Source Localization in Cross Modality Matching of

Brightness and Loudness in Young Adults

Tawnya Nadine Coates

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David L. McPherson, Chair
Richard Harris
Christopher Dromey

Department of Communication Disorders

Brigham Young University

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ABSTRACT

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Tawnya Nadine Coates
Department of Communication Disorders, BYU
Master of Science

Cross modality matching is a magnitude matching procedure, developed to study the relationships between sensory modalities. Auditory and visual sensory integration can be examined through cross modality matching of brightness and loudness. Brightness and loudness are natural correlates of one another as they both represent the parameter of intensity for their respective sensory modalities. Past studies have demonstrated that typical individuals tend to match brighter lights with louder sounds and dimmer lights with softer sounds. The current study utilized a modified cross modality matching procedure, combined with electroencephalography (EEG) data, to examine the cortical response to sensory integration. It was hypothesized that the response latency and cortical distribution of the EEG data would show differences between matched and unmatched conditions of light and sound stimuli. Light and sound stimuli were presented to 10 participants (five males and five females between the ages of 18 and 28 years) in a forced choice paradigm. The behavioral responses, reaction times, and EEG data were recorded for each patient. Results demonstrated that there were significant differences in behavioral reaction time among the stimulus conditions. However, reaction times were only significantly faster for the loudest sound paired with the brightest light. No other pairs of matched stimuli resulted in faster reaction times. Event related potentials (ERPs) were identified for matched and unmatched stimulus conditions. No differences were identified in latency of the ERPs among conditions. Additionally, source localization revealed that dipole locations for each stimulus condition remained relatively constant in the prefrontal cortex. As the prefrontal cortex has been found to be associated with decision-making and sensory integration, it can be concluded that sensory integration did occur. However, the processing of sensory information did not change for matched or unmatched conditions of light and sound.

Keywords: cross modality matching, sensory integration, brightness, loudness, brain mapping, event related potentials, source localization, electroencephalography

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DESCRIPTION OF THESIS STRUCTURE

This thesis is integrates current journal publication format and traditional thesis format. This includes current university requirements for submission and the requirements for research report submissions to peer reviewed journals in communication disorders. Appendix A contains an annotated bibliography. Appendix B contains an Informed Consent form, which was approved by the Brigham Young University Institutional Review Board. The Informed Consent form was read and signed by all participants.

Introduction

In his 1975 study, Lawrence E. Marks defined synesthesia as, "the translation of attributes of sensation from one sensory domain to another" (Marks, 1975, p. 303). In other words, when synesthesia occurs, one attribute of a sensation (e.g., sound, light, touch) evokes a psychophysical response of an unrelated attribute, which can be of an entirely different sensory modality. There are individuals who experience unique and curious forms of synesthesia, such as the philosopher Ludwig Wittgenstein to whom the vowel *e* was the color yellow (Ward, 2013). Over a century of research has proven that while synesthesia is peculiar, there are certain types of synesthesia which are commonplace and predictable among the normal population. Consider the relationship of the olfactory system to the gustatory system. Aromas are known to stimulate a psychophysical response from the olfactory system. However, the scent from a savory meal may also elicit a predictable psychophysical experience from the gustatory system, such as when an individual smelling a meal feels as if they have already tasted it.

Synesthesia and the integration of the senses have been heavily explored by researchers in the field of psychophysics. Aristotle (*ca*. 350 B.C.) was one of the first to touch on the subject as he pondered the notion of a *sensus communis*, or in other words, a common sense that unites the sensations of the human experience (as cited in Marks, 1978). Newton (1704) reflected on the subject as well. He deliberated over a possible relationship between the seven notes of the musical scale and the seven primary colors (as cited in Marks, 1974). Over the years, researchers have studied and identified relationships among many combinations of sensory stimuli (Karwoski & Odbert, 1938; Marks, 1974; Walk & Walker, 2012; Zigler, 1930). However, the relative lack of knowledge regarding the neural underpinnings of sensory integration leaves much to be desired. The purpose of this study was to examine the cortical response to sensory integration through the previously established relationship of brightness and loudness. This was done through the magnitude matching method of modified cross modality matching (CMM).

Cross Modality Matching of Sensory Function

In the 20th century, psychophysical researchers began capitalizing on matching procedures to identify patterns in human perception with regard to sensory integration. Cross modality matching is one type of matching procedure. It is a ratio scaling method which takes advantage of the unity among sensations of the human sensory system. In CMM, sensations of one sensory modality are directly matched with sensations arising from another (Underwood, 1966).

A mathematical explanation for the relationship between the matched sense modalities was developed by Gustav Fechner in 1860. As per Fechner's law, if the stimulus dimension (*S*) is plotted in log-units, then these would be paralleled by equal units of response to the sensation (*R*), or, the plot would give a straight line (Pepermans & Corlett, 1983):

$$R = k \log S \tag{1}$$

Stevens (1957, 1960) adapted Fechner's law to be applicable to quantitative sense continua (e.g., brightness and loudness) after determining that the original version of the law was only applicable to qualitative sense continua. The model proposed by Stevens is a power model in which sensation (response) is equal to the stimulus magnitude raised to the *n*-th power (Stevens 1961, 1964):

$$R = k\,(S - S_o)^n \tag{2}$$

Identical to Fechner's model, Steven's employed R as the response and S as the stimulus. However, Stevens also included S_o, which is the best approximation to the absolute threshold for the stimulus modality, and n, which depends on attributes of the sense modalities (e.g., the range of the stimuli, the position of the standard in the range; Pepermans & Corlett, 1983).

With Stevens' power model in mind, Root and Ross (1965) reported that if sensation values are equated at various intensity levels for two prothetic stimuli, the slope of the function generated by the cross modality comparison on a log-log plot will be defined as the ratio of the two exponents. The following relation should be found for the two R values at the various intensity levels:

$$\log R_1 = n \log R_2 / m \quad (3)$$

Using Stevens' (1955) exponent ratios given as .30 for the loudness-function and .33 for the brightness function, Root and Ross (1965) predicted the slope to approximate .909. This is the slope of the line for the exponents of the subjective-magnitude functions for brightness and loudness. The slope for the line of the cross modality matching function was found to be .908, which is extremely close to the predicted value. The near match of the slope for the cross modality matching function and the equal-sensation function validates the cross modality matching procedure.

Auditory and Visual Sensory Integration

Brightness and loudness. A pattern of association between the brightness of a light and the loudness of a sound has been reported by several different psychophysical researchers (Marks, 1974; McPherson, 1975; Stevens, 1965). Past studies demonstrate that it is common for a typical population of individuals to associate a brighter light with a louder sound and a dimmer light with a softer sound. Brightness and loudness are two sensory parameters that represent the intensity attribute of their respective sensory systems. Intensity is the degree of strength or force of a stimulus. All sensory systems can vary in intensity. For example, auditory sensations can be low intensity (a soft whisper) or high intensity (a loud drum). Visual sensations can likewise vary, with low intensity dim moonlight compared to high intensity bright sunlight. All other sensory stimuli can vary in level of intensity as well. The universality of intensity makes it an ideal variable for studies exploring the relationships between particular sensory systems (Marks 1978). Marks referred to brightness and loudness stimuli as natural correlates of one another as they both represent the dimension of intensity in their corresponding sensory system (Marks, 1974). Thus, intensity is a convenient parameter for examining the psychophysical relationship of two distinct sensory stimuli.

Additionally, loudness and brightness are both prothetic in nature. Prothetic stimuli are defined by Stevens as, "continua having to do with *how much*," (1957, p. 2). Thus, the discrimination of their levels involves an additive process and the physical continuum associated with them is based upon intensity of the stimulus (Root & Ross, 1965). The current study took advantage of the outlined similarities between brightness and loudness and their previously established relationship.

