to each condition. Following the completion of six conditions, participants were debriefed and asked to rate emotional words in L1 or L2 by a scale from 1 to 5 with 1 as the lowest emotional valence and 5 as the highest emotional valence.

### ***Statistical Analysis Results***

Participants' responses were correct on 96.7% of trials. Reaction time data on incorrect trials were not analyzed. Two 3-way (2 x 2 x 3) between-subjects analyses of variance (ANOVAs) were conducted on reaction time (RT) as the dependent variable. The first one used language (2), target (2) and emotion (3) as independent variables and the second used language (2), target (2) and category (3) as independent variables.

Major results, as summarized in Table 4, showed statistical significance for four main effects and three 2-way interaction effects on reaction time at the .01 level. The first main effect was language with  $F_{(1, 15147)} = 66.47, p < .00001$ , as found in emotional conditions (I-IV), and  $F_{(1, 7445)} = 73.15, p < .00001$ , as found in categorical conditions (V & VI). The second main effect was category with  $F_{(2, 7445)} = 47.97, p < .00001$ , as found in categorical conditions. The third main effect was emotion with  $F_{(2, 15147)} = 16.38, p < .00001$ , as found in emotional conditions. The

fourth main effect was target with  $F_{(1, 15147)} = 1218.60, p < .00001$ , as found in emotional conditions, and  $F_{(1, 7445)} = 714.99, p < .00001$ , as found in categorical conditions. The first statistically significant 2-way interaction effect was between emotion and target with  $F_{(2, 15147)} = 7.24, p < .01$ , as found in emotional conditions. The second and the third ones were between language and target with  $F_{(1, 7445)} = 77.98, p < .00001$ , and between language and category with  $F_{(2, 7445)} = 24.89, p < .00001$ , as found in categorical conditions.

#### **INSERT TABLE 4 HERE**

Simple comparisons revealed that responses to Chinese (L1) stimuli ( $m = 520.25$  ms,  $SE = 2.02$  in emotional conditions and  $m = 511.15$  ms,  $SE = 2.51$  in categorical conditions) were significantly faster than to English (L2) stimuli ( $m = 544.77$  ms,  $SE = 2.01$  in emotional conditions and  $m = 530.01$  ms,  $SE = 2.59$  in categorical conditions). Responses to math word stimuli in categorical conditions ( $m = 484.86$  ms,  $SE = 2.84$ ) were significantly faster than responses to measure word stimuli ( $m = 510.64$  ms,  $SE = 2.89$ ) which in turn were significantly faster than responses to object word stimuli ( $m = 543.41$  ms,  $SE = 2.98$ ). Responses to non-target stimuli ( $m = 486.44$  ms,  $SE = 1.26$  in emotional conditions and  $m = 486.38$  ms,  $SE = 1.91$  in categorical conditions) were significantly faster than to target stimuli ( $m = 601.62$  ms,  $SE = 3.03$  in emotional conditions and  $m = 623.17$  ms,  $SE = 4.36$  in categorical conditions). Figure 22 summarizes the two statistically significant (at the .01 level) main effects on reaction time of language and target found in emotional and in categorical conditions.

#### **INSERT FIGURE 22 HERE**

Figure 23 shows another two statistically significant (at the .01 level) main effects on reaction time of emotion as found in emotional conditions and category as found in categorical conditions, as well as the statistically significant 2-way interaction effect between emotion and target as found in emotional conditions. Responses to neutral word stimuli ( $m = 495.52$  ms,  $SE = 1.94$ ) were significantly faster than to negative ( $m = 545.05$  ms,  $SE = 2.40$ ) and to positive ( $m = 538.47$

ms, SE = 2.45) word stimuli. There was no statistically significant difference in reaction time between positive and negative stimuli. The gaps in reaction time between target and non-target stimuli were significantly different across emotional valence (positive, negative, or neutral). The difference in reaction time between target negative stimuli ( $m = 480.58$  ms, SE = 2.29) and non-target negative ( $m = 609.53$  ms, SE = 4.21), a gap of 128.95 ms, was significantly larger than between target positive stimuli ( $m = 483.22$  ms, SE = 2.28) and non-target positive stimuli ( $m = 593.71$  ms, SE = 4.34), a gap of 110.49 ms.

### **INSERT FIGURE 23 HERE**

Figure 24 shows the two statistically significant (at the .01 level) 2-way interaction effects on reaction time between language and target and between language and category as found in categorical conditions. The difference in reaction time between English (L2) target stimuli ( $m = 656.51$  ms, SE = 6.31) and Chinese (L1) target stimuli ( $m = 589.82$  ms, SE = 6.02), a gap of 66.69 ms, was significantly larger than between English non-target stimuli ( $m = 487.84$  ms, SE = 2.74) and Chinese non-target stimuli ( $m = 484.93$  ms, SE = 2.68), a gap of 2.91 ms. The difference in reaction time between English (L2) math word stimuli ( $m = 499.97$  ms, SE = 4.05) and Chinese (L1) math stimuli ( $m = 469.76$  ms, SE = 3.99), a gap of 30.20 ms, was significantly larger than between English measure word stimuli ( $m = 519.25$  ms, SE = 4.14) and Chinese measure word stimuli ( $m = 502.04$  ms, SE = 4.04), a gap of 17.20 ms, and between English object word stimuli ( $m = 550.41$  ms, SE = 4.29) and Chinese object word stimuli ( $m = 536.40$  ms, SE = 4.14), a gap of 14.01 ms. The gap in reaction time between English measure words and Chinese measure words was not statistically different from the gap between English object words and Chinese object words.

### **INSERT FIGURE 24 HERE**

## Discussion

### *The Peak 1 Component: an Index of Second Language Acquisition?*

The current studies revealed an unexpected but interesting finding about an early ERP component with a latency window between 250 and 350 ms after stimulus onset. The ERP data showed more positivity to English (L2) than to Chinese (L1) stimuli (or more negativity to stimuli in L1 than to stimuli in L2) for this ERP component, identified as Peak 1. The maximal Peak 1 amplitude enhancement was observed at the frontal and central scalp locations, which is believed to be associated with language comprehension and production and common in both humans and monkeys (Gil-da-Costa et al., 2006). This finding, which was not proposed originally in the current studies, might result from the different properties of the two languages, such as the script differences between Chinese (an ideographic script) and English (an alphabetic script), or from the age of first and second language acquisition or language proficiency of the bilingual subjects. The later explanation seems more plausible based on preliminary data analysis on three early learners of the English (L2) among the participants, one of whom was born in the US and the other two immigrated to the US in early childhood (about 8 years old). Their ERP waveforms showed a different pattern of the Peak 1 component from that of other participants. English (L2) stimuli did not elicit an enhanced Peak 1 component in these three participants when compared with Chinese stimuli. Four grand-average ERP waveforms were created across the three participants at each of the nine electrodes (F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4). The first one averaged three English stimulus types (positive, negative, and neutral) in four emotional conditions (I-IV). The second one averaged three Chinese stimulus types (positive, negative, and neutral) in four emotional conditions (I-IV). The third one averaged three English stimulus types (math, object, and measure) in two categorical conditions (V&VI). The fourth one averaged three Chinese stimulus types (math, object, and measure) in two categorical conditions (V&VI). As illustrated in Figure 25, at frontal and central electrode sites (F3, FZ, F4, C3, CZ, C4) and one

parietal electrode site (P3), Peak 1 amplitudes in response to English (L2) stimuli (in green color for emotional conditions and red for categorical) were more negative than to Chinese (L1) stimuli (in light blue color for emotional conditions and yellow for categorical) for the 3 participants. This was in contrast to the Peak 1 waveform pattern averaged across all 20 participants which showed that Peak 1 amplitudes in response to Chinese (L1) stimuli were more negative than to English (L2) stimuli (see Figure 12 in ERP Waveforms). Another difference was that the Peak 1 latency for the 3 participants shifted forward to between 175 and 275 ms from between 250 and 350 ms for 17 other participants who acquired English (L2) at later ages. This reversed pattern for amplitude and latency shift might be related to the bilingual background difference between the 3 participants and the other 17 participants, also suggesting that Peak 1 ERP component may be a neural correlate of language acquisition and proficiency among bilinguals.

### **INSERT FIGURE 25 HERE**

#### ***Peak 2 Component: a Late P300***

The ERP data from the current studies confirmed the hypothesis that target words elicit an enhanced P300 relative to non-target words, reiterating classic oddball findings that the infrequent, task-relevant target stimuli are associated with a large P300 peaking between 300 and 600 ms post-stimulus with largest amplitude at centro-parietal scalp sites (Squires & Ollo, 1999; Polich, Eischen, & Collins, 1994; Polich, 1993; Courchesne, Hillyard, & Galambos, 1975). This “target” P300, found to peak in a latency window between 400 and 700 ms at frontal/central scalp sites in all six conditions, compared well with the parietal maximum “target” P300 (or P3b) found in the traditional two-stimulus oddball paradigm. More importantly, non-target words in the same language as target words elicited an enhanced P300 when compared with non-target words in a different language from targets. This non-target P300 component was found to peak in a shorter latency window between 400 and 600 ms at frontal/central electrode sites. Furthermore, words in L1 when compared with in L2 elicited larger P300 in a latency window between 500 and 600 ms

at C3, CZ, C4, and PZ electrode sites. The current studies identified the enhanced late P300 as “Peak 2” component with a latency window between 500 and 700 ms in conditions I, III, and V with English (L2) words as target stimuli, and between 400 and 600 ms in conditions II, IV, and VI with Chinese (L1) words as target stimuli. An earlier ERP study also identified a larger late P300 in a latency window between 500 and 700 ms elicited by unpleasant words in English (L2) when compared with pleasant ones in English (L2) within sentences regardless of task (Holt et al., 2005).

Changes in P300 amplitude, latency, and scalp topography are generally thought to be associated with information content, stimulus probability structure, stimulus properties, and task relevance or task difficulty, which is defined as the amount of attention required by the stimulus (Donchin & Coles, 1988; Oken, 1989; Sommer et al., 1998; Verleger, 1988). Stimuli with high emotional value or with informative feedback or stimuli that are targets usually elicit larger P300s than stimuli that do not have these properties (Johnson, 1988, Picton, 1992, and Pritchard, 1981). In addition, P300 is sensitive to the general and specific arousal effects that contribute to attention activation and information processing (Pribram and McGuinness, 1975; Kok, 1990). The latency of P300 is an index of stimulus evaluation time and task difficulty (e.g., Coles, Smid, Scheffers, & Otten, 1995). Thus, the difference in Peak 2 latency between conditions II, IV, and VI (400 - 600 ms) with L1 words as target stimuli, and conditions I, III and V (500 – 700 ms) with L2 words as target stimuli, reflects the difference in stimulus evaluation time and task difficulty between L1 and L2 (i.e., the latency of the enhanced Peak 2 elicited by Chinese (L1) stimuli is shorter than by English (L2) stimuli as the task of mentally counting target stimuli in L1 is easier and requiring less evaluation time than in L2 among bilinguals).

### ***The Peak 2 Component: an Index of Target/Non-Target Similarity in Language and Emotion***

Based on recent findings on P300 as an index of similarity between a target and non-target stimuli (e.g., Azizian, Freitas, Parvaz, & Squires, 2006), the current studies predicted an enhanced

P300 to non-target words that have the same emotional valence as target words (positive or negative) but in a different language from targets, relative to other non-target words. In particular, when target words are positive, non-target positive words in a different language from targets would elicit a larger P300 than non-target negative words (L1 slightly larger than L2), which in turn would elicit a larger P300 than non-target neutral words (L1 slightly larger than L2). When target words are negative, non-target negative words in a different language would elicit a larger P300 than non-target positive words (L1 slightly larger than L2) which in turn would elicit a larger P300 than non-target neutral words (L1 slightly larger than L2). Thus P300 was thought to be an index of similarity in emotional valence rather than in language between a target and non-target.

Results from multiple comparisons on mean Peak 2 amplitude (see Table 2 and Table 3 in Statistical Analysis Results) showed an index of emotional valence (positive, negative, neutral) combined with language (L1, L2) that was quite different from the prediction. The first non-target stimulus type that elicited the second largest mean Peak 2 amplitude following the target stimulus type, was in the same language as the target stimulus type but opposite in emotional valence. The mean Peak 2 amplitudes for the rest of the non-target stimuli lined up descendingly in similar order with the non-target positive stimuli eliciting the smallest mean Peak 2 amplitude. In particular, there is an increased mean Peak 2 amplitude to Chinese (L1) non-targets when the target is the Chinese (L1) positive in condition II. This did not happen with English (L2) positive as target in condition I, suggesting an asymmetry between L1 and L2. This result suggested that the Peak 2 component as a late P300 is an index of similarity in language between a target and non-target, and in emotional valence between a target and non-target in L1 but not in L2, among Chinese-English bilinguals.

The ERP results confirmed the hypothesis about an enhanced P300 to L1 target words relative to L2 target words, but disproved the hypothesis about the P300 amplitude pattern for non-targets.

Specifically, condition I showed only the oddball effect, i.e., an enhanced Peak 2 to target L2 positive words relative to non-target words. Condition II showed enhanced Peak 2 to target L1 positive words relative to non-target words, and to non-target L1 negative and neutral words relative to non-target L2 words. Condition III showed enhanced Peak 2 to target L2 negative words relative to non-target words, and to non-target L2 positive words relative to non-target L1 positive words. Condition IV showed enhanced Peak 2 to target L1 negative words relative to non-target words, and to non-target L1 positive and neutral words relative to non-target L2 positive words. Conditions V and VI showed that non-target words in the same language as the target, while eliciting significantly smaller Peak 2 amplitude than target, elicited significantly larger Peak 2 amplitude than non-target stimuli in the language different from the target.

In summary, the ERP results from conditions I-IV suggested that Peak 2 amplitude is an index of similarity more in language than in emotion. In addition, the arousal by target positive stimuli but not by target negative stimuli seemed to indicate that people tend to take in more information when in a mode to expect positive events, but generally reject when anticipating negative events. This happened with L1 but not with L2 seemed to suggest different modes of information processing in L1 from in L2 when anticipating positive stimuli. The results from ANOVAs (see Table 4 in Statistical Analysis Results) on mean Peak 2 amplitudes reemphasized that language (L1, L2) was more statistically significant than emotional valence (negative, neutral, positive) in effects on Peak 2 amplitude (i.e. a statistically significant main effect was found for language but for emotion).

### ***The Peak 2 Component: a Neural Correlate of Interaction between Language and Emotion***

ERP data from the current studies showed that Chinese (L1) negative words when compared with Chinese (L1) positive or neutral words elicit a larger P300, an index of attentional and contextual updating, with a latency window between 400 and 600 ms and maximal amplitudes at frontal and central electrode sites. This is consistent with the “negativity bias” reported in earlier



findings (Holt et al., 2005) that processing negative words requires more cognitive resources than positive words. However, this “negativity bias” was not observed when English (L2) negative words were compared with English (L2) positive or neutral words (See Figures 26 and 27). This asymmetry in “negativity bias” between L1 and L2 seemed to indicate a greater emotional arousal associated with the L1 than the L2.

**INSERT FIGURE 26 HERE**

**INSERT FIGURE 27 HERE**

Statistical ANOVA results revealed that the gap in Peak 2 enhancement elicited by Chinese (L1) relative to English (L2) negative words was significantly larger than by L1 relative to L2 positive words, and by L1 relative to L2 neutral words. This implies that L1 negative words relative to L2 generate wider gap in emotional resonance than L1 positive words relative to L2 and L1 neutral words relative to L2 do. Thus the significant interaction between language and emotion on Peak 2 amplitude provided evidence supporting early findings that languages learned early in life seem to have a stronger emotional resonance and hold on bilinguals than languages learned later (Amati-Mehler et al., 1993; Javier, 1989; Santiago-Rivera & Altarriba, 2002). It also supported the hypothesis that L1 is more closely attached to the limbic system of the brain which processes emotions, and emotional memories are more strongly associated with L1 (Pavlenko 2006).