Behavioral response. The behavioral response to the integration of brightness and loudness has been studied at length. Psychophysical researchers of the late 1960s and early 1970s employed the cross modality matching procedure to observe behavioral response patterns for sensory integration of these two stimuli (McPherson, 1975; Root & Ross, 1965; Stevens & Marks, 1965). In recent years, psychophysical research has adapted the cross modality matching procedure to study integration of atypical stimuli in unique ways rather than a basic matching procedure (Beauchamp, Lee, Argall, & Martin, 2004; Crisinel & Spence, 2011; Walker & Walker, 2012). The object of the present study was to explore the cortical response to the integration of brightness and loudness. For that reason, a straightforward brightness and loudness matching procedure was employed. This task was similar to those utilized prior to the 21st century. In this task, the participants were asked to determine if the brightness of a light and the loudness of a sound matched. This direct task minimized any additional variables, which may have influenced the cortical response.

Basic cross modality matching studies of brightness and loudness reveal that individuals tend to associate brighter lights with louder sounds and dimmer lights with softer sounds (Marks, 1987; McPherson, 1975; Stevens & Marks, 1965). Thus, the intensities of the two sensory modalities are positively correlated. Stevens and Marks (1965) worked together to quantify the relationship between brightness and loudness. They questioned whether an equal-sensation function, whose exponent is the ratio of the exponents previously determined (0.3 for loudness and 0.33 for brightness; Stevens, 1955), would be produced by brightness and loudness during a cross modality matching procedure. This was tested against S. S. Stevens' proposed psychophysical power law, which states that the subjective magnitude grows as a power function of the stimulus magnitude (Stevens, 1957).

Stevens and Marks' cross modality matching study demonstrated that, "…the power law relating subjective magnitude to physical intensity can be corroborated by nonnumeric assessments of subjective magnitude, and that brightness and loudness are similar functions of stimulus energy" (1965, p. 410). Therefore, the cross modality matching procedure was successful in supporting Stevens' power law in relating the subjective magnitude of light and sound (i.e., brightness and loudness) to the physical intensity of the light and sound. These results were supported by McPherson's 1975 cross modality matching study of brightness and loudness. McPherson concluded that his findings support the power law. The power law expresses the relationship between physical and psychological intensity. According to

McPherson, “loudness and brightness are clearly related to each other by a power function” (1975, p. 71).

Neurophysiological response. Despite all that is known regarding behavioral patterns of auditory and visual sensory matching, current research on the neurophysiology of sensory integration leaves much to be desired. Marks (1974) commented on the potential for further research and knowledge regarding cortical reaction to sensory integration. According to Marks, “The system that mediates these cross modal equivalences is unknown but may best be thought of as a cognitive mechanism that is capable of manipulating dimensions of sensory experience” (p. 173).

Although recent sensory integration studies have incorporated a brain imaging component, the cortical location in which cross modality matching tasks are represented remains in question (Spence, 2011). The posterior superior central sulcus (pSTS) and middle temporal gyrus (MTG) have been suggested as points of integration for simultaneous auditory and visual stimuli (Beauchamp, Lee, Argall, & Martin, 2004). When congruent pairings of auditory and visual components of objects or animals were displayed simultaneously, the pSTS/MTG gave a stronger response than when incongruent pairings were displayed (Beauchamp et. al., 2004). The cortical response patterns of this task are significant because this type of stimuli correlate well with authentic sensory integration tasks that the human brain performs daily. However, the findings from this study do not answer the question of how the brain would respond to a cross modality matching task in which the intensity of brightness and loudness are equated. Spence (2011) made this point as well, pondering whether the same neural underpinnings would be seen by cross modality matching of more basic stimulus features. A study by Fuster, Bodner, and Kroger (2000) identified cortical regions of activity in primates during a basic cross modality matching task of auditory and visual stimuli. This study by Fuster et al. revealed that the prefrontal cortex was a primary region activated during the cross modal task. It has yet to be seen whether these findings translate to the human brain.

Electrophysiological Measures

Electroencephalography. Electroencephalography (EEG) is an electrophysiological technique that has allowed for increased understanding of brain function. Through EEG, researchers are able to identify when a cortical response to an exogenous stimulus occurs. This method of brain imaging provides detailed information regarding the temporal dynamic of the human brain's neuronal circuits (Michel et al., 2004). Through EEG, electrical activity of neurons is measured on the sub-millisecond level (Michel et al., 2004). The present study utilized comprehensive temporal data, from EEG, to compare the latency of the brain's response for each paired level of brightness and loudness. The use of EEG has also made it possible for researchers to measure brain activity and localize active neuronal populations for specific cortical regions (Cook, O'Hara, Uijtdhaage, Mandelkem, & Leuchter, 1998; Gevins, 2002). While EEG is not primarily employed for localization of brain activity, source reconstruction techniques make it possible to use EEG data to analyze the location of cortical responses. Electroencephalography was used in the present to study to examine the brain's response to the simultaneous presentation of stimuli to different sensory channels.

Quantitative electroencephalography. Quantitative EEG (QEEG) is an analytical technique applied to the mathematical and statistical analysis of brainwave activities. It provides researchers with the analytical ability to view and describe dynamic changes in brainwave activity arising from exogenous stimuli. Results from QEEG lead to an estimate of cortical activities engaged in sensory and other types of brain processing. Comparison of brainwave activity across individuals and established databases is possible through QEEG (Bagic & Sata, 2007). It primarily involves measurements of power (the extent and amount of brainwave activity), spectrum (the frequency bands of the brainwave activity), asymmetry (the distribution of the power spectrum of brainwave activity), coherence (what areas of the brain are talking to each other), and phase (the temporal aspect of brainwave activity). Furthermore, when isopotential contours are created from these types of analyses, a map of brainwave activity across the scalp is seen (Congedo, John, De Ridder, Prichep, & Isenhart, 2010; Mathewson et al., 2012). In the current study, QEEG was used to identify levels of brain activity used to match sensory stimuli of differing modalities. It was also used to map that activity to determine coherence and phase.

Event related potential. The event related potential (ERP) is a measure of brain electrical activity, and is a record of a brain's response to a stimulus. It has been defined as a set of potential changes that are functionally related to an experimental variable (Luck, 2014). Averaging of EEG data is necessary in order to identify ERPs. This is because much of the electrical activity recorded from the scalp during EEG is irrelevant to the stimulus (Empson, 1986). Consequently, the ERP waveforms are isolated from the background EEG by signal averaging (Luck, 2014). Research through EEG has demonstrated that ERPs are an effective way to study cerebral auditory processing of non-speech and speech stimuli alike (Cook et al., 1998). The ERP latencies were analyzed in the present study to determine if there were patterns or changes among stimulus conditions.

Source localization. While EEG is known for its temporal detail, data collected through EEG is not limited to analysis of ERP latency. According to Michel et al., "most EEG applications fail to capitalize on all of the data's available information, particularly that concerning the location of active sources of the brain" (2004, p. 2195). Source reconstruction can be used to locate cortical sites of electrical activity, known as dipoles. This is possible depending on the number and positioning of the electrodes. Precision of dipole localization drastically increases when 63 electrodes are used compared to 31 (Michel et al., 2004). Precision also increases with improved accuracy of electrode position on the scalp. This is achieved by measuring exact 3D electrode positions with a digitizer. Error in electrode placement is further avoided by use of an electrode cap, which conserves electrode spacing and positions. Source reconstruction of ERP components was utilized in the present study to localize dipoles for each stimulus condition. This allowed for comparison of conditions, adding to current knowledge about the location of sensory integration in the human brain.

The purpose of the present study was to identify the type and location of cortical responses to sensory integration of light intensity (brightness) and sound intensity (loudness). This was accomplished by recording EEG data during a cross modality matching task in which participants identified whether the intensity of a visual stimulus matched the intensity of an auditory stimulus. Response latency and cortical distribution of the response was analyzed for both matched and unmatched conditions. It was hypothesized that QEEG analysis would show differences between the matched and the unmatched conditions.

Method

Participants

Ten individuals (5 males and 5 females) between the ages of 18 and 28 years of age participated in this study. The participants had no history of cognitive, learning, or neurological impairment. All participants had normal hearing. Hearing screening included otoscopy, tympanometry, and pure tone testing. Hearing screening met the specifications set forth by the

American Speech-Language-Hearing Association (1990). This included bilateral clear and healthy tympanic membranes. It also included bilateral type A tympanograms with static acoustic admittance measures between 0.3 and 1.4 mmhos, and peak pressure between -100 and +50 daPa. Normal pure tone thresholds were defined as ≤ 15 dB HL for octave intervals between 250-4000 Hz, and ≤ 30 dB HL for 8000 Hz, with threshold differences not greater than ≤ 5 dB HL between ears (American Speech-Language-Hearing Association, 1990). Instrumentation used for the hearing screening included a Welch Allyn otoscope for otoscopy, a desktop-mounted Grason-Stadler model GSI-33 impedance meter for tympanometry, and a Grason-Stadler model GSI-1761 audiometer with Etymotic ERA3 earphones for the auditory testing. Pure tone testing was conducted in a double-walled, sound-treated test booth. Noise levels were within the limits specified by ANSI S3.1-1999 R2008 Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms (American National Standards Institute, 2008). All participants had visual acuity better than or equal to 20/40 corrected in either eye. Vision was measured using a Snellen® visual acuity chart. Participants correctly identified all five letters on the fifth line of the chart while standing 20 feet away from the chart at eye level. Each eye was tested independently.

The use of human subjects was approved by the Institutional Review Board (IRB) at Brigham Young University on June 6, 2014. Each participant read and signed an informed consent document approved by the IRB before participating in the study.

Instrumentation

Stimuli preparation. Visual stimuli, consisting of a gray scale of nine degrees of luminance, were created. The brightest visual stimulus on the scale was white, the darkest was black, with seven incremental degrees of gray in between. These nine luminance levels were presented one at a time to five individuals (three females and two males). Each visual stimulus was paired with nine selections of auditory stimuli, all of which consisted of white noise. The only difference between each auditory stimulus was the intensity level. The participants were asked to look at each visual stimulus, listen to the nine auditory stimuli, and then select the auditory stimulus that was as loud as the image was bright. Data from this preliminary procedure were analyzed and used to select the degrees of luminance and levels of intensity utilized in the present study.

Visual stimuli. The visual stimuli were measured using candela per square meter ($cd/m^{2)}$, as defined by the International System of Units (National Institute of Standards and Technology & U.S. Department of Commerce, 2008). The visual stimuli consisted of four degrees of luminance: (a) 240 cd/m^2, labeled V1; (b) 119 cd/m^2, labeled V2; (c) 60 cd/m^2, labeled V3; and (d) 15 cd/m^2, labeled V4. The visual stimuli were presented on an 18 inch flat screen digital monitor placed 1 m from the participant at 0° visual angle. The participant was tested using binocular vision. The visual stimulus on time was 1200 ms.

Auditory stimuli. The auditory stimuli consisted of white noise, with four intensity levels: (a) 93 dB SPL, labeled A1; (b) 90 dB SPL, labeled A2; (c) 84 dB SPL, labeled A3; and (d) 78 dB SPL, labeled A4. The auditory stimuli rise/decay time was 25 ms. The on time was 500 ms, thus the total duration for each auditory stimulus was 1200 ms. Etymotic EA-3 insert phones were used to present the auditory stimuli binaurally. The auditory stimuli were calibrated in accordance with ANSI 2004 standards prior to the beginning of data collection and at the end of data collection for each participant.

The visual and auditory stimuli were presented simultaneously. The length of time the stimuli were presented matched the published norms for visual and auditory integration of brightness and loudness such that further continuance of the stimuli did not change the perceptual values of either modalities. Sensory integration for auditory and visual stimuli is known to occur by about 1200 ms (Brockmole & Irwin, 2005; Picton, 2011).

EEG data acquisition and instrumentation. The participants were fitted with an electrode cap (ElectroCap International, Inc., 2003) having 64 silver-silver chloride electrodes resting against the scalp and distributed according to the 10-20 International System (Jurcak, Tsuzuki, & Dan, 2007). In addition to the scalp electrodes, six hanging electrodes were placed: the right and left mastoid process, the outer canthi of each eye, and above and below the supraorbital foramen of the left eye. These additional six electrodes were used to monitor activity and movement of the eye and facial muscles. Electrode impedances of the cap did not exceed 3000 ohms.

Compumedics software (2008) was used for EEG data collection and initial analysis (NeuroScan 4.5). NeuroScan Stim 2 software was used for stimulus presentation. In addition, CURRY 6 (Compumedics Neuroscan, 2008) software was used for cortical localization of the EEG responses, post-hoc.

Procedure

Participant response. The participants were given a response pad and asked to press one of two buttons. They were asked to press button number one if the brightness of the light and the loudness of the sound did not match and button number two if the brightness of the light and the loudness of the sound matched. Prior to the presentation of the stimuli, the participants were read the following instructions:

> During the data collection the door to the sound booth will be closed and the lights will be off. You will see a light on this computer. Sometimes it will be bright white, dark

> gray, or something in between. When you see the light, you will hear a sound. I want you to decide whether or not the brightness of the light matches the loudness of the sound. If they do not match press the button next to the number one on this pad. If they match, press the button next to the number two. The presentation will not continue until a button is pushed. Following the light and sound, the screen will be black and silent until you input a response. Another light and sound combination will come as soon as you enter your response, so if that does not occur press your response button again. Many repetitions will be presented to you, so move along and use your initial instinct to determine if the loudness and brightness match.

The participants were then presented with a training series in which they responded once to each stimulus condition. This was done in order to provide the participants with a framework of the maximum and minimum intensities of brightness and loudness that they could expect to encounter. The training series was also beneficial as it allowed the participants to become accustomed to the response method.

Stimulus presentation matrix. Following the training series, the instructions were repeated and the participants began the stimulus presentation matrix. During the stimulus presentation matrix, reaction time (RT), hits, misses, and response were recorded using NeuroStim software. Additionally, EEG data were recorded via NeuroScan 4.5 Compumedics software (2008). The participants were able to take a break at any time during the presentation of the stimulus presentation matrix. They were told when they had responded to half of the trials in the stimulus presentation matrix.

The stimulus presentation matrix consisted of all stimulus conditions, which would be presented to the participant. The stimulus conditions were presented in a series in which the 16 conditions were repeated 100 times (this was necessary for obtaining an evoked potential). The order of the conditions within each series was randomized, and a separate randomization was presented to each participant. The series consisted of the conditions listed in Table 1.

Table 1

Stimulus Presentation Matrix

Type	Auditory-Visual Combination
1	A1-V1
2	A1-V2
3	A1-V3
4	A1-V4
5	A2-V1
6	A2-V2
7	A2-V3
8	A2-V4
9	A3-V1
10	A3-V2
11	A3-V3
12	A3-V4
13	A4-V1
14	A4-V2
15	A4-V3
16	A4-V4

Note. A = auditory stimulus, V = visual stimulus, 1 = the highest intensity, 4 = the lowest intensity.