### ***Behavioral Data***

The reaction time (RT) data from part two of the current studies confirmed the original hypothesis that responses to non-targets are faster than targets, to L1 faster than to L2, and responses to emotionally-neutral stimuli are different from those to positive or negative stimuli. This was in line with findings that a complex stimulus (or task complexity) produces a slower reaction time (Brebner and Welford, 1980; Teichner and Krebs, 1974; Luce, 1986). Faster

responses to Chinese (L1) stimuli than to English (L2) stimuli in both emotional and categorical conditions implies that it requires more processing for language complexity (i.e. words in L2 are more complex than in L1 for bilinguals). Faster responses to emotionally-neutral words than to positive or negative words implies that it requires more processing for emotion complexity (i.e. positive or negative words are more complex than neutral words in emotional valence).

Significantly faster responses to non-target than to target stimuli suggest that a non-target exclusion strategy based on differences in language scripts between Chinese (L1) and English (L2) might be involved in making response decisions about target versus non-target stimuli (i.e., when target stimuli are in Chinese, all English non-targets are excluded fast based on their apparent script difference from Chinese targets). Faster responses to non-targets than to targets implies that target visual stimuli might require more attention (or more ‘arousal’) than do non-targets. This supports earlier findings that reaction time is fastest with an intermediate level of arousal, and deteriorates when the subject is either too relaxed or too tense (Welford, 1980; Broadbent, 1971; Freeman, 1933).

In accordance with the Mobilization-Minimization hypothesis (Taylor, 1991) that negative events and stimuli occupy more cognitive resources, the current studies revealed faster responses to emotionally-neutral words than to positive or negative words, suggesting that negative or positive words may require more cognitive resources than neutral words and thus requires more processing or reaction time. However, no significant difference was found in reaction time between positive and negative stimuli, contrary to the findings by Dahl (2001) that negative words relative to positive words elicited significantly prolonged response latencies in the subsequent detection task when using an affective orienting task.

### ***Implications of Emotion-Language Interaction among Bilinguals***

The current studies provided both ERP and behavioral perspectives on human knowledge of

emotion and bilingualism by comparing bilinguals' responses to emotional or categorical word stimuli in their first language (L1) and second language (L2) during a multistimulus oddball paradigm. The interaction between emotion and language from the bilingual perspective implies a greater emotional arousal associated with the L1 than the L2. Extending earlier studies on emotional word processing in monolinguals, the current studies investigated the mechanisms of how bilinguals process emotionally valenced or categorical visual word stimuli in an L1 versus an L2 from an ERP perspective, and revealed that bilingual speakers have a uniquely formed and highly interactive linguistic and emotional system. This system, rather than being composed of two monolingual systems, is in fact a compound and dynamic system of multicompetence as theorized by Cook (1991) and Grosjean (1998). The current studies provided meaningful pioneering work and a strong case for making bilingualism a necessary component in the study of emotions in the fields of linguistics, psychology, and anthropology.

### ***Limitations and Future Plans***

Despite the limited number of available Chinese-English bilinguals in the subject pool at Stony Brook University, the current studies managed to balance the factors that might affect the results including age, gender, and education level. Still there were three subjects who acquired English (L2) at an earlier age than other subjects. This was not as in the original recruiting plan. The word stimuli were balanced in terms of word frequency and emotional valence. But there were differences in terms of familiarity and perception of emotional word stimuli in L1 versus in L2 among Chinese-English bilinguals. In terms of demographic differences, subjects came from mainland China, Hong Kong and Taiwan with most speaking Chinese mandarin but a few speaking Chinese Cantonese. The good ERP and behavioral data from the current studies provided the foundation for the successful and unexpected findings. Future plans include adding English monolinguals in the subject pool and comparing emotional word processing between bilinguals and monolinguals.

Further studies on Chinese-English bilinguals of different age of acquisition are needed to investigate and demonstrate the Peak 1 effect. And studies on English monolinguals can be run in parallel to investigate if the language effect of the Peak 1 component also results from perceptual differences between languages (i.e., Chinese as an ideographic script versus English as an alphabetic script).

### ***Summary and Conclusions***

In summary, the current studies provided evidence supporting the hypothesis that target word stimuli in L1 relative to in L2 elicited a larger late P300 and revealed that first language (L1) plays a bigger role than second language (L2) in bilinguals' processing of emotional or categorical words. Meanwhile, language and emotion interacted in their effects on late P300 amplitude with a larger enhancement elicited by L1 relative to L2 negative words than by L1 relative to L2 positive words and by L1 relative to L2 neutral words. This implies a greater emotional arousal associated with the L1 than the L2. Both ERP and recognition reaction task provided evidence supporting the Mobilization-Minimization hypothesis (Taylor, 1991) that negative events and stimuli occupy more cognitive resources when compared with positive and neutral events.

The current studies further extended the hypothesis that P300 is an index of similarity between target and non-target stimuli by revealing that the P300 indexing of target/non-target similarity is more in language than in emotional valence. In particular, non-target word stimuli in the same language as the target, while exhibiting P300s that were similar to but smaller in amplitude than those elicited by target stimuli, elicited larger P300s than non-target stimuli that were in a different language from the target. When target stimuli were in L1, the late P300 was a useful index of emotional valence (positive, neutral, negative) among Chinese-English bilinguals.

The current studies also suggested that an early ERP component (with the latency between 250

and 350 ms) may be strongly correlated with language acquisition and proficiency in L1 and L2 among Chinese-English bilinguals.

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## Tables (1 – 4)

**Table 1: Summary of target/non-target word stimuli in six experiment conditions**

| <b>STIMULI (all equally probable)</b> |                     |                 |                |                     |                 |                |
|---------------------------------------|---------------------|-----------------|----------------|---------------------|-----------------|----------------|
| <b>Condition #</b>                    | <b>English (L2)</b> |                 |                | <b>Chinese (L1)</b> |                 |                |
|                                       | <b>Positive</b>     | <b>Negative</b> | <b>Neutral</b> | <b>Positive</b>     | <b>Negative</b> | <b>Neutral</b> |
| I                                     | Target              |                 |                |                     |                 |                |
| II                                    |                     |                 |                | Target              |                 |                |
| III                                   |                     | Target          |                |                     |                 |                |
| IV                                    |                     |                 |                |                     | Target          |                |
| <b>Condition #</b>                    | <b>Math</b>         | <b>Object</b>   | <b>Measure</b> | <b>Math</b>         | <b>Object</b>   | <b>Measure</b> |
| V                                     |                     | Target          |                |                     |                 |                |
| VI                                    |                     |                 |                |                     | Target          |                |

Note: blank refers to Non-Target

**Table 2: Mean Peak 2 amplitudes in response to targets/non-targets in six conditions**

| Condition | Oddball       |                    | Mean Peak 2 Amplitude ( $\mu\text{V}$ ) | Standard Deviation | Standard Error | Language | Emotional |          |
|-----------|---------------|--------------------|---|--------------------|----------------|----------|-----------|----------|
|           | Paradigm Type | Stimulus Type      |   |                    |                |          | Valence   | Category |
| I         | Target        | English Positive   | 3.92                                    | 0.32               | 0.24           | L2       | Positive  | N/A      |
|           | Non-Target    | 1 English Neutral  | 1.40                                    | 0.31               | 0.24           | L2       | Neutral   | N/A      |
|           | Non-Target    | 2 Chinese Neutral  | 1.37                                    | 0.20               | 0.24           | L1       | Neutral   | N/A      |
|           | Non-Target    | 3 English Negative | 0.93                                    | 0.25               | 0.24           | L2       | Negative  | N/A      |
|           | Non-Target    | 4 Chinese Negative | 0.88                                    | 0.20               | 0.24           | L1       | Negative  | N/A      |
|           | Non-Target    | 5 Chinese Positive | 0.68                                    | 0.23               | 0.24           | L1       | Positive  | N/A      |
| II        | Target        | Chinese Positive   | 4.28                                    | 0.30               | 0.22           | L1       | Positive  | N/A      |
|           | Non-Target    | 1 Chinese Negative | 2.84                                    | 0.23               | 0.22           | L1       | Negative  | N/A      |
|           | Non-Target    | 2 Chinese Neutral  | 2.02                                    | 0.24               | 0.22           | L1       | Neutral   | N/A      |
|           | Non-Target    | 3 English Neutral  | 1.03                                    | 0.19               | 0.22           | L2       | Neutral   | N/A      |
|           | Non-Target    | 4 English Negative | 0.64                                    | 0.17               | 0.22           | L2       | Negative  | N/A      |
|           | Non-Target    | 5 English Positive | 0.53                                    | 0.21               | 0.22           | L2       | Positive  | N/A      |
| III       | Target        | English Negative   | 3.35                                    | 0.28               | 0.20           | L2       | Negative  | N/A      |
|           | Non-Target    | 1 English Positive | 1.71                                    | 0.19               | 0.20           | L2       | Positive  | N/A      |
|           | Non-Target    | 2 Chinese Neutral  | 1.17                                    | 0.21               | 0.20           | L1       | Neutral   | N/A      |
|           | Non-Target    | 3 Chinese Negative | 1.14                                    | 0.22               | 0.20           | L1       | Negative  | N/A      |
|           | Non-Target    | 4 English Neutral  | 1.10                                    | 0.20               | 0.20           | L2       | Neutral   | N/A      |
|           | Non-Target    | 5 Chinese Positive | 0.50                                    | 0.21               | 0.20           | L1       | Positive  | N/A      |
| IV        | Target        | Chinese Negative   | 4.75                                    | 0.30               | 0.23           | L1       | Negative  | N/A      |
|           | Non-Target    | 1 Chinese Positive | 1.89                                    | 0.24               | 0.23           | L1       | Positive  | N/A      |
|           | Non-Target    | 2 Chinese Neutral  | 1.18                                    | 0.21               | 0.23           | L1       | Neutral   | N/A      |
|           | Non-Target    | 3 English Neutral  | 0.85                                    | 0.25               | 0.23           | L2       | Neutral   | N/A      |
|           | Non-Target    | 4 English Negative | 0.85                                    | 0.23               | 0.23           | L2       | Negative  | N/A      |
|           | Non-Target    | 5 English Positive | 0.02                                    | 0.18               | 0.23           | L2       | Positive  | N/A      |
| V         | Target        | English Object     | 3.03                                    | 0.28               | 0.23           | L2       | N/A       | Object   |
|           | Non-Target    | 1 English Measure  | 2.06                                    | 0.27               | 0.23           | L2       | N/A       | Measure  |
|           | Non-Target    | 2 Chinese Object   | 1.34                                    | 0.26               | 0.23           | L1       | N/A       | Object   |
|           | Non-Target    | 3 English Math     | 1.21                                    | 0.23               | 0.23           | L2       | N/A       | Math     |
|           | Non-Target    | 4 Chinese Measure  | 1.19                                    | 0.23               | 0.23           | L1       | N/A       | Measure  |
|           | Non-Target    | 5 Chinese Math     | 0.74                                    | 0.23               | 0.23           | L1       | N/A       | Math     |
| VI        | Target        | Chinese Object     | 4.31                                    | 0.31               | 0.23           | L1       | N/A       | Object   |
|           | Non-Target    | 1 Chinese Measure  | 2.12                                    | 0.25               | 0.23           | L1       | N/A       | Measure  |
|           | Non-Target    | 2 Chinese Math     | 1.40                                    | 0.26               | 0.23           | L1       | N/A       | Math     |
|           | Non-Target    | 3 English Measure  | 0.97                                    | 0.20               | 0.23           | L2       | N/A       | Measure  |
|           | Non-Target    | 4 English Math     | 0.59                                    | 0.21               | 0.23           | L2       | N/A       | Math     |
|           | Non-Target    | 5 English Object   | 0.54                                    | 0.17               | 0.23           | L2       | N/A       | Object   |

**Table 3: Significant main and interaction effects on mean Peak 1 and Peak 2 amplitudes**

| MEAN ERP AMPLITUDE<br>LATENCY WINDOW<br>EXPERIMENTAL<br>EFFECT<br>CONDITION | PEAK 1<br>250 - 350ms                 |                                       | PEAK 2<br>500 - 700ms (I,III,V)/400 - 600ms (II,IV,VI) |                                       |
|---|---------------------------------------|---------------------------------------|--|---------------------------------------|
|   | Emotional<br>(I - IV)                 | Categorical<br>(V & VI)               | Emotional<br>(I - IV)                                  | Categorical<br>(V & VI)               |
| LANGUAGE  | $F_{(1,4230)} = 323.32$<br>$p < .001$ | $F_{(1,2088)} = 105.32$<br>$p < .001$ | $F_{(1,4230)} = 29.72$<br>$p < .001$                   | $F_{(1,2088)} = 10.53$<br>$p < .001$  |
| CATEGORY  |                                       | $F_{(2,2088)} = 10.51$<br>$p < .001$  |  | $F_{(2,2088)} = 8.36$<br>$p < .001$   |
| EMOTION   | $F_{(2,4230)} = 4.72$<br>$p = .009$   |                                       |  |                                       |
| TARGET  |                                       | $F_{(1,2088)} = 8.46$<br>$p = .004$   | $F_{(1,4230)} = 530.24$<br>$p < .001$                  | $F_{(1,2088)} = 136.41$<br>$p < .001$ |
| LOCALITY  | $F_{(2,4230)} = 29.78$<br>$p < .001$  | $F_{(2,2088)} = 10.51$<br>$p < .001$  | $F_{(2,4230)} = 132.00$<br>$p < .001$                  | $F_{(2,2088)} = 81.50$<br>$p < .001$  |
| LATERALITY  | $F_{(2,4230)} = 22.20$<br>$p < .001$  | $F_{(2,2088)} = 11.84$<br>$p < .001$  | $F_{(2,4230)} = 27.49$<br>$p < .001$                   | $F_{(2,2088)} = 11.98$<br>$p < .001$  |
| LANGUAGE * EMOTION  |                                       |                                       | $F_{(2,4230)} = 5.03$<br>$p = .007$                    |                                       |
| LANGUAGE * LOCALITY   | $F_{(2,4230)} = 62.54$<br>$p < .001$  | $F_{(2,2088)} = 11.74$<br>$p < .001$  | $F_{(2,4230)} = 16.41$<br>$p < .001$                   |                                       |
| TARGET * LOCALITY   | $F_{(2,4230)} = 4.85$<br>$p = .008$   | $F_{(2,2088)} = 7.51$<br>$p = .001$   | $F_{(2,4230)} = 12.57$<br>$p < .001$                   |                                       |
| TARGET * LATERALITY   |                                       |                                       | $F_{(2,4230)} = 9.32$<br>$p < .001$                    |                                       |
| LOCALITY * LATERALITY   |                                       |                                       | $F_{(4,4230)} = 14.22$<br>$p < .001$                   | $F_{(4,2088)} = 8.31$<br>$p < .001$   |
| LANGUAGE * TARGET * LOCALITY  |                                       |                                       | $F_{(2,4230)} = 13.18$<br>$p < .001$                   |                                       |