Data Analysis

Behavioral data. Four behavioral measures were recorded during the presentation of the stimulus matrix: hits, misses, RT, and response. Two independent variables were analyzed: stimulus condition and response. The single dependent variable analyzed with regard to the behavioral data was RT. An ANOVA for repeated measures was performed to determine if differences in RT among stimulus conditions were significant. In addition, tests of within subjects contrasts were used to determine which stimulus conditions had statistically significant differences in RT. The mean RT for each stimulus condition for each participant was calculated. It was then measured against the ERP latency to determine if there were differences between the behavioral and neural response latencies. An ANOVA was also performed to determine if perception of matched or unmatched conditions (as identified via the response) resulted in statistically significant differences in RT. Descriptive statistics were used to display the results of the behavioral data.

EEG data. The Curry 7 software was used to remove artifacts such as eye and jaw movement prior to averaging the raw EEG data (Compumedics Neuroscan, 2008). Averages of the EEG data were then calculated for each participant, resulting in ERP data displays for each stimulus combination. All ERP data files were averaged together for each stimulus condition, resulting in a total of 16 ERP grand averages. The latency (ms) of the ERP of the grand averages was measured against condition type in an ANOVA for repeated measures to determine if there were significant differences in processing time for any of the conditions.

Dipoles were localized through source reconstruction of the individual ERP averages and for the grand averaged ERP files using CURRY 7 software (Compumedics Neuroscan, 2008). Dipole locations and ERP latencies (ms) were analyzed as dependent variables, with stimulus condition acting as the independent variable. Locations of each dipole were compared for each stimulus condition using the grand average ERP files.

Results

Latencies

Latency was analyzed as a dependent variable for both the behavioral (RT) and EEG data (ERP latency). The RT data were examined to determine whether or not there were significant differences in the RT of the participants based on the stimulus condition. Descriptive statistics were computed for the RT of each stimulus condition (Table 2).

An ANOVA for repeated measures revealed a significant within subjects effect of the stimulus condition on RT, $F(15, 135) = 3.040$, $p < .001$. Tests of within subjects contrasts for RT was significantly different among 10 conditions. Six of the 10 significant differences occurred between condition one and other conditions. The condition combinations with statistically significant differences in RT are recorded in Table 3. Stimulus condition one (A1-V1) had the quickest mean RT, at 1531.30 ms. Three other stimulus conditions had mean RTs under 1600 ms; these were conditions two (A1-V2), nine (A3-V1), and 13 (A4-V1). Stimulus condition 10 (A3-V2) had the slowest mean RT, at 1731.13 ms. Stimulus conditions 11 (A3-V3) and 12 (A3-V4) were also accompanied by RTs slower than 1700 ms. All other stimulus conditions had mean RTs between 1600 and 1700 ms. Comparison of Table 2 and Table 3 provides detailed information regarding which stimulus combinations resulted in faster or slower RTs.

Table 2

Descriptive Statistics for Behavioral Reaction Time, in ms, for the 16 Conditions

Condition	*M*	*SD*	Minimum	Maximum
1 (A1-V1)	1531.3	379.3	705	7596
2 (A1-V2)	1584.2	612.4	640	12030
3 (A1-V3)	1606.5	484.5	702	8806
4 (A1-V4)	1627.1	741.8	795	16539
5 (A2-V1)	1612.4	466.0	211	7026
6 (A2-V2)	1648.3	543.7	672	7030
7 (A2-V3)	1674.2	598.8	880	9461
8 (A2-V4)	1682.4	604.3	103	7630
9 (A3-V1)	1570.4	471.7	593	7761
10 (A3-V2)	1731.1	2420.2	541	77450
11 (A3-V3)	1714.7	686.6	148	11024
12 (A3-V4)	1703.8	952.7	662	22366
13 (A4-V1)	1581.5	443.7	119	6115
14 (A4-V2)	1613.2	629.5	668	11323
15 (A4-V3)	1694.6	673.6	850	9977
16 (A4-V4)	1657.4	712.8	588	9111
Total	1639.1	872.0	103	77450

Note. A = auditory stimulus, V = visual stimulus, 1 = the highest intensity, 4 = the lowest intensity.

Table 3

Tests of Within Subjects Contrasts for Conditions with Statistically Significant (p-values less than or equal to cell value) Reaction Time Differences

Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1 (A1-V1)							0.020	0.013		0.001	0.001	0.001			0.005	
2 (A1-V2)										0.015						
3 (A1-V3)																
4 (A1-V4)																
5 (A2-V1)																
6 (A2-V2)																
7 (A2-V3)																
8 (A2-V4)																
9 (A3-V1)										0.006	0.042					
10 (A3-V2)																
11 (A3-V3)																
12 (A3-V4)																
13 (A4-V1)										0.010						
14 (A4-V2)																
15 (A4-V3)																
16 (A4-V4)																

Note. Condition values defined on the y-axis are equal to conditions listed on the x-axis. A = auditory stimulus, V = visual stimulus, 1 = the highest intensity, 4 = the lowest intensity.

A second ANOVA was performed using RT. This second ANOVA measured response type against RT. This was done to determine if the subjects used more cognitive processing time for conditions they perceived as matched or unmatched. This analysis failed to show any significant differences in RT between the perceived matched vs. unmatched conditions, $F(1, 15367) = 2.452$, $p < .117$. Descriptive statistics are outlined in Table 4.

Table 4

Descriptive Statistics for Reaction Time, in ms, for Response Type

Response	*M*	*SD*	Minimum	Maximum
1.0[a]	1625.7	566.6	103	12248
2.0[b]	1640.7	624.6	119	16539
Total	1632.7	594.5	103	16539

[a]1.0 = unmatched. [b]2.0 = matched.

The EEG data were analyzed by employing ERP latency as a dependent variable. A long latency ERP was identified between 1249 and 1584 ms for each stimulus condition in the grand averaged EEG files. The ERP latency was measured against the stimulus condition in an ANOVA for repeated measures. This was done to determine if there were statistical differences in the latency of the ERP for different stimulus conditions. The ANOVA revealed no significant difference in ERP latency between conditions, $F(15, 135) = 1.267$, $p < .231$.

Source Localization

Source reconstruction of the grand averaged EEG files was used to identify sLORETA dipole locations for the long latency ERP for each of the stimulus conditions. The primary and secondary dipole locations for each stimulus condition are recorded in Table 5. The dipole location for each stimulus condition is also displayed graphically (Figures 1 and 2). These figures were also created through source reconstruction of the ERPs. Figure 1 is an axial view of the brain map for each of the 16 stimulus conditions. Figure 2 depicts the scalp distribution of the electrical brain activity across the scalp for the same averaged files. A green dot on each image in Figure 1 indicates the approximate location of the sLORETA dipole. A black dot on each image in Figure 2 indicates the approximate location of the sLORETA dipole. The direction of each dipole can be discerned by examining the direction of the rod attached to each spherical green or black mark.

The brain maps and scalp distributions display activity primarily in the frontal lobe, split between the left and right hemispheres. Further analysis reveals that dipoles in five of the 16 conditions are located in the superior frontal gyrus. Dipoles in 10 of the 16 conditions are located in the medial frontal gyrus. Brodmann's area 11 was a secondary location for 14 of the 16 conditions. Stimulus condition four was the only condition in which the dipole was not located primarily in the superior or medial frontal gyrus, paired with Brodmann's area 10 or 11. The location of the dipole for stimulus condition four was the inferior semi-lunar lobule, with secondary locations in the uvula, declive, and pyrmis. The latency of the ERP for this stimulus condition was 1249 ms. This was 282 ms earlier than the ERP latencies for the remainder of the stimulus conditions.

Discussion

The purpose of the current study was to determine whether or not there are differences in the cortical response to matched or unmatched conditions of brightness and loudness. It has previously been established that integration between two sensory modalities is performed on a regular basis by the human brain (Beauchamp et al., 2004; Spence, 2011). Likewise, it has been shown that general patterns exist in the way individuals match the brightness of a light to the loudness of a sound in a cross modality matching procedure (Marks, 1974; McPherson, 1975; Stevens & Marks, 1965). This study examined the underlying neural activity accompanying the sensory integration task of cross modality matching of brightness and loudness.