**Table 4: Significant main and interaction effects on reaction time (RT)**

| EFFECT              | REACTION TIME (ms) - CORRECT RESPONSES    |   |
|---------------------|---|---|
|                     | EMOTIONAL<br>(I - IV)                     | CATEGORICAL<br>(V & VI)                 |
| LANGUAGE            | $F_{(1,15147)} = 66.47$<br>$p < .00001$   | $F_{(1,7445)} = 73.15$<br>$p < .00001$  |
| CATEGORY            |   | $F_{(2,7445)} = 47.97$<br>$p < .00001$  |
| EMOTION             | $F_{(2,15147)} = 16.38$<br>$p < .00001$   |   |
| TARGET              | $F_{(1,15147)} = 1218.60$<br>$p < .00001$ | $F_{(1,7445)} = 714.99$<br>$p < .00001$ |
| EMOTION * TARGET    | $F_{(2,15147)} = 7.24$<br>$p = .007$      |   |
| LANGUAGE * TARGET   |   | $F_{(1,7445)} = 77.98$<br>$p < .00001$  |
| LANGUAGE * CATEGORY |   | $F_{(2,15147)} = 24.89$<br>$p < .001$   |

## Figures (1 – 27)

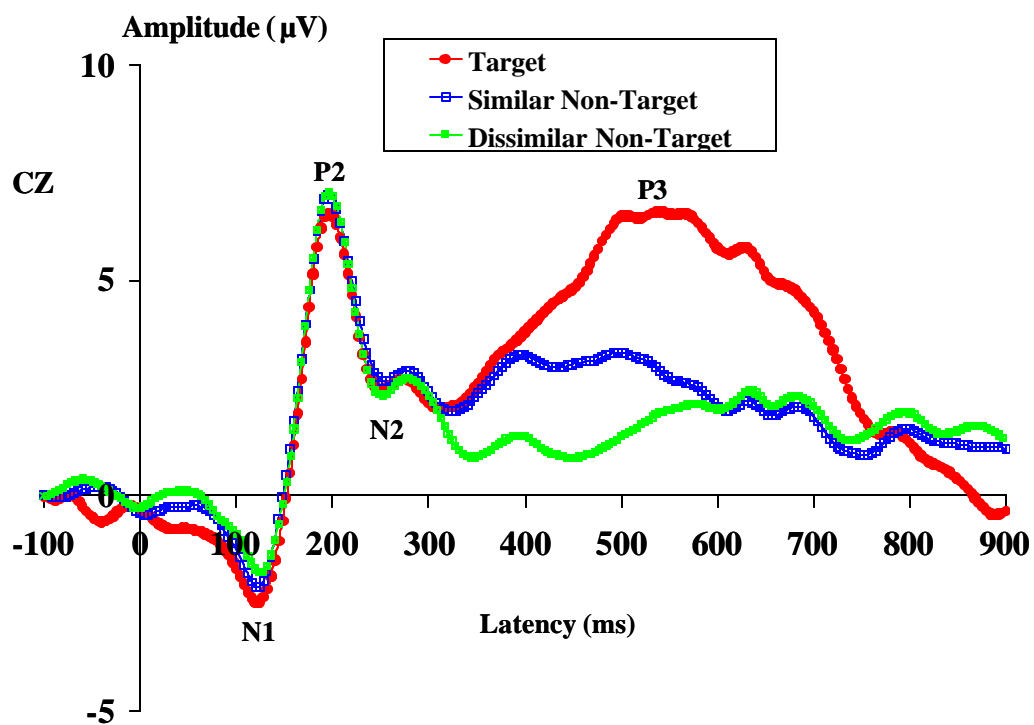
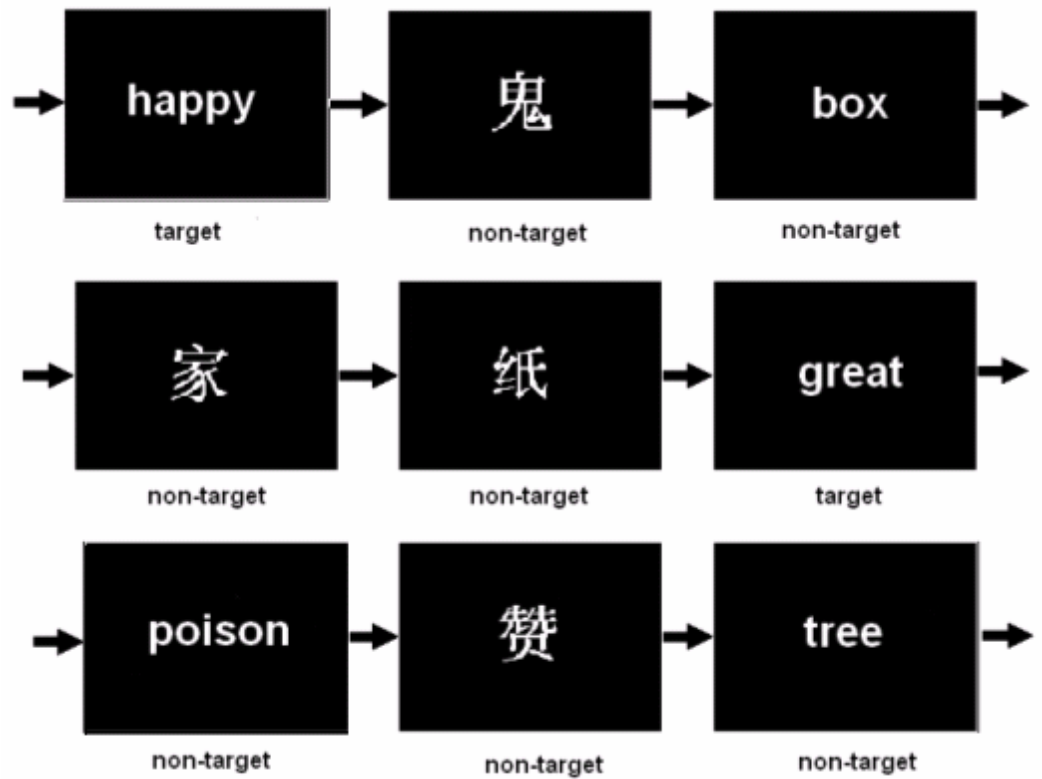
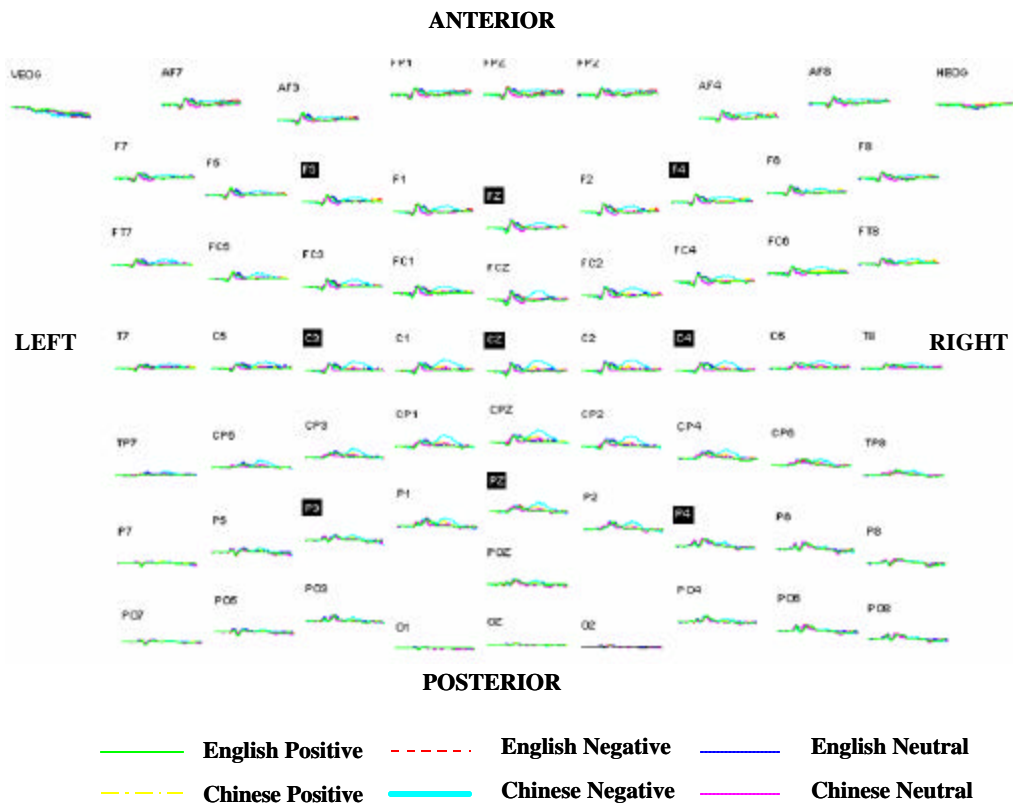


Figure 1: The visual oddball paradigm with different P300 amplitudes in response to infrequent target, frequent similar non-target, and frequent dissimilar non-target

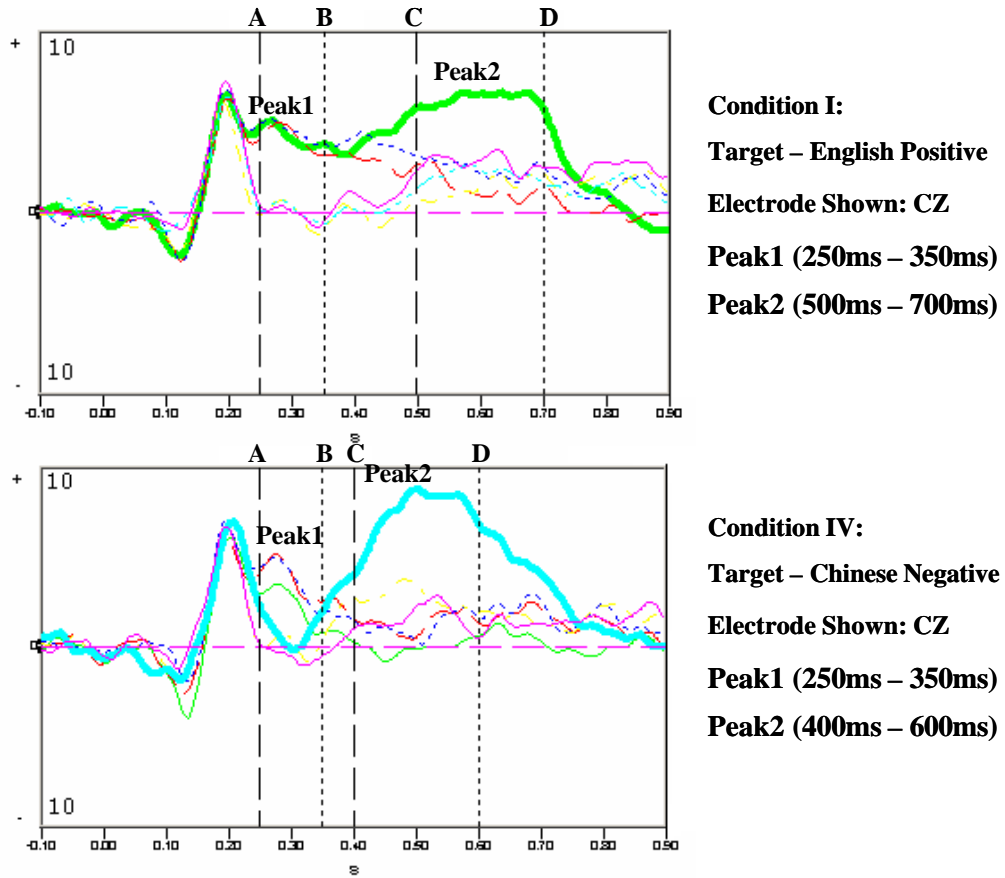


**Figure 2:** Example of 9 word stimuli from a total of 180 in Chinese (L1) and English (L2) in condition I with English positive words (1/6 frequency) as target stimuli versus the other 5 types as non-target stimuli in a randomized sequence.

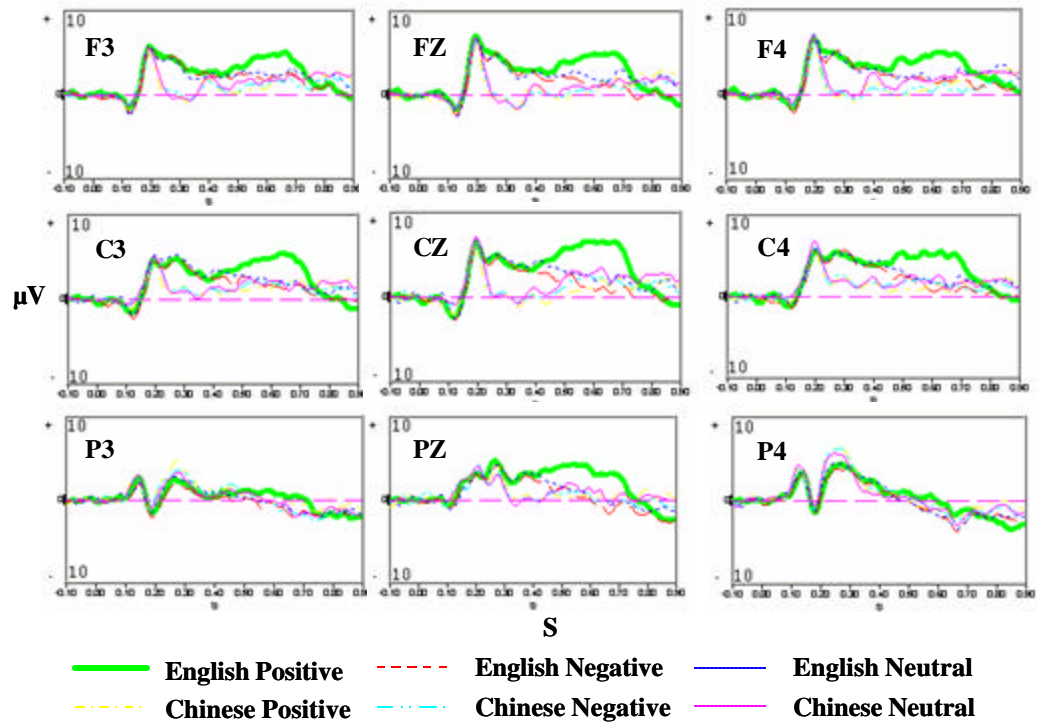




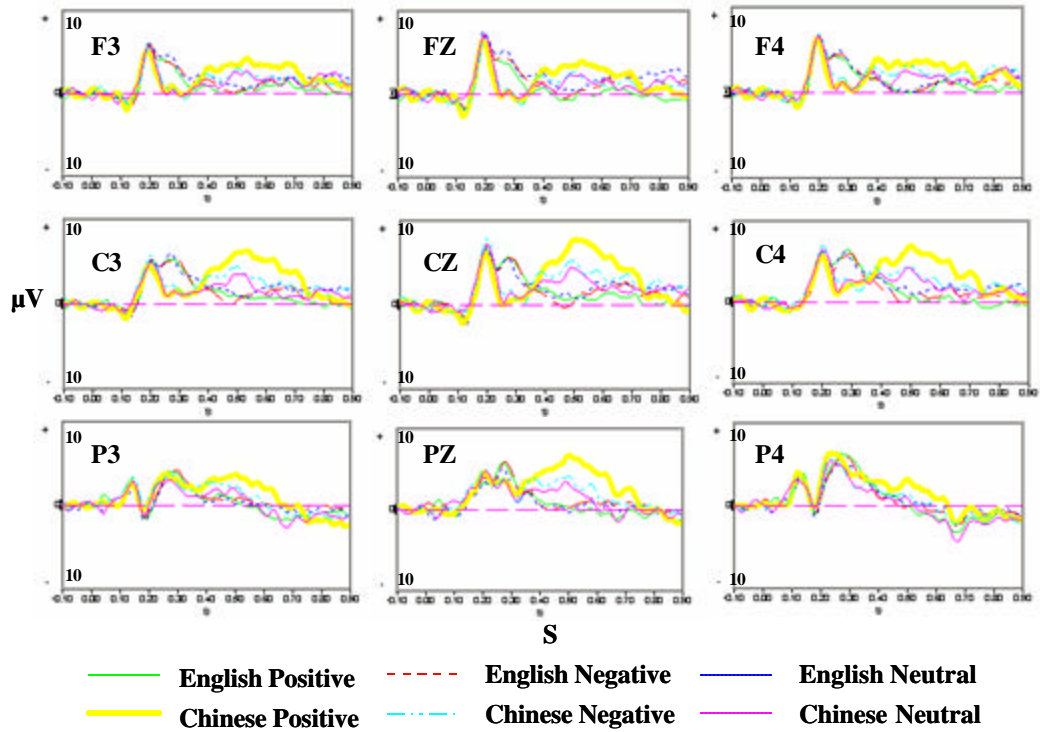
**Figure 3: Grand-average ERP waveforms at 64 electrode sites in response to six stimulus types in condition IV with 9 electrode sites (F3, FZ, F4, C3, CZ, C4, P3, PZ, P4) highlighted for statistical analysis.**



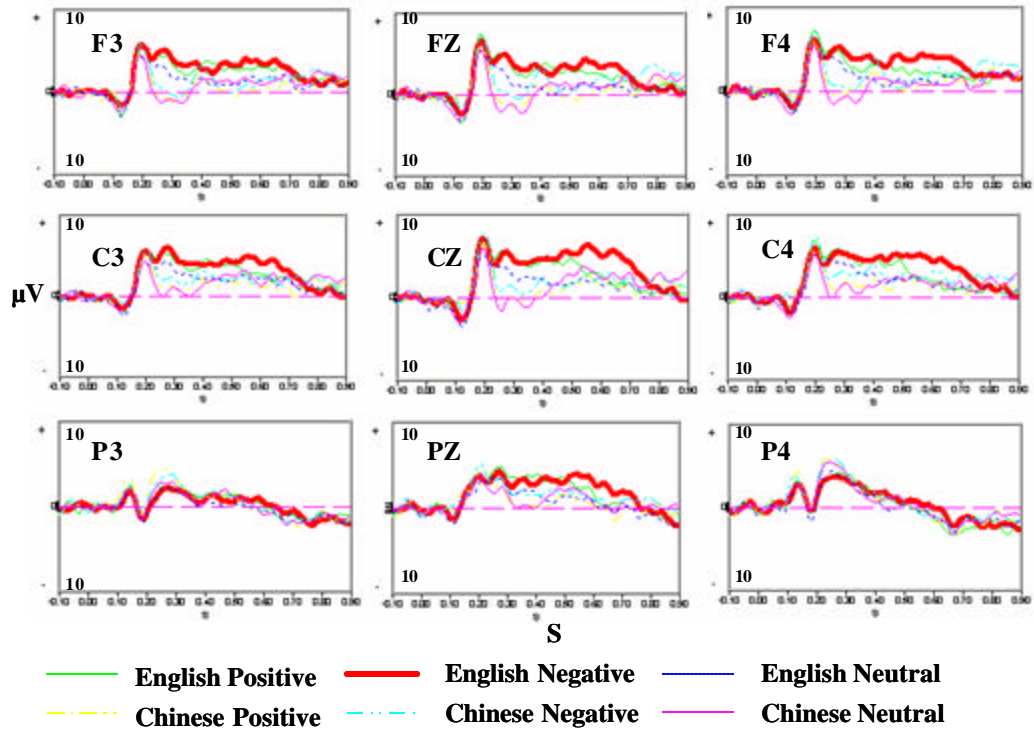
**Figure 4: Peak 1 and Peak 2 ERP components as shown in conditions I and IV.**



**Figure 5:** Grand-average ERP waveforms at 9 electrode sites in response to six different types of emotionally-valenced words in condition I with English positive words (thick in green) as target stimuli and the other 5 types of non-target stimuli.



**Figure 6:** Grand-average ERP waveforms at 9 electrode sites in response to six different types of emotionally-valenced words in condition II with Chinese positive words (thick in yellow) as target stimuli and the other 5 types of non-target stimuli.



**Figure 7:** Grand-average ERP waveforms at 9 electrode sites in response to six different types of emotionally-valenced words in condition III with English negative words (thick in red) as target stimuli and the other 5 types of non-target stimuli.

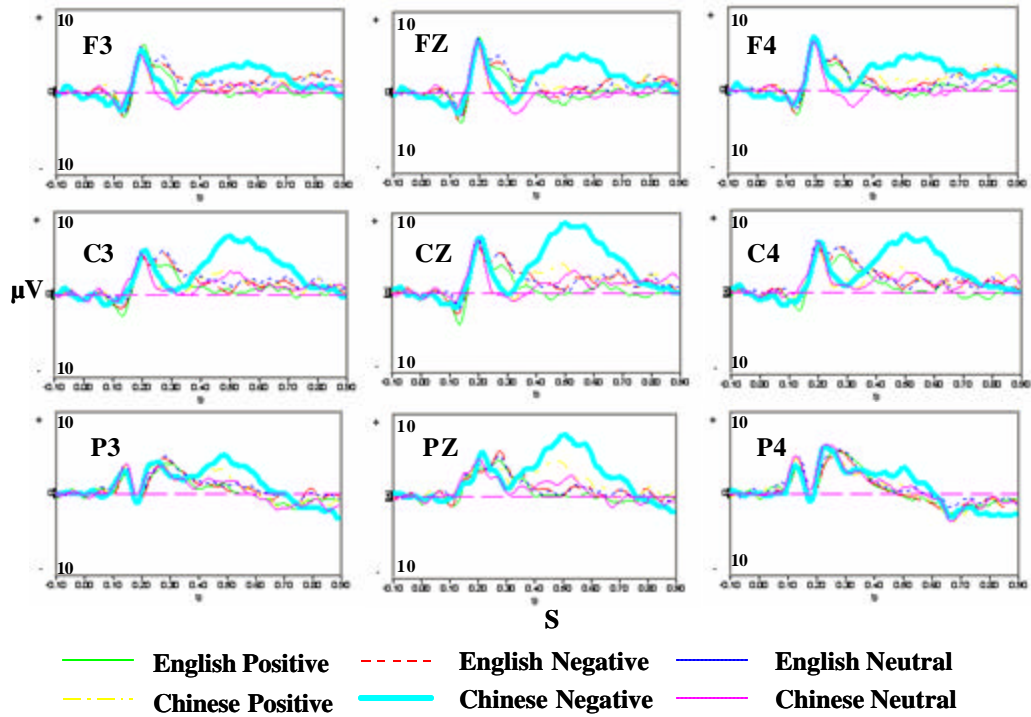
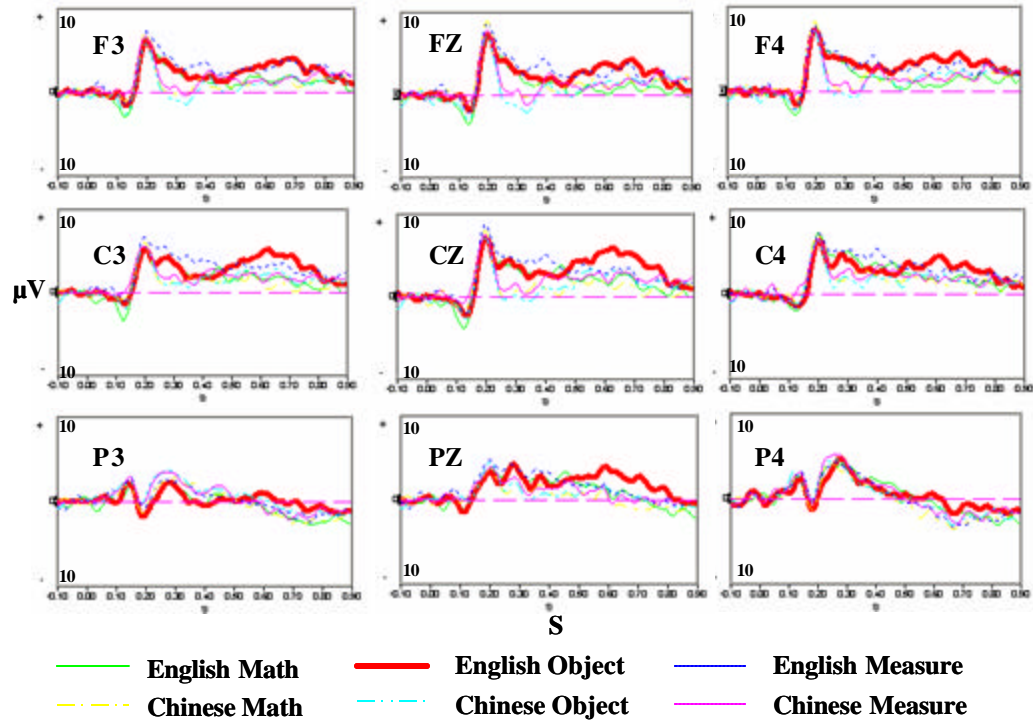
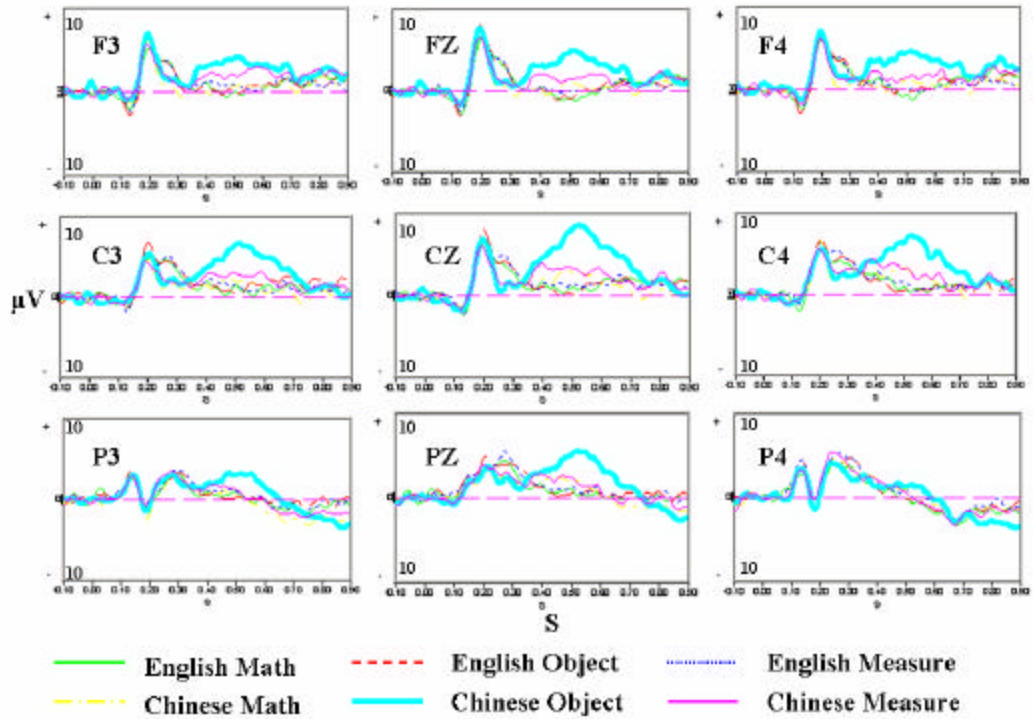


Figure 8: Grand-average ERP waveforms at 9 electrode sites in response to six different types of emotionally-valenced words in condition IV with Chinese negative words (thick in light blue) as target stimuli and the other 5 types of non-target stimuli.

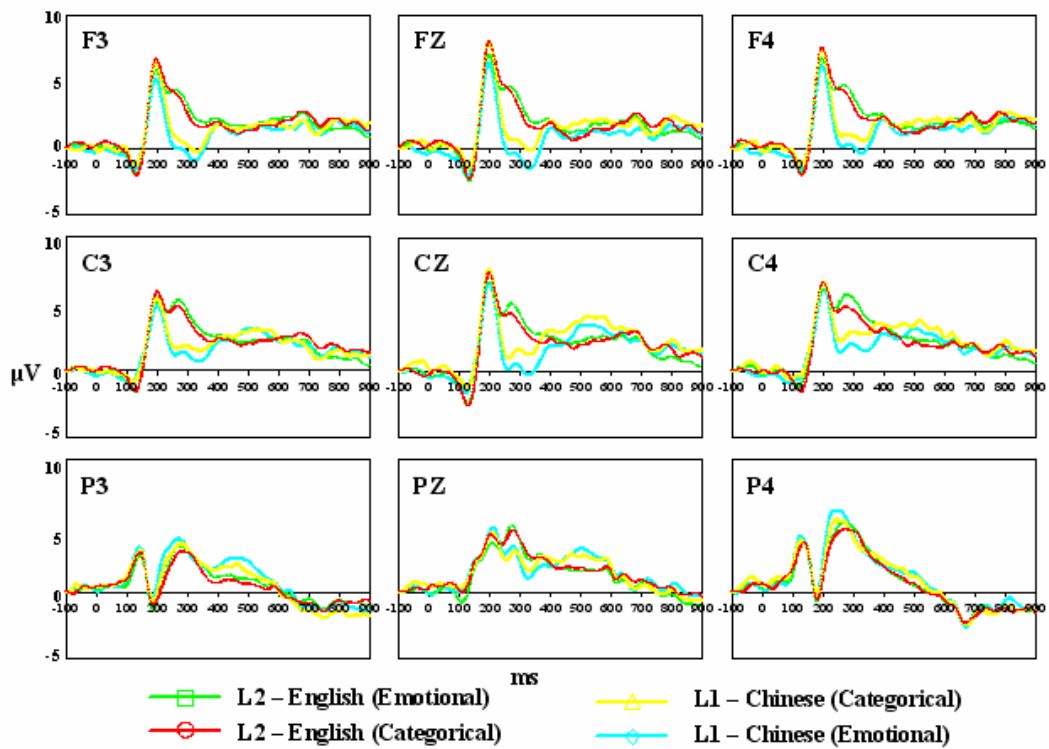


**Figure 9:** Grand-average ERP waveforms in response to six different types of categorical words in condition V with English object words (thick in red) as target stimuli versus the other 5 types of non-target stimuli.



**Figure 10:** Grand-average ERP waveforms at 9 electrode sites in response to six different types of categorical words in condition VI with Chinese object words (thick in light blue) as target stimuli versus the other 5 types of non-target stimuli.