Table 5

Dipole Locations for All Conditions

Condition	Latency (ms)	Primary Dipole Source	Secondary Dipole Source	Hemisphere
1 (A1-V1)	1546	Superior Frontal Gyrus	NA	Left
2 (A1-V2)	1531	Medial Frontal Gyrus	NA	Left
3 (A1-V3)	1584	Medial Frontal Gyrus	Brodmann 10	Left
4 (A1-V4)	1249	Inf. Semi-Lunar Lobule	Uvula, Declive, Pyrmis	Left
5 (A2-V1)	1547	Medial Frontal Gyrus	Brodmann 11	Right
6 (A2-V2)	1541	Superior Frontal Gyrus	Brodmann 11	Left
7 (A2-V3)	1557	Superior Frontal Gyrus	Brodmann 11	Left
8 (A2-V4)	1568	Medial Frontal Gyrus	Brodmann 11	Left
9 (A3-V1)	1557	Medial Frontal Gyrus	Brodmann 11	Right
10 (A3-V2)	1541	Medial Frontal Gyrus	Brodmann 11	Right
11 (A3-V3)	1536	Superior Frontal Gyrus	Brodmann 11	Left
12 (A3-V4)	1577	Superior Frontal Gyrus	Brodmann 11	Right
13 (A4-V1)	1547	Medial Frontal Gyrus	Brodmann 11	Right
14 (A4-V2)	1552	Medial Frontal Gyrus	Brodmann 11	Right
15 (A4-V3)	1541	Medial Frontal Gyrus	Brodmann 11	Left
16 (A4-V4)	1564	Medial Frontal Gyrus	Brodmann 11	Right

Note. A = auditory stimulus, V = visual stimulus, 1 = the highest intensity, 4 = the lowest intensity.

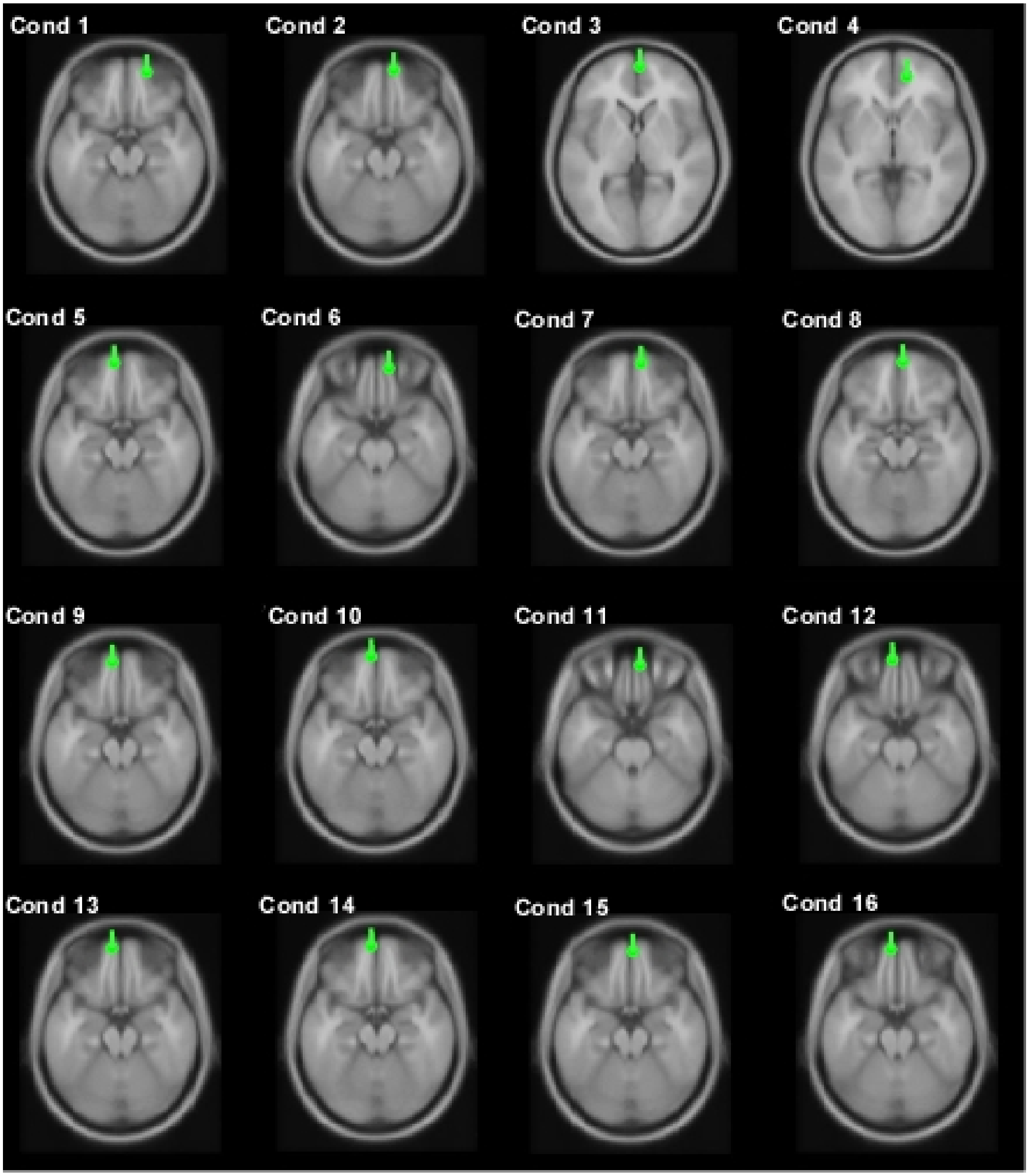

Figure 1. Axial spatial view of the grand averaged brain maps of the dipole source locations for the 16 conditions. The green dots identify the approximate location of the dipole.