**Figure 11: Grand-average ERP waveforms at 9 electrode sites in response to visual word stimuli in L1 versus in L2 in conditions I-IV (emotional) versus conditions V-VI (categorical).**

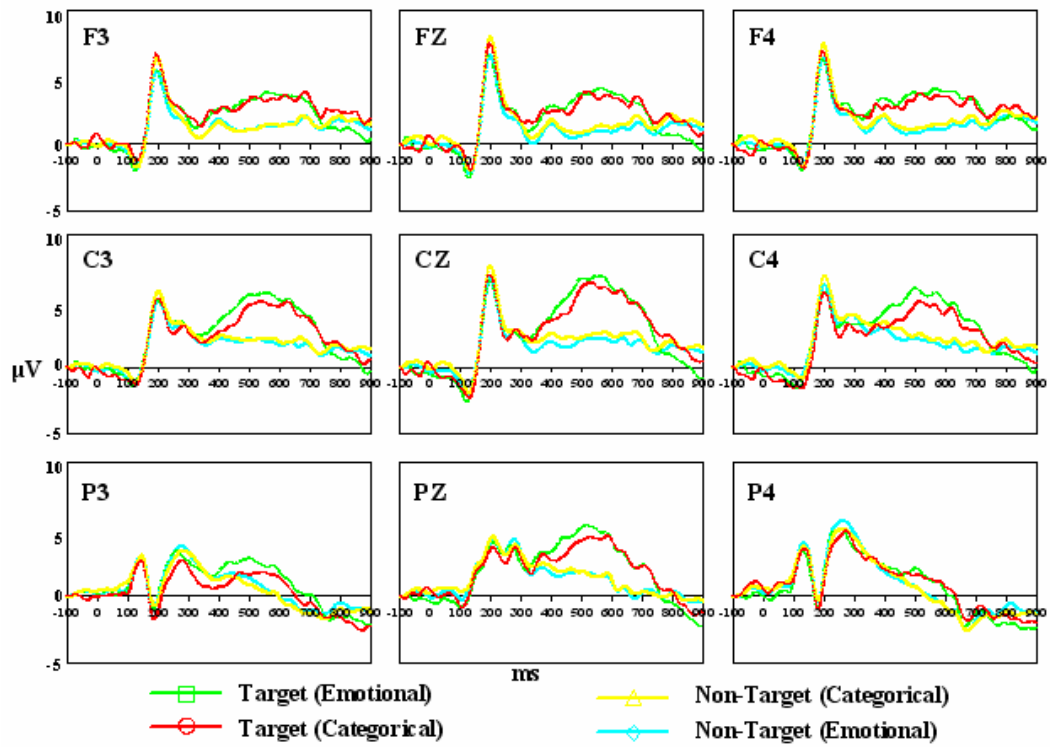
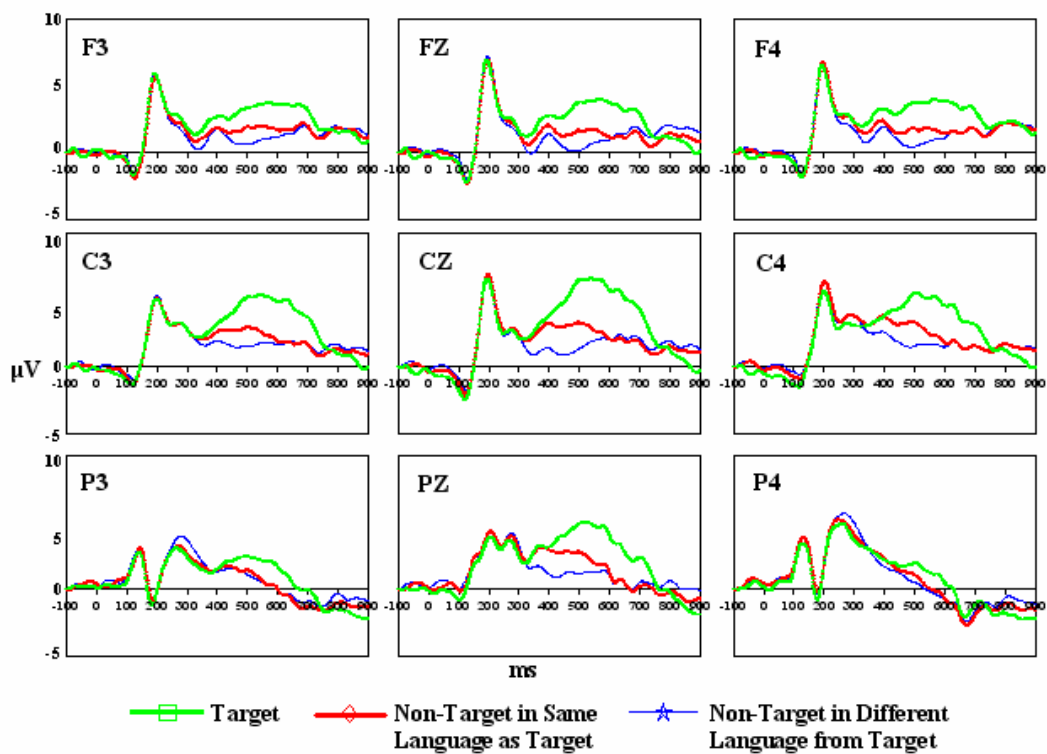


Figure 12: Grand-average ERP waveforms at 9 electrode sites in response to visual word stimuli as target versus non-target in conditions HIV (emotional) versus conditions V-VI (categorical).



**Figure 13: Grand-average ERP waveforms at 9 electrode sites in response to target stimuli versus non-target stimuli in the same language as target and non-target in different language from target in conditions I-VI.**

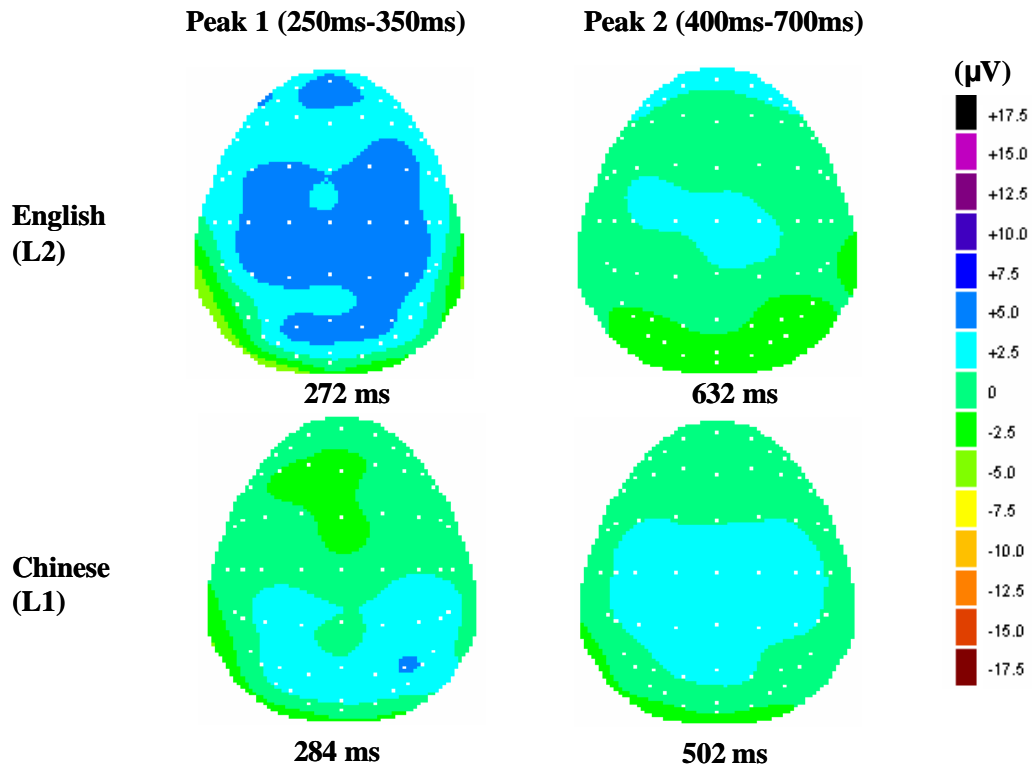
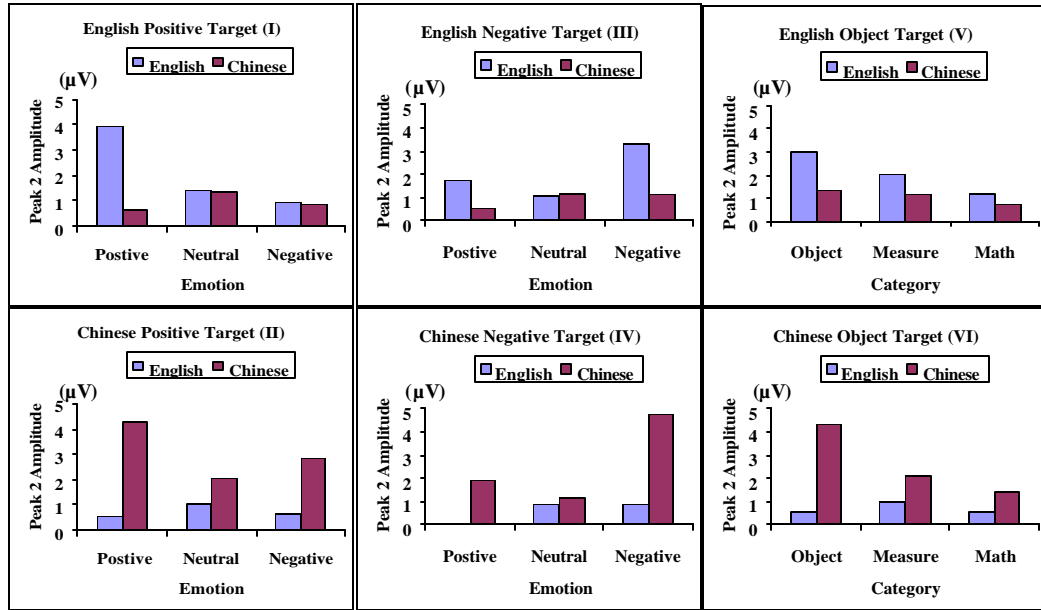
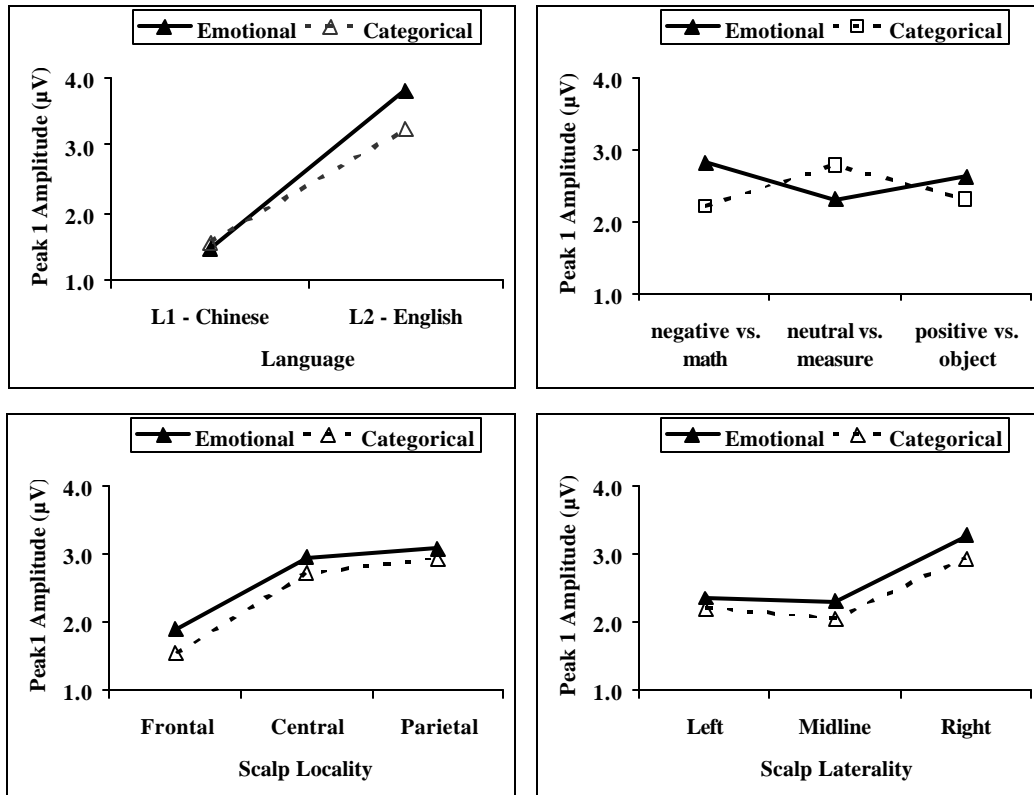


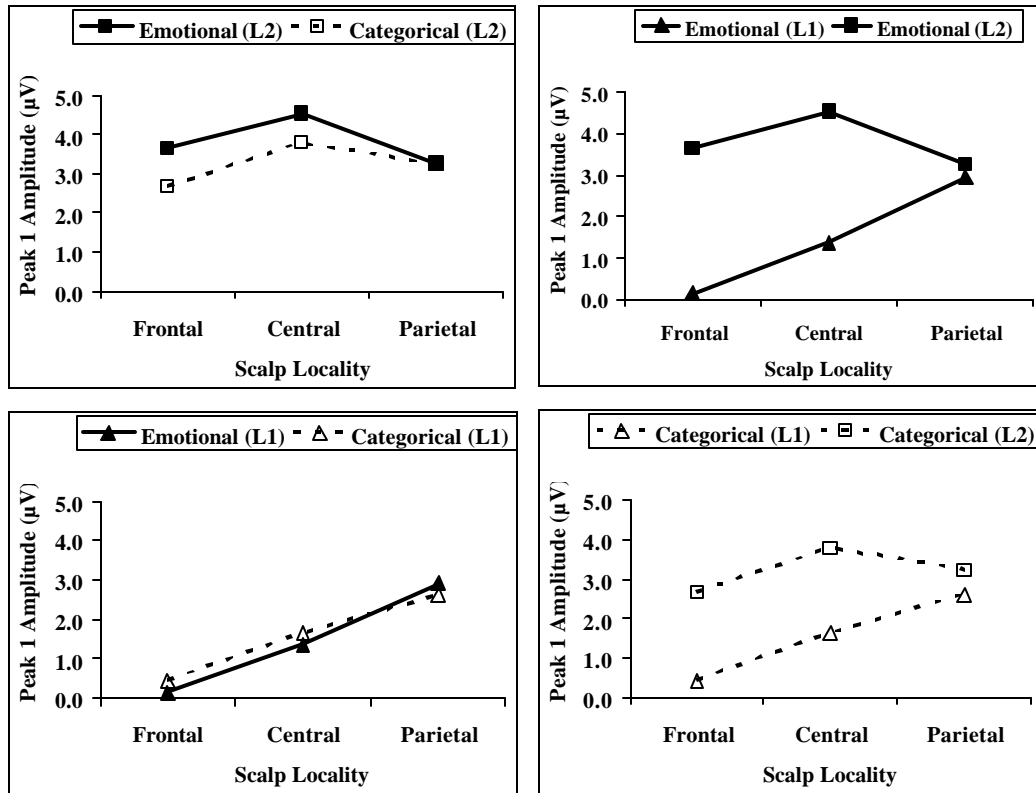
Figure 14: The 64-channel ERP topographical maps taken at the CZ electrode site for latencies corresponding to the maximal grand-average Peak 1 and Peak 2 amplitudes in response to stimuli in L1 versus in L2 in four emotional conditions (I-IV)



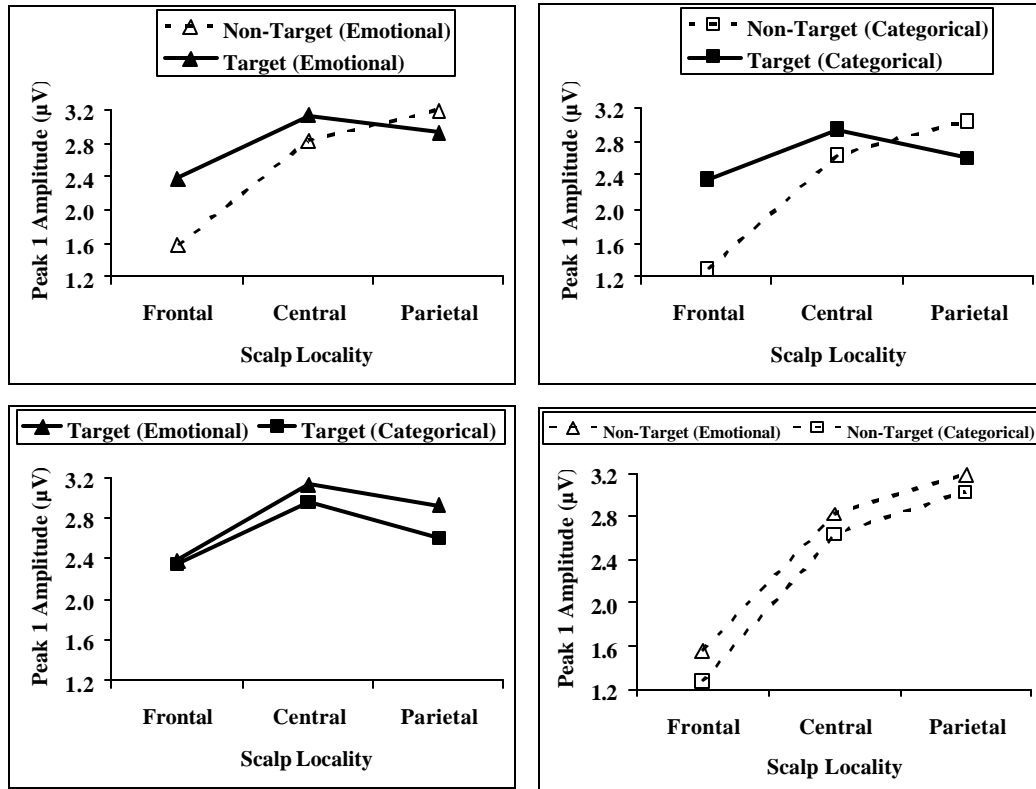
**Figure 15: Grand-average Mean Peak 2 Amplitude in response to six stimulus types (L1 versus L2) in four emotional conditions (I-IV) and two categorical conditions (V & VI).**



**Figure 16:** Grand-average mean Peak 1 amplitudes ( $\mu\text{V}$ ) in response to stimuli in L1 vs. in L2 and with emotional vs. categorical at different locality and laterality sites.

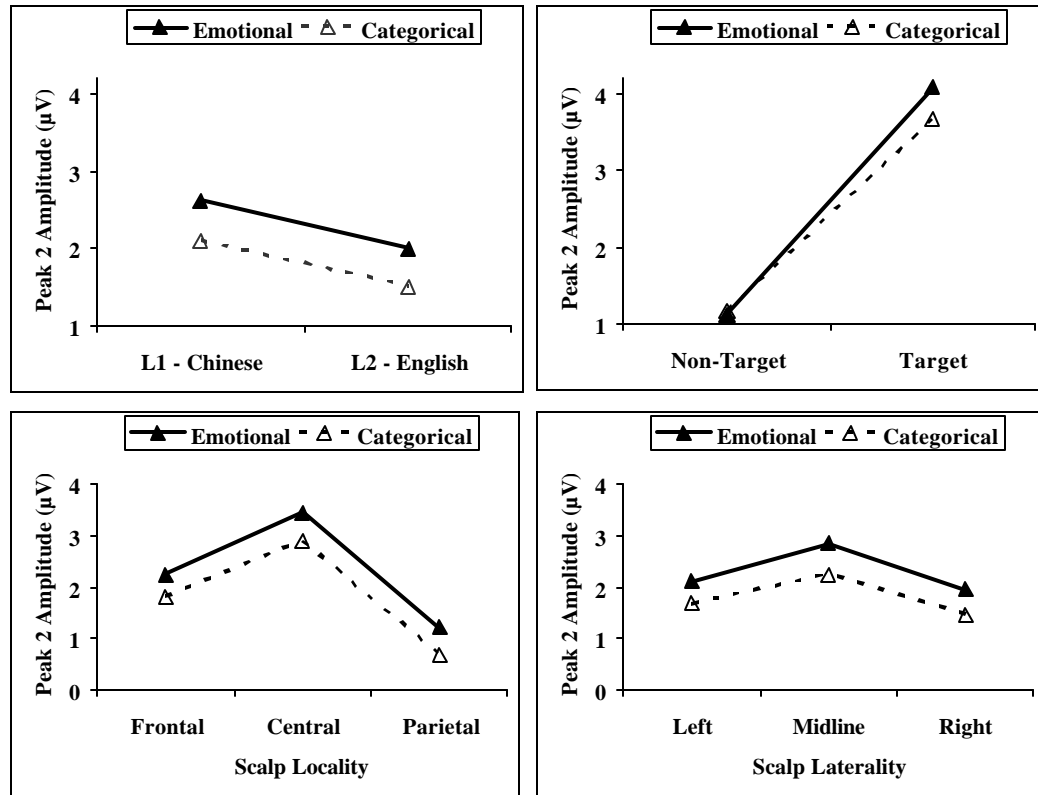


**Figure 17: Grand-average mean Peak 1 amplitudes at 3 locality sites in response to L1 words versus L2 words in emotional and categorical conditions.**

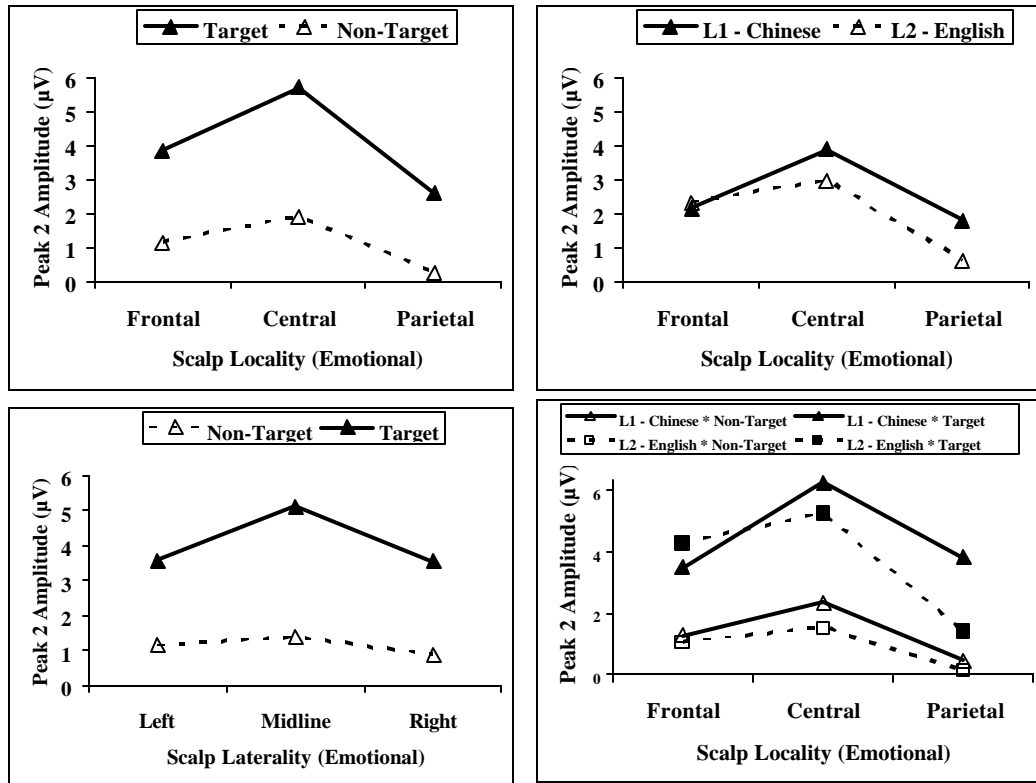


**Figure 18: Grand-average mean Peak 1 amplitudes at 3 locality sites in response to target/non-target stimuli in emotional and categorical conditions.**

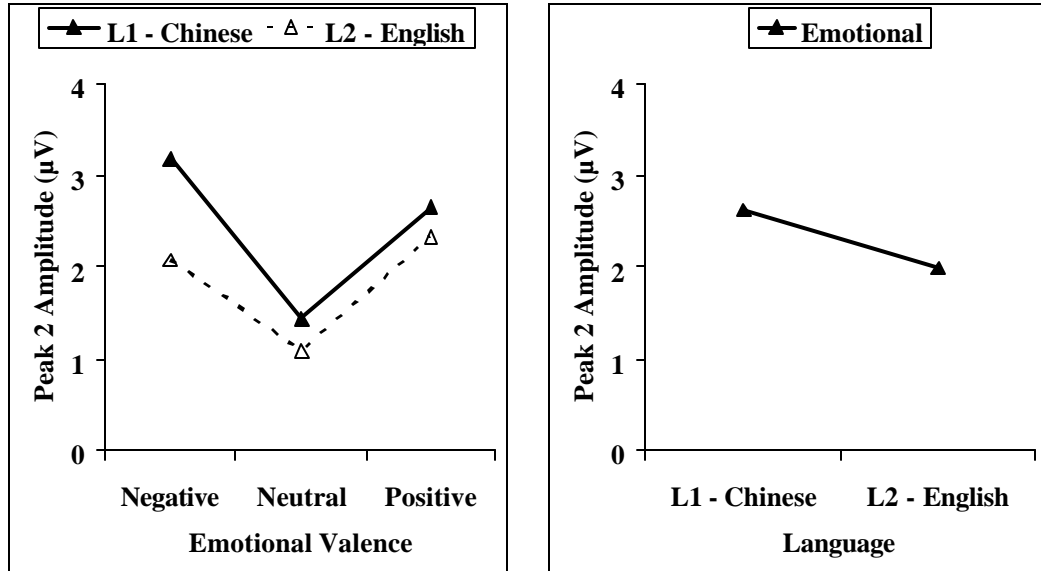




**Figure 19:** Grand-average mean Peak 2 amplitudes at 3 locality sites and at 3 laterality sites in response to word stimuli (L1 vs. L2, target vs. non-target) in emotional (I-IV) and category (V&VI) conditions.



**Figure 20:** Grand-average mean Peak 2 amplitudes at 3 locality sites and at 3 laterality sites in response to word stimuli (target vs. non-target, in L1 vs. in L2) in four emotional conditions (I-IV).



**Figure 21: Grand-average mean Peak 2 amplitudes in response to emotionally-valenced words (negative, neutral and positive) in L1 versus in L2 in emotional conditions.**

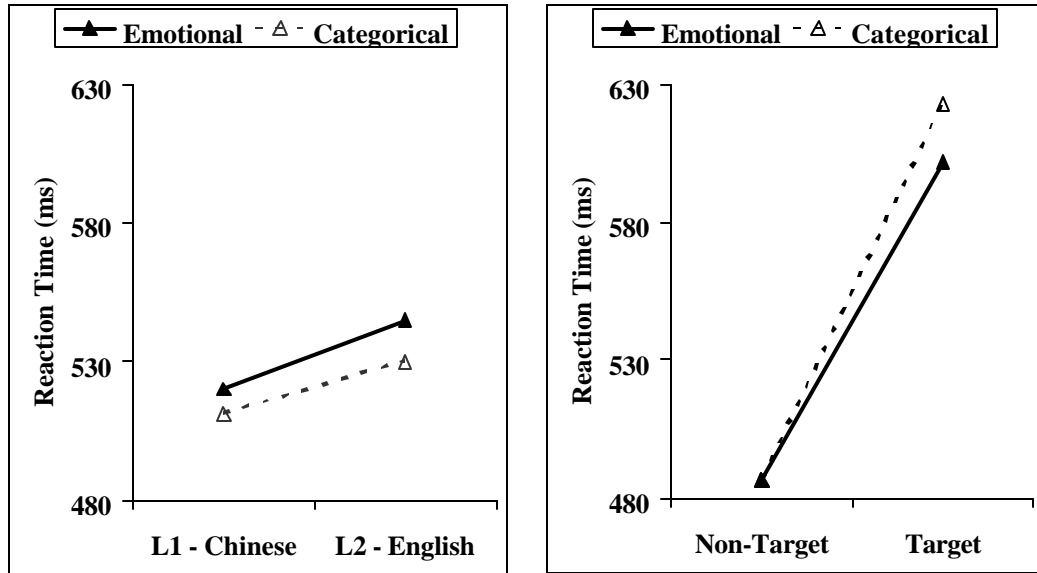
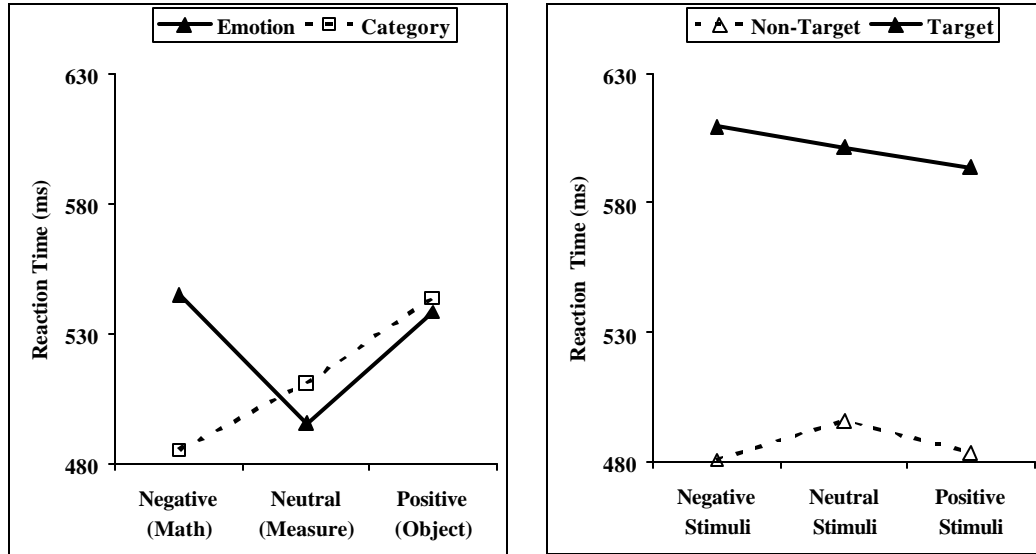
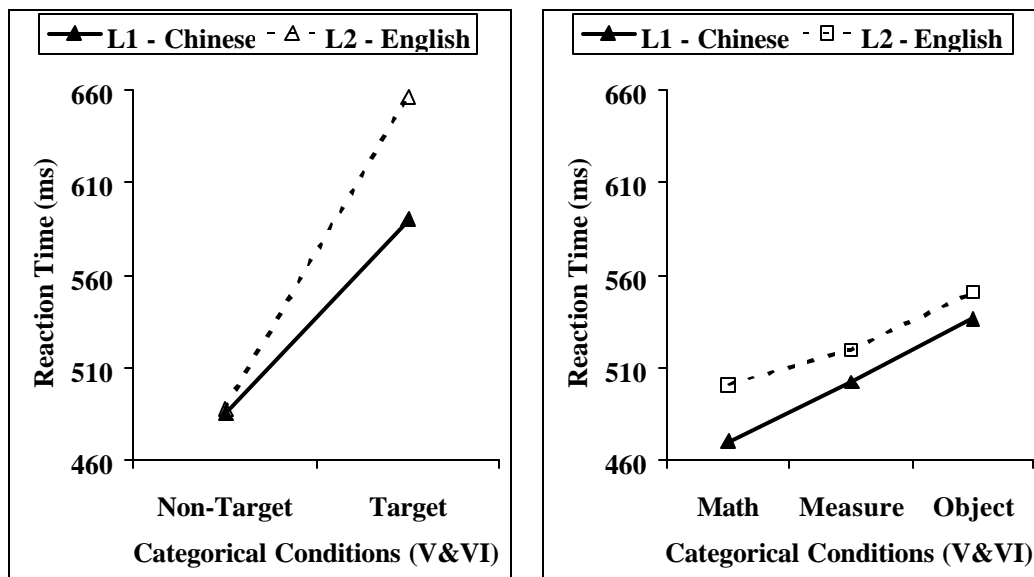