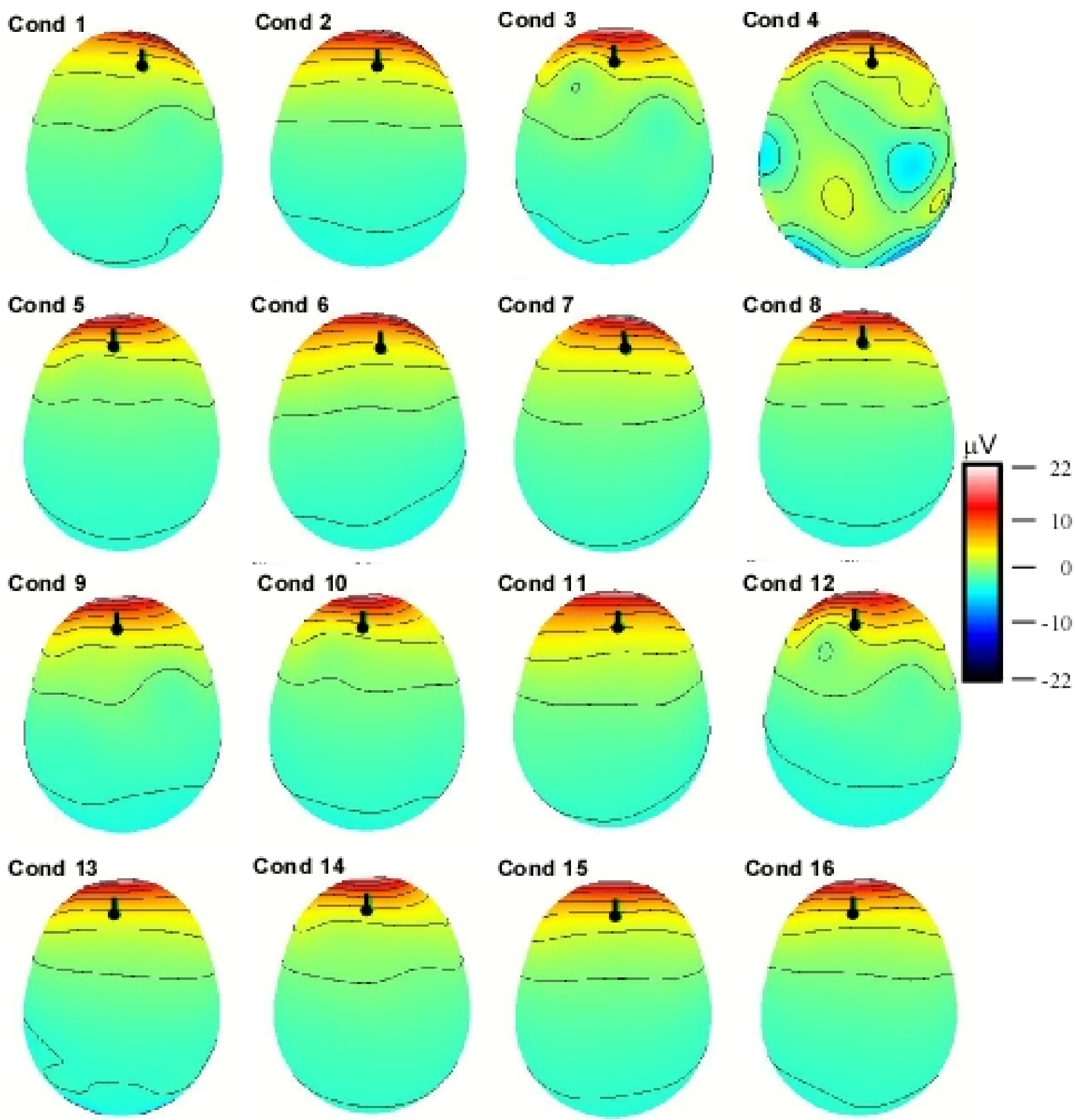

Figure 2. Axial view of the grand averaged brain maps of the dipole source locations for the 16 conditions. The black dots identify the approximate location of the dipole.

Summary and Evaluation of Results

Reaction time. The time it took from the completion of the stimulus presentation to the determination of whether the condition was matched or unmatched was analyzed as the RT. Statistical analysis of the behavioral data revealed significant differences in RT among several stimulus conditions. Stimulus condition one had the quickest mean RT (1531.30 ms), and was statistically faster than six other conditions. Condition one was comprised of the brightest light, V1, and the loudest sound, A1, in the series. These data demonstrate that individuals in the study were able to process this matched condition and respond to it more quickly than to many other stimulus conditions. However, there is no clear distinction indicating that all matched conditions were easier to process than all unmatched conditions. This is illustrated further by examination of the three other stimulus conditions which resulted in mean RTs faster than 1600 ms. These conditions are two (A1-V2), nine (A3-V1), and 13 (A4-V1). By analyzing these four conditions as the conditions with the quickest processing speed, it becomes apparent that it was not matched vs. unmatched which had the biggest effect on RT. One interpretation of these results could be that the participants were able to react more quickly to extreme conditions. That is, they were able to respond quickly to the loudest sound and brightest light and also to the loudest sound and dimmest light. It is likely that the participants became accustomed to which sounds were the loudest or softest and which images were the brightest or darkest. When A3-V1 or A4-V1 was presented, it took minimal cognitive processing to determine that they did not match because they were composed of a very loud sound with a very dim light. When A1-V1 or A1-V2 was presented, it also took minimal cognitive processing to identify the images and sounds as likely matching because they both contained the loudest sound paired with the brightest (or what looked like the brightest) light.

The mid-range combinations of sounds and lights were likely more difficult to discriminate one from another. This is corroborated by the RTs of the three other matched conditions (condition six [A2-V2], 11 [A3-V3], and 16 [A4-V4]). These conditions all resulted in mean RTs slower than 1600 ms. Furthermore, the matched condition 11 (1714.73 ms, A3-V3) is one of the six conditions which was significantly slower in RT than stimulus condition one (A1-V1). It was hypothesized that the matched conditions would result in decreased processing time compared to the unmatched conditions. The opposite occurred for condition 11. Analysis of the components of condition 11 compared to the other conditions reveals that there was slower processing speed in general associated with its sound component, A3. Three of the four stimulus conditions containing A3 resulted in mean RTs slower than 1700 ms. All but A3-V1 (condition nine) proved to require longer processing time than the other stimulus conditions. Stimulus condition 10 had the slowest mean RT (1731.13 ms), and was statistically slower than four other conditions. This suggests that condition 10 was the most challenging for the participants to make a decision. Condition 10 was comprised of the third loudest sound paired with the second loudest light (A3-V2). These data support the conclusion that there was increased difficulty in discriminating the lights and sounds that were mid-range in intensity, rather than the loudest or softest and brightest or darkest.

An additional analysis was performed to determine if the participant's perception of a condition as matched or unmatched had a significant effect on the RT. Thus, the response type was measured against RT in an ANOVA. Statistical analysis failed to show significant differences in RT based on response type. However, this does not fully dismiss the chance of changes in neurologic processing between matched and unmatched conditions. While the RTs and ERP latencies were essentially the same across all response types, the dipole source varied slightly.

Event related potential latency. Latencies for the ERPs of the grand averages were analyzed to obtain information about the cortical processing of the stimulus conditions. Statistical analysis revealed that there were no significant differences among the ERP latencies for the various stimulus conditions. This leads to the conclusion that processing difficulty is equal for all cross modality matching decisions, both matched and unmatched conditions. If confusion had occurred, this would most likely be represented by differences in both neural latencies and behavioral RTs. Latencies of the ERPs were relatively similar to the behavioral RTs. All ERP latencies were within 1500-1580 ms. The similar latencies of the ERPs and behavioral RTs provides evidence that the behavioral response occurred within the same time frame as the neural processing time.

Source localization. Dipole source localization was utilized to gain information about the cortical processing of the stimulus conditions. The superior frontal gyrus (SFG) and medial frontal gyrus (MFG) were the main dipole locations identified through source localization of the EEG data (Figures 1 and 2). Additionally, Brodmann's area 11 was a recurring secondary location. It was identified as a secondary location for 12 of the 16 stimulus conditions. Brodmann's area 10 was identified as a secondary condition for one of the 16 stimulus conditions. Brodmann's areas 10 and 11 are located in the oribitofrontal cortex (OFC). The SFG, MFG, and OFC are all part of the prefrontal cortex of the frontal lobe. Dipoles centered in these regions for all stimulus conditions, regardless of matched or unmatched auditory and visual stimuli.

The prefrontal cortex is known to be associated with decision making, reasoning, attention, and working memory (Boisgueheneuc et al., 2006; Fuster, 2008; Li et al., 2013; Volz, Schubotz, & Von Cramon, 2006). It has been documented that the prefrontal cells of primates integrate sensory stimuli of different modalities across time (Fuster et al., 2000). The dipole locations of the present sensory integration task would suggest that the same occurs in the human brain. While no significant changes were identified among the locations of matched or unmatched stimuli in the current study, it is noteworthy that the dipole location held constant in the exact location that Fuster et al. identified as an integrative network that represents behaviorally meaningful cross modal associations. It can be concluded that the prefrontal cortex functions as an area of sensory integration for humans and primates alike.