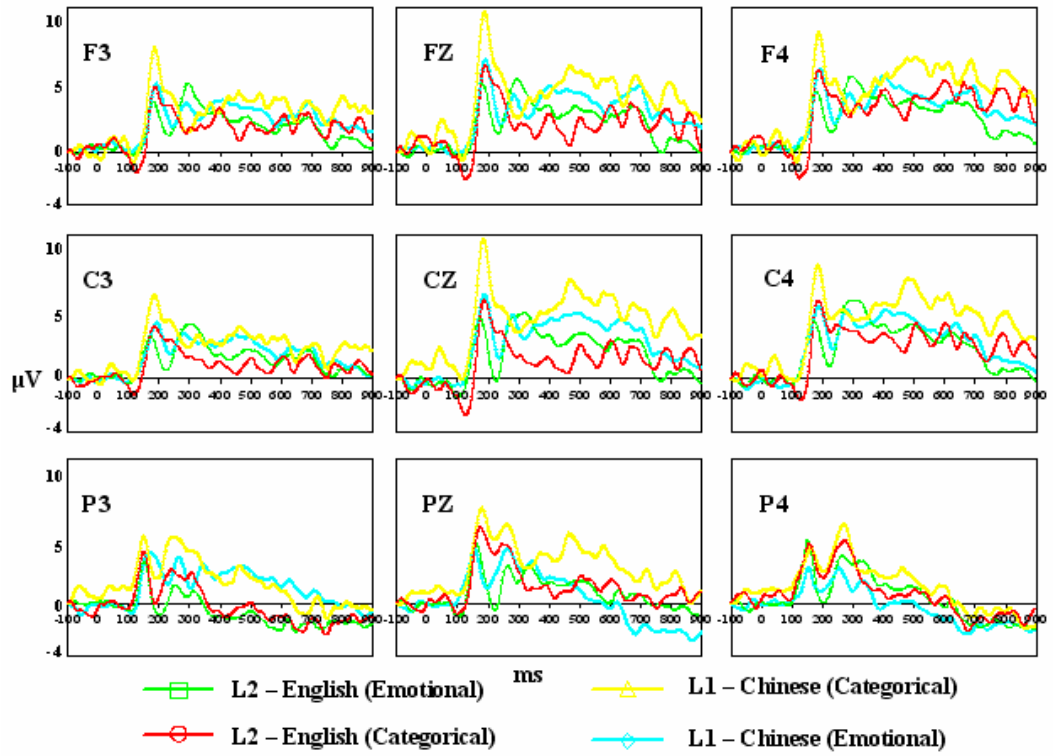
Figure 22: Grand-average reaction time (RT) in milliseconds in response to word stimuli (L2 vs. L2 and target vs. non-target) in emotional and categorical conditions.



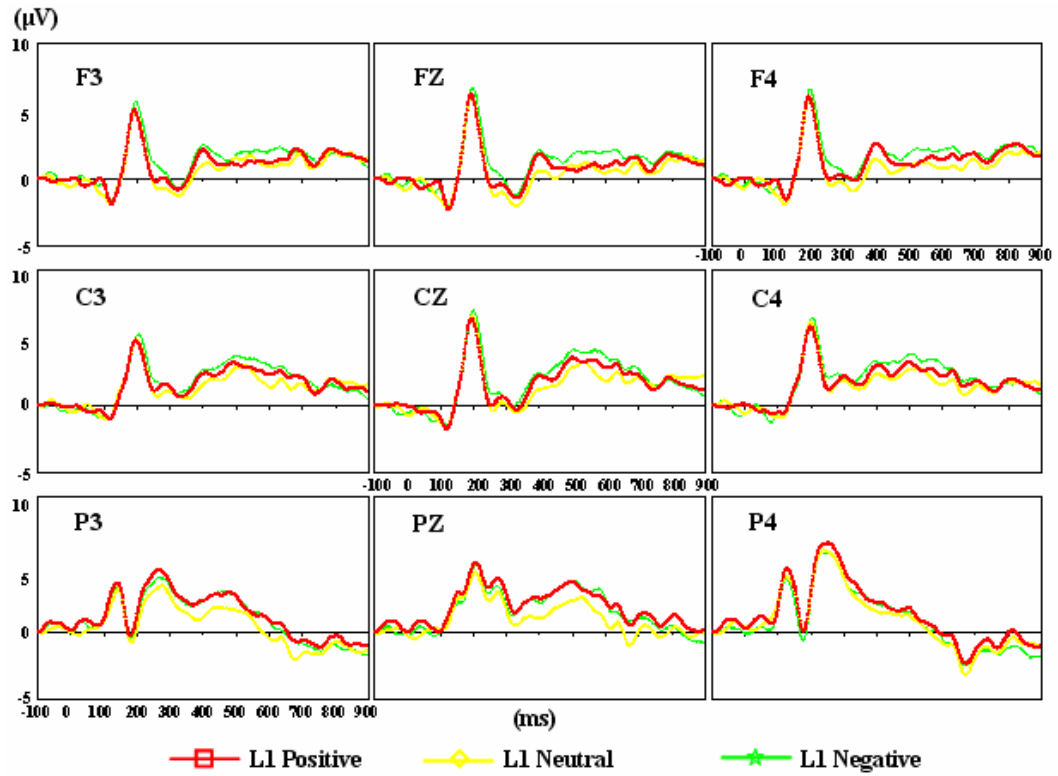
**Figure 23: Grand-average reaction time (RT) in milliseconds in response to word stimuli of different emotional valence in conditions (I-IV) relative to conditions (V & VI).**



**Figure 24:** Grand-average reaction time (RT) in milliseconds in response to categorical word stimuli in L1 vs. in L2 interacting with target vs. non-target and in L1 vs. in L2 interacting with category (math, measure, and object) in conditions V & VI.

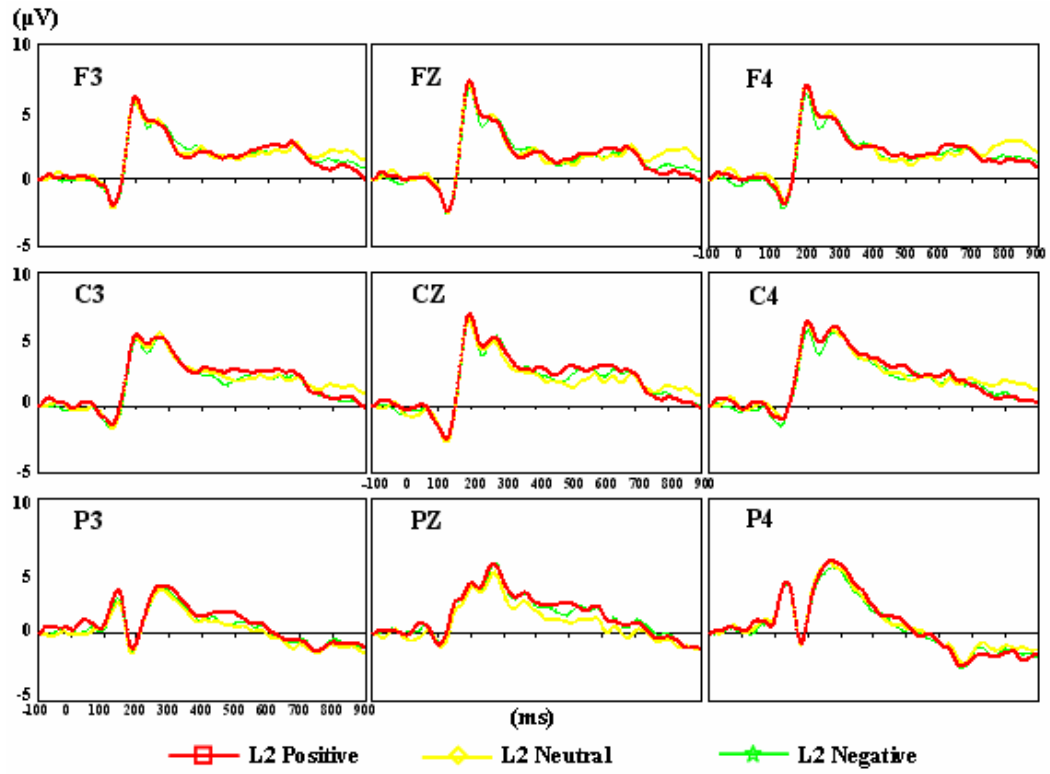


**Figure 25:** Grand-average ERP waveforms across 3 participants at 9 electrode sites in response to stimuli in L1 vs. in L2 in emotional (I-IV) and categorical (V&VI) conditions.



**Figure 26: Grand-average ERP waveforms across all participants at 9 electrode sites in response to emotionally-valenced stimuli in L1 in conditions I-IV.**





**Figure 27: Grand-average ERP waveforms across all participants at 9 electrode sites in response to emotionally-valenced stimuli in L2 in conditions I-IV.**

## Appendices (A – F)

### Appendix A: List of word stimuli and ratio/frequency in L2 for Emotional Conditions (I-IV)

| neutral_English | ratio* | positive_English | ratio* | negative_English | ratio* |
|-----------------|--------|------------------|--------|------------------|--------|
| branch          | 3.92   | lucky            | 2.85   | dead             | 5.58   |
| cloth           | 2.63   | bless            | 1.69   | abuse            | 3.50   |
| outcome         | 2.94   | beautiful        | 5.34   | cancer           | 5.45   |
| name            | 8.07   | like             | 4.88   | crime            | 6.54   |
| address         | 6.03   | happy            | 4.88   | cruel            | 2.01   |
| reason          | 6.17   | kind             | 2.14   | danger           | 3.11   |
| street          | 5.08   | excellent        | 3.70   | terror           | 2.15   |
| selection       | 4.21   | love             | 3.65   | disease          | 8.07   |
| circle          | 2.45   | home             | 11.15  | suicide          | 2.61   |
| square          | 2.18   | great            | 12.60  | tomb             | 2.56   |
| fragment        | 3.77   | friendly         | 2.71   | disaster         | 2.40   |
| swim            | 1.77   | praise           | 1.80   | murder           | 5.78   |
| forest          | 5.87   | smile            | 6.59   | kill             | 3.21   |
| walk            | 3.07   | joy              | 2.51   | ghost            | 2.30   |
| title           | 6.18   | healthy          | 2.73   | poison           | 2.18   |
| grass           | 3.65   | faithful         | 1.68   | awful            | 2.54   |
| give            | 4.58   | cheerful         | 1.80   | bad              | 5.41   |
| move            | 3.88   | proud            | 2.42   | stupid           | 3.31   |
| economy         | 7.37   | trust            | 4.19   | failure          | 4.12   |
| answer          | 4.07   | hope             | 2.93   | trouble          | 4.01   |
| signal          | 3.31   | glory            | 2.26   | injury           | 5.41   |
| transfer        | 2.40   | pleasant         | 2.38   | ill              | 2.53   |
| conclude        | 1.60   | peace            | 5.61   | bomb             | 3.75   |
| listen          | 2.29   | pleased          | 2.08   | shame            | 2.01   |
| resident        | 1.99   | care             | 7.75   | sad              | 2.71   |
| speak           | 3.68   | charm            | 1.88   | sorry            | 6.56   |
| store           | 2.96   | lively           | 1.89   | weak             | 2.48   |
| liquid          | 2.03   | warmth           | 2.49   | cry              | 2.24   |
| jacket          | 3.52   | honest           | 2.28   | grief            | 2.18   |
| factory         | 3.80   | enjoy            | 2.51   | loss             | 5.16   |
| Grand Average   | 3.85   | Grand Average    | 3.78   | Grand Average    | 3.73   |

\* ratio = word frequency / number of files the word occurs in from British National Corpus (BNC).

**Appendix B: List of word stimuli and ratio/frequency in L1 for Emotional Conditions (I-IV)**

| neutral_Chinese | frequency** | positive_Chinese | frequency** | negative_Chinese | frequency** |
|-----------------|-------------|------------------|-------------|------------------|-------------|
| 交叉              | 97.86       | 吉利               | 86.50       | 亡                | 88.42       |
| 布               | 69.88       | 保佑               | 98.92       | 虐                | 98.76       |
| 结果              | 59.30       | 美                | 49.92       | 癌                | 96.29       |
| 名               | 56.09       | 喜欢               | 82.35       | 罪                | 83.26       |
| 地址              | 96.51       | 乐                | 80.29       | 残暴               | 89.58       |
| 原因              | 55.04       | 善良               | 86.06       | 险                | 81.97       |
| 街               | 90.62       | 优秀               | 91.08       | 恐怖               | 87.20       |
| 选择              | 88.49       | 爱                | 70.67       | 疾病               | 72.43       |
| 圆圈              | 93.50       | 家                | 32.14       | 自杀               | 28.44       |
| 方块              | 85.13       | 伟大               | 90.70       | 坟墓               | 96.37       |
| 碎片              | 93.95       | 友好               | 79.43       | 灾祸               | 93.34       |
| 游泳              | 98.67       | 称赞               | 91.61       | 凶杀               | 79.18       |
| 森林              | 89.60       | 微笑               | 81.39       | 杀害               | 69.17       |
| 走               | 56.49       | 欢                | 82.35       | 鬼                | 86.44       |
| 标题              | 74.63       | 康                | 87.38       | 毒害               | 74.99       |
| 草               | 85.04       | 忠诚               | 93.10       | 糟糕               | 96.64       |
| 给               | 53.62       | 爽快               | 98.23       | 恶劣               | 81.61       |
| 移动              | 86.99       | 自豪               | 94.65       | 蠢                | 97.38       |
| 经济              | 68.68       | 信任               | 54.28       | 失败               | 66.09       |
| 回答              | 78.16       | 希望               | 76.14       | 困扰               | 86.17       |
| 信号              | 75.25       | 荣耀               | 96.31       | 伤害               | 74.99       |
| 转移              | 86.99       | 愉快               | 97.06       | 患病               | 68.22       |
| 总结              | 59.30       | 和平               | 57.29       | 炸弹               | 80.96       |
| 听               | 63.51       | 高兴               | 77.08       | 耻辱               | 95.07       |
| 居民              | 82.15       | 关心               | 46.38       | 悲                | 89.48       |
| 说话              | 52.43       | 魅力               | 98.76       | 懊悔               | 94.80       |
| 商店              | 89.78       | 轻快               | 74.04       | 软弱               | 88.36       |
| 液体              | 94.19       | 热情               | 79.85       | 哭泣               | 87.81       |
| 外套              | 90.49       | 诚实               | 91.30       | 悲痛               | 83.01       |
| 工厂              | 88.52       | 喜爱               | 81.85       | 损失               | 66.09       |
| Grand Average   | 78.69       | Grand Average    | 80.24       | Grand Average    | 82.75       |

\*\* frequency is in cumulative percentage from the combined character frequency list of classical and modern Chinese (Da, J., 2004).

**Appendix C: List of word stimuli and ratio/frequency in L2 for Categorical Conditions  
(V&VI)**

| math_English  | ratio | object_English | ratio | measure_English | ratio |
|---------------|-------|----------------|-------|-----------------|-------|
| minus         | 4.08  | plane          | 3.93  | inch            | 2.34  |
| zero          | 2.22  | tape           | 4.02  | foot            | 4.14  |
| formula       | 2.86  | piano          | 4.12  | yard            | 3.23  |
| equation      | 6.05  | shoe           | 2.28  | mile            | 2.99  |
| function      | 5.27  | box            | 4.53  | year            | 20.85 |
| statistics    | 3.38  | paper          | 6.49  | hour            | 4.98  |
| seven         | 5.95  | chair          | 5.46  | month           | 6.08  |
| eight         | 6.11  | ferry          | 2.67  | meter           | 2.32  |
| nine          | 5.41  | table          | 8.52  | centimeter      | 2.45  |
| curve         | 3.91  | lamp           | 2.27  | millimeter      | 1.44  |
| eleven        | 2.79  | desk           | 4.27  | acre            | 1.97  |
| twelve        | 3.57  | submarine      | 2.62  | kilometer       | 3.60  |
| thirteen      | 2.26  | subway         | 1.63  | gallon          | 2.21  |
| fourteen      | 2.49  | train          | 4.57  | liter           | 2.27  |
| fifteen       | 3.27  | truck          | 2.77  | second          | 3.18  |
| sixteen       | 2.43  | television     | 5.26  | minute          | 3.98  |
| seventeen     | 2.13  | computer       | 8.55  | degree          | 4.88  |
| eighteen      | 2.59  | pillow         | 1.87  | pound           | 5.42  |
| nineteen      | 4.82  | lock           | 2.58  | gram            | 2.65  |
| geometry      | 2.52  | package        | 4.50  | kilogram        | 2.05  |
| thirty        | 5.21  | purse          | 1.65  | ounce           | 1.72  |
| forty         | 4.31  | machine        | 5.11  | hectare         | 4.18  |
| fifty         | 5.41  | telephone      | 4.27  | carat           | 4.64  |
| sixty         | 3.92  | pencil         | 2.24  | pint            | 2.57  |
| seventy       | 3.37  | battery        | 2.87  | dollar          | 4.33  |
| eighty        | 4.39  | fan            | 2.45  | yen             | 3.12  |
| ninety        | 5.06  | window         | 5.96  | franc           | 2.89  |
| angle         | 2.89  | envelope       | 2.54  | mark            | 2.74  |
| thousand      | 5.79  | globe          | 1.48  | penny           | 1.93  |
| average       | 2.43  | ship           | 4.28  | ton             | 1.67  |
| Grand Average | 3.90  | Grand Average  | 3.86  | Grand Average   | 3.76  |

\* ratio = word frequency / number of files the word occurs in from British National Corpus (BNC).

**Appendix D: List of word stimuli and ratio/frequency in L1 for Categorical Conditions  
(V&VI)**

| math_Chinese  | frequency | object_Chinese | frequency | measure_Chinese | frequency |
|---------------|-----------|----------------|-----------|-----------------|-----------|
| 减             | 84.18     | 飞机             | 44.97     | 英寸              | 80.69     |
| 零             | 92.34     | 磁带             | 64.91     | 英尺              | 79.06     |
| 公式            | 66.03     | 钢琴             | 94.20     | 码               | 93.53     |
| 方程            | 65.80     | 鞋              | 94.92     | 英里              | 47.83     |
| 函数            | 96.38     | 盒              | 96.77     | 年               | 24.88     |
| 统计            | 61.13     | 纸              | 88.21     | 小时              | 26.98     |
| 七             | 64.61     | 椅              | 94.95     | 月份              | 63.90     |
| 八             | 62.54     | 渡船             | 75.97     | 米               | 78.86     |
| 九             | 63.79     | 桌              | 90.73     | 厘米              | 88.09     |
| 曲线            | 86.08     | 灯              | 88.39     | 毫米              | 82.95     |
| 十一            | 29.71     | 书桌             | 49.81     | 英亩              | 82.26     |
| 十二            | 33.36     | 潜艇             | 89.13     | 公里              | 33.42     |
| 十三            | 32.72     | 地铁             | 19.83     | 加仑              | 74.13     |
| 十四            | 45.77     | 火车             | 65.63     | 升               | 82.49     |
| 十五            | 48.54     | 卡车             | 65.63     | 秒钟              | 90.75     |
| 十六            | 61.85     | 电视             | 60.91     | 分钟              | 60.92     |
| 十七            | 64.61     | 电脑             | 60.91     | 度               | 51.91     |
| 十八            | 62.54     | 枕头             | 44.55     | 磅               | 99.06     |
| 十九            | 63.79     | 锁              | 93.64     | 克               | 61.35     |
| 几何            | 55.09     | 包裹             | 73.74     | 公斤              | 67.01     |
| 三十            | 32.72     | 钱包             | 71.66     | 盎司              | 77.23     |
| 四十            | 45.77     | 机器             | 44.97     | 公顷              | 67.21     |
| 五十            | 48.54     | 电话             | 50.60     | 克拉              | 64.31     |
| 六十            | 61.85     | 铅笔             | 86.10     | 品脱              | 75.08     |
| 七十            | 64.61     | 电池             | 60.91     | 美元              | 53.82     |
| 八十            | 62.54     | 风扇             | 61.99     | 日元              | 44.94     |
| 九十            | 63.79     | 窗户             | 78.49     | 法郎              | 57.06     |
| 角             | 82.56     | 信封             | 51.80     | 马克              | 57.09     |
| 千             | 65.97     | 地球             | 19.83     | 美分              | 43.33     |
| 均值            | 86.82     | 轮船             | 75.97     | 吨               | 95.78     |
| Grand Average | 61.87     | Grand Average  | 68.67     | Grand Average   | 66.86     |

\*\* frequency is in cumulative percentage from the combined character frequency list of classical and modern Chinese (Da, J., 2004).

## Appendix E: T-Test Results of Word Stimuli Ratio/Frequency Comparison

t-Test: Paired Two Sample for Means

|                                 | <i>English<br/>Neutral</i> | <i>English<br/>Negative</i> | <i>English Math</i> | <i>English<br/>Measure</i> |
|---------------------------------|----------------------------|-----------------------------|---------------------|----------------------------|
| Mean                            | 3.849086213                | 3.729514849                 | 3.896189144         | 3.761641067                |
| Variance                        | 2.816526895                | 2.808520014                 | 1.758935921         | 11.8670446                 |
| Observations                    | 30                         | 30                          | 30                  | 30                         |
| Pearson Correlation             | 0.159158367                |                             | 0.166978005         |                            |
| Hypothesized Mean<br>Difference | 0                          |                             | 0                   |                            |
| df                              | 29                         |                             | 29                  |                            |
| t Stat                          | 0.301139407                |                             | 0.211856327         |                            |
| P(T<=t) one-tail                | 0.382728433                |                             | 0.41685053          |                            |
| t Critical one-tail             | 1.699127097                |                             | 1.699127097         |                            |
| P(T<=t) two-tail                | 0.765456866                |                             | 0.833701059         |                            |
| t Critical two-tail             | 2.045230758                |                             | 2.045230758         |                            |

|                                 | <i>Chinese<br/>Neutral</i> | <i>Chinese<br/>Negative</i> | <i>Chinese Math</i> | <i>Chinese<br/>Measure</i> |
|---------------------------------|----------------------------|-----------------------------|---------------------|----------------------------|
| Mean                            | 78.69431257                | 82.75073599                 | 61.86703547         | 66.86433673                |
| Variance                        | 234.2678672                | 200.4541556                 | 303.6750952         | 399.727434                 |
| Observations                    | 30                         | 30                          | 30                  | 30                         |
| Pearson Correlation             | -0.190263657               |                             | -0.054233969        |                            |
| Hypothesized Mean<br>Difference | 0                          |                             | 0                   |                            |
| df                              | 29                         |                             | 29                  |                            |
| t Stat                          | -0.976971035               |                             | -1.005380276        |                            |
| P(T<=t) one-tail                | 0.16833172                 |                             | 0.161514694         |                            |
| t Critical one-tail             | 1.699127097                |                             | 1.699127097         |                            |
| P(T<=t) two-tail                | 0.33666344                 |                             | 0.323029388         |                            |
| t Critical two-tail             | 2.045230758                |                             | 2.045230758         |                            |

## Appendix F: Peak 2 Multiple Comparison Results

Significant mean Peak 2 amplitude differences between target and non-target stimuli and among non-target stimuli in conditions I-VI from Bonferroni multiple-comparison analysis at the .01 level

| Condition  | Oddball Type   | Sinuoth EKRiting |                  | Mean Peak 2 Amplitude Difference |            | Standard Error | P-value | Language EKRiting |            | Emotional Valence EKRiting |            | Category EKRiting |             |
|------------|----------------|------------------|------------------|----------------------------------|------------|----------------|---------|-------------------|------------|----------------------------|------------|-------------------|-------------|
|            |                | High Peak 2      | Low Peak 2       | High Peak 2                      | Low Peak 2 |                |         | High Peak 2       | Low Peak 2 | High Peak 2                | Low Peak 2 |                   |             |
| I          | Target         | English Positive | English Neutral  | 2.52                             | *          | 0.34           | 0.000   | L2                | L3         | Positive                   | Neutral    | Neutral           | High Peak 2 |
|            |                | Chinese Neutral  | Chinese Negative | 2.54                             | *          | 0.34           | 0.000   | L1                | L1         | Neutral                    | Neutral    | Neutral           | Low Peak 2  |
|            |                | English Negative | Chinese Negative | 2.99                             | *          | 0.34           | 0.000   | L2                | L2         | Negative                   | Negative   | Negative          | Low Peak 2  |
|            | Non-Target     | Chinese Positive | Chinese Positive | 3.04                             | *          | 0.34           | 0.000   | L1                | L1         | Negative                   | Positive   | Positive          | High Peak 2 |
|            |                | Chinese Positive | Chinese Positive | 3.24                             | *          | 0.34           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | Chinese Positive | Chinese Positive | 3.24                             | *          | 0.34           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
| II         | Target         | Chinese Positive | Chinese Negative | 1.44                             | *          | 0.32           | 0.000   | L1                | L1         | Positive                   | Negative   | Negative          | High Peak 2 |
|            |                | Chinese Neutral  | Chinese Neutral  | 2.25                             | *          | 0.32           | 0.000   | L1                | L1         | Neutral                    | Neutral    | Neutral           | Low Peak 2  |
|            |                | English Neutral  | English Negative | 3.34                             | *          | 0.32           | 0.000   | L2                | L2         | Neutral                    | Negative   | Negative          | Low Peak 2  |
|            | Non-Target     | Chinese Positive | Chinese Positive | 3.64                             | *          | 0.32           | 0.000   | L2                | L2         | Negative                   | Positive   | Positive          | High Peak 2 |
|            |                | English Positive | English Neutral  | 3.74                             | *          | 0.32           | 0.000   | L2                | L2         | Positive                   | Neutral    | Neutral           | Low Peak 2  |
|            |                | English Positive | English Negative | 4.72                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Negative   | Negative          | Low Peak 2  |
| III        | Target         | Chinese Positive | Chinese Negative | 1.81                             | *          | 0.32           | 0.000   | L1                | L2         | Negative                   | Neutral    | Neutral           | High Peak 2 |
|            |                | Chinese Neutral  | Chinese Neutral  | 2.30                             | *          | 0.32           | 0.000   | L2                | L2         | Negative                   | Negative   | Negative          | Low Peak 2  |
|            |                | English Neutral  | English Positive | 2.30                             | *          | 0.32           | 0.000   | L2                | L2         | Negative                   | Positive   | Positive          | Low Peak 2  |
|            | Non-Target     | Chinese Neutral  | Chinese Neutral  | 1.38                             | *          | 0.32           | 0.000   | L1                | L2         | Positive                   | Negative   | Negative          | High Peak 2 |
|            |                | English Positive | English Positive | 1.49                             | *          | 0.32           | 0.000   | L2                | L2         | Negative                   | Positive   | Positive          | Low Peak 2  |
|            |                | English Positive | English Positive | 1.49                             | *          | 0.32           | 0.000   | L2                | L2         | Negative                   | Positive   | Positive          | Low Peak 2  |
| IV         | Target         | English Negative | English Positive | 1.63                             | *          | 0.28           | 0.000   | L2                | L2         | Negative                   | Positive   | Positive          | High Peak 2 |
|            |                | Chinese Neutral  | Chinese Neutral  | 2.18                             | *          | 0.28           | 0.000   | L1                | L1         | Neutral                    | Neutral    | Neutral           | Low Peak 2  |
|            |                | Chinese Negative | Chinese Negative | 2.21                             | *          | 0.28           | 0.000   | L1                | L1         | Negative                   | Negative   | Negative          | Low Peak 2  |
|            | Non-Target     | English Neutral  | English Positive | 2.45                             | *          | 0.28           | 0.000   | L2                | L2         | Neutral                    | Positive   | Positive          | High Peak 2 |
|            |                | Chinese Positive | Chinese Positive | 2.85                             | *          | 0.28           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | Chinese Positive | Chinese Positive | 1.21                             | *          | 0.28           | 0.000   | L2                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
| V          | Target         | Chinese Positive | Chinese Negative | 2.86                             | *          | 0.33           | 0.000   | L1                | L1         | Negative                   | Positive   | Positive          | High Peak 2 |
|            |                | Chinese Neutral  | Chinese Neutral  | 3.57                             | *          | 0.33           | 0.000   | L1                | L1         | Neutral                    | Neutral    | Neutral           | Low Peak 2  |
|            |                | English Neutral  | English Negative | 3.90                             | *          | 0.33           | 0.000   | L2                | L2         | Neutral                    | Negative   | Negative          | Low Peak 2  |
|            | Non-Target     | Chinese Positive | Chinese Positive | 4.72                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Positive   | Positive          | High Peak 2 |
|            |                | English Positive | English Positive | 1.87                             | *          | 0.33           | 0.000   | L1                | L2         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | English Positive | English Positive | 1.15                             | *          | 0.33           | 0.008   | L1                | L2         | Neutral                    | Positive   | Positive          | Low Peak 2  |
| VI         | Target         | Chinese Object   | Chinese Object   | 1.69                             | *          | 0.33           | 0.000   | L2                | L1         | Positive                   | Positive   | Positive          | High Peak 2 |
|            |                | English Math     | English Math     | 1.81                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | Chinese Measure  | Chinese Measure  | 1.84                             | *          | 0.33           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            | Non-Target     | Chinese Math     | Chinese Math     | 2.29                             | *          | 0.33           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | High Peak 2 |
|            |                | Chinese Math     | Chinese Math     | 1.32                             | *          | 0.33           | 0.001   | L2                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | Chinese Measure  | Chinese Measure  | 2.19                             | *          | 0.33           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | Low Peak 2  |
| VII        | Target         | Chinese Object   | Chinese Object   | 2.91                             | *          | 0.33           | 0.000   | L1                | L1         | Positive                   | Positive   | Positive          | High Peak 2 |
|            |                | English Math     | English Math     | 3.34                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | English Math     | English Math     | 3.72                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            | Non-Target     | Chinese Object   | Chinese Object   | 3.78                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Positive   | Positive          | High Peak 2 |
|            |                | English Measure  | English Measure  | 1.15                             | *          | 0.33           | 0.007   | L1                | L2         | Positive                   | Positive   | Positive          | Low Peak 2  |
|            |                | English Math     | English Math     | 1.53                             | *          | 0.33           | 0.000   | L2                | L2         | Positive                   | Positive   | Positive          | Low Peak 2  |
| Non-Target | Chinese Object | Chinese Object   | 1.59             | *                                | 0.33       | 0.000          | L2      | L2                | Positive   | Positive                   | Positive   | High Peak 2       |             |
|            | English Object | English Object   | 1.59             | *                                | 0.33       | 0.000          | L2      | L2                | Positive   | Positive                   | Positive   | Low Peak 2        |             |
|            | English Object | English Object   | 1.59             | *                                | 0.33       | 0.000          | L2      | L2                | Positive   | Positive                   | Positive   | Low Peak 2        |             |