Limitations and Recommendations for Future Research

The current study expanded on previous studies relative to sensory integration of brightness and loudness through cross modality matching by providing spatial-temporal neural processing data in addition to behavioral data (Beauchamp et al., 2004; Marks, 1987; McPherson, 1975). The spatial-temporal findings in the current study provide additional theoretical information about the simultaneous processing of light and sound during a cross modality matching task. However, this study has limitations that call for further investigation.

First, the present study did not permit the participants to manually adjust the light or sound to match one another. According to Stevens (1971), cross modality matching is an appropriate design to use when the stimulus for a continuum can be readily varied by means of an accessible control. Unfortunately, this response method was not practical for the present study. In order to identify an ERP using EEG data, many trials must be repeated of the same stimulus. In the present study, each stimulus condition was presented to the participants 100 times. This resulted in a participant response for 1600 trials each. By using a forced choice method of response, the participants were able to respond to all the trails in a reasonable amount of time. Allowing the participants to manually adjust the brightness or loudness to match the other would have taken too long for the scope of the present study. Therefore, the yes/no button push response method was employed rather than a manual adjustment method.

If a future investigation does employ a manual adjustment response method, it is recommended that the study implement a balanced design in which each stimulus serves as both the standard stimulus and the variable. For example, the light is adjusted to match the sound and the sound is adjusted to match the light. It has been found that in cross modality matching observers are likely to constrict the range of adjustment on whichever variable is controlled. This is identified by Root & Ross (1965) as a centering tendency or regression effect. This causes the slope of the equal-sensation function to change depending on which stimulus is fixed and which is adjusted. In order to minimize regression effects, a balanced design is ideal. To achieve a balanced procedure, each continuum should be matched in turn to the other continuum so each stimulus serves both as the variable and as the standard stimulus (Root & Ross, 1965; Stevens & Greenbaum, 1966).

The second limitation of the present study is with regard to the visual stimuli. The stimuli in the present study consisted of a gray scale image paired with white noise as stimuli for the auditory and visual components. This may have influenced the type of sensory integration identified via the EEG data. Past behavioral studies have suggested that the strength of the relationship between the brightness of a light and the loudness of a sound may vary depending on whether the individual is assessing the brightness of an image, as in a gray scale, or the brightness of the light coming from something similar to a light bulb (Marks, 1982). Future researchers may wish to expand on the current study by examining processing of light and sound integration when the light stimulus consists of light from a light bulb. Additionally, the white noise used for the auditory stimuli proved to be rather harsh and fatiguing for many of the participants. Future research may wish to use a more pleasant auditory stimulus, such as a pink noise.

Lastly, the present study would have benefitted from a functional magnetic resonance imaging (fMRI) component for each of the participants. While EEG data are able to provide valuable temporal information with regard to neurological responses, fMRI is much more valuable in providing spatial information. The overlaying of an fMRI onto the EEG significantly improves the prediction of the EEG as it relates to the distribution of the sensory response across the scalp as a function of time (Dale & Halgren, 2001).

The current study provides further insight into the neural processing of sensory integration. Quantitative electrophysiological techniques and source localization were used to identify latencies and dipoles associated with a modified cross modality matching task. The study found that there were no significant differences in processing between matched or unmatched light and sound stimuli. Event related potential latencies and dipoles were not significantly different between the matched and unmatched conditions. However, the study also concluded that portions of the frontal lobe (specifically the superior central gyrus, medial central gyrus, and Brodmann's area 11) all play a role in the sensory integration task. While the current study builds on previous sensory integration studies of brightness and loudness, certain questions remain unanswered including: Does the response method in a cross modality matching procedure play a significant role in the processing of sensory integration? Is auditory and visual sensory integration significantly affected by the type of the stimuli? Are there differences in the processing of sensory integration between individuals with normal neurological function and individuals with impaired neurological function? Future investigations are recommended for resolving these questions and for furthering the general understanding of sensory integration.

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Appendix A

Annotated Bibliography

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Objective: The purpose of this study was to determine which areas of the brain integrate visual and auditory features of complex environmental objects. *Study sample:* This study contained two parts, both of which investigated sensory integration. The first sensory integration task consisted of seven participants. The second consisted of eight participants. *Method:* During the first set of procedures, each participant viewed line drawings of animals or man-made objects, heard the noises these objects typically make, or saw the drawing and heard the sound simultaneously. The participants completed a semantic decision task to ensure they accurately identified each object. Reaction time was recorded for unimodal visual and auditory tasks, in which the participants identified the objects presented. Reaction time was also recorded during the auditory-visual integration task in which the participants identified whether the sound and the line drawing presented to them were congruent or incongruent. All three tasks were then repeated during the second set of procedures, involving eight participants. During the second portion of the study, the participants performed an object identification task during the auditory-visual integration (rather than the more complex congruent/incongruent task). Throughout all procedures, fMRI data was collected. *Results:* In the first set of tasks, reaction times were significantly slower for the auditory identification task than the visual identification task. The reaction times for the auditory-visual integration task were significantly slower than both the visual and auditory unimodal tasks. Portions of the frontal, parietal, and temporal regions of the brain were noted to respond to unimodal auditory and unimodal visual tasks. The superior temporal sulcus and medial temporal gyrus were found to respond more strongly to the auditory-visual integration task than to the unimodal auditory or visual tasks. In the final set of tasks, the reaction times for the visual identification task were significantly faster than the other two tasks. The reaction times for the multimodal task were intermediate, and the auditory reaction times were the slowest. Again, the superior temporal sulcus and medial temporal gyrus displayed an enhanced response to the multimodal task, but not to the unimodal task. *Conclusion:* The superior temporal sulcus and medial temporal gyrus were pinpointed as an associative learning device, important for integrating different sensory modalities. *Relevance to the current work:* This study uses fMRI to determine cortical locations for sensory integration. This is similar to the present study, which employed averaged EEG files (taken during a sensory integration task) to identify the location of dipoles in participants. *Level of evidence:* Level IIIa.

Cook, I. A., O'hara, R., Uijtdehaage, S. H., Mandelkern, M., & Leuchter, A. F. (1998). Assessing the accuracy of topographic EEG mapping for determining local brain function. *Electroencephalography and Clinical Neurophysiology, 107*, 408. doi: 10.1016/S0013-4694(98)00092-3

Objective: The purpose of this study was to determine the accuracy of topographic electroencephalographic (EEG) maps in assessing brain function. *Study sample:* The participants of the study consisted of 6 right-handed adult males, aged 22 to 30. The participants had no history of neurological or psychiatric disease. *Method:* The participants performed a simple motor task while EEG recordings and positron emission tomography (PET) scans were taken simultaneously. Three different montages were used to process EEG data. The two EEG power measures of absolute and relative power were also examined. Power values were calculated for a linked ears reference montage, a source-derived montage, and a bipolar electrode montage. *Results:* The relative power was found to have stronger associations with perfusion than did absolute power. Furthermore, calculating power for bipolar electrode pairs and averaging power over electrode pairs sharing a common electrode yielded stronger associations with perfusion than data from referential or single source montages. *Conclusion*: The results of this study are indicative that EEG mapping is a reliable way of assessing local cerebral functioning and is comparable in accuracy to other methods. The results also lead to the conclusion that the choice of EEG measures and montage significantly impact the degree of accuracy of EEG mapping. *Relevance to the current work:* Topographic EEG mapping will be used in the present study to assess cerebral function during a sensory cross modality matching task. The findings of this study indicate that topographic EEG mapping is an accurate method of studying local cerebral function. *Level of evidence:* Level II.

Crisinel, A., & Spence, C. (2011). Crossmodal associations between flavoured milk solutions and musical notes. *Acta Psychologica, 138*, 155-161. doi: 10.1016/j.actpsy.2011.05.018

Objective: The purpose of this work was to determine if there is a specific relationship between tastes or flavors of milk (created by varying fat contents) and musical notes. *Study sample:* The study consisted of 22 participants, age 18 to 55 (13 females and nine males). All participants had normal neurological functioning and had no impairment of smell or taste. *Method:* To begin the study, each participant rinsed their mouth with tap water. For each trial, the participants were instructed to take the whole sample into their mouth, keep it in for a few seconds and then spit it back into the cup. The participants then chose a sound to match the taste. They were presented with four different sounds, associated with four different musical instruments. Participants chose the type of sound and pitch of sound that best matched the taste of the sample. They then rated the pleasantness, intensity, complexity, sweetness, sourness, bitterness, saltiness, and familiarity of the sample on a 9-point scale. Lastly, the participants were asked to identify the sample. *Results:* The flavors of the milk had an effect on the associated pitch, but the fat content (nor the interaction between the flavor and fat content) of the milk did not. Post-hoc *t*-tests were analyzed to determine that differences in associated pitch between the lemon and vanilla flavors, as well as the orange flower and vanilla flavors, were significant. *Conclusion:* The flavor of the milk had a significant effect on the associated pitch and instrument. However, the fat content of the milk did not have a significant influence on either choice of pitch or of instrument.

Additionally, participants of the control study were not able to reliably determine differences in fat content among unflavored milk samples. *Relevance to the current work:* This is a recent study which employed the cross modality matching procedure to identify relationships between taste and pitch. *Level of evidence:* Level II.

Gevins, A. (2002). Electrophysiological imaging of brain function. In A. W. Toga & J. C. Mazziotta (Eds.), *Brain mapping: The methods* (p. 259-276). San Diego, CA: Academic Press.

Objective: The purpose of this work is to discuss the role and abilities of electroencephalogram (EEG) and acquisition of application of averaged evoked potentials. The author identifies several factors and considerations to take into account when designing, carrying out, and analyzing a study which incorporates EEG. *Discussion:* There are several factors which determine how well a cortical potential will be recorded at the scalp level. These include the amplitude of the signal at the cortex, the proportion of cells in that region which are in synchrony, the location and orientation of the cells in relations to the scalp surface, and the amount of signal attenuation and spatial smearing produced by conduction through the intervening tissue layers of the dura, skull, and scalp. While further research is required, current evidence is suggestive that the EEG can reflect important aspects of cortical information processing. The author identifies items which may contaminate an EEG recording. These include artifacts originating from the subject’s eye or head movements, heart beats, or poor electrode contacts. Researchers are encouraged to take care to remove such artifacts before performing further analyses. This work outlines specific aspects to keep in mind with designing a study with the use of EEG. It is noted that brain signals vary due to many different factors and outside stimulation, thus the design of the study should take these variables into account and work to eliminate them as variables which may influence study results. Evoked potentials are defined as the electrical response of the brain to a specific stimulus. Evoked potentials are described as valuable research tools as they provide precise detail regarding timing and cortical distribution of neuroelectrical activity. *Relevance to the current work:* This work provided excellent recommendations for the design of the present study. It also outlined protocol for use and analysis of EEG. Additionally, evoked potentials are defined and explained. This was significant as latency of evoked potentials was a variable of the present study. *Level of evidence:* Level IV.

Marks, L. E. (1974). On associations of light and sound: The mediation of brightness, pitch, and loudness. *The American Journal of Psychology, 87*, 173-188. doi: 10.2307/1422011

Objective: The purpose of this study was to determine if visual brightness correlates with both auditory pitch and loudness. *Study sample:* Experiment IA and IB: Twelve young adult subjects (11 male and one female). Experiment IIA and IIB: Ten subjects (eight male and two female). Five of the males participated in Experiment IA and IB as well. Experiment III: Twelve subjects (10 male and two female). Five of the males participated in Experiments I and II as well. One male participated in Experiment I only. Two males and two female participated in Experiment II only. Two men did not participate in any previous experiments. *Method:* The study consisted of five separate experimental conditions. All experiments took place in a sound-isolated room. Experiment IA: Pitch and brightness matching experiment. Participants varied the pitch of a sound to match the brightness of a gray square which remained constant on a black background. Experiment IIA: Pitch and brightness matching experiment. Participants varied the pitch of a sound to match the brightness of a gray square which remained constant on a white background. Experiment IB: Loudness and brightness matching experiment. Participants varied the intensity of a sound to match the brightness of a gray square which remained constant on a black background. Experiment IIB: Loudness and brightness matching experiment. Participants varied the intensity of a sound to match the brightness of a gray square which remained constant on a white background. In experiments IA, IB, IIA, and IIB, each subject produced three matches of tone to each brightness stimulus. Experiment III: Loudness and brightness matching experiment with varied pitch (four different pitches). Participants matched the loudness of a sound to the brightness of a gray square at four different frequencies. In Experiment III, three matches were obtained at each of the four sound frequencies. Then, a new gray square replaced the previous gray square and the series was repeated. Neutral gray squares were derived from Munsell values of two, four, six, and eight. *Results:* Experiment IA: Twelve subjects associated increasing frequency with increasing surface brightness (as measured by Munsell value). Experiment IIA: Ten subjects associated increasing frequency with increasing surface brightness. One did not. Experiment IB and IIB: Ten subjects matched increasing loudness to increasing brightness. Two subjects did not. Experiment IIB: Four subjects matched increasing loudness to increasing brightness, five matched increasing loudness to increasing darkness. One subject did not follow either of these matching systems. Experiment III: Ten subjects responded to the stimuli by lowering the set sound pressure as the frequency raised higher. However, these ten subjects did vary in the way they matched loudness to different grays. *Conclusion:* Most subjects associated low pitch and low loudness to darker squares and high pitch and high loudness to lighter squares. However, some subjects reversed the pattern entirely and matched increasing loudness to increasing darkness. *Relevance to the current work:* This a cross modality matching study testing the idea that the frequency of a sound and the brightness of a light have a perceptual correlation. It has been said that the color of a light and the pitch of a sound are the quality of the stimulus and the brightness of a light and the loudness of a sound are the intensity of the stimulus. This study sought to cross boundaries by investigating whether participants display patterns of association between pitch and brightness. *Level of evidence:* Level IIIa.

Marks, L. E. (1975). On colored-hearing synesthesia: Cross-modal translations of sensory dimensions. *Psychological Bulletin, 82*(3), 303-331. doi: 1037/0033-2909.82.3.303

Objective: This work reviews current knowledge on color-hearing synesthesia. This is a type of sensory integration in which sounds stimulate visual images. *Discussion:* Research on color-hearing synesthesia indicate two general themes. First, the brightness of visual images vary with the brightness (density) of the stimulating sound. Second, the size of the visual images vary with the size (intensity) of the stimulating sound. Additionally, the way individuals classified as synesthetes were found to align dimensions of different modalities is qualitatively similar to the way nonsynesthetes were found to align them. The associations between color and sound may seem idiosyncratic, but in actuality they are often systematic and consistent from person to person. In addition to this, the author noted that evidence suggests that there is an intrinsic relationship between vowel quality and colors. The author concludes that evidence supports the notion that the relationship between vowel quality and color is as intimate as the relationship between brightness and loudness in nonsynesthetic subjects. *Relevance to the current work:* This article contains a review of eighteenth century research on synesthesia and cross modality matching. According to this article, the regular nature of cross modal analogies was established around 1880 due to findings by such researchers as Fechner (1876) and Bleuler and Lehmann (1881). This article also gives an analysis of the relationship between brightness and loudness, stating that when individuals are asked to align brightness with loudness they align increasing luminance with increasing sound pressure in a systematic manner. *Level of evidence:* Level I.

Marks, L. E. (1982). Bright sneezes and dark coughs, loud sunlight and soft moonlight. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 177-193. doi:10.1037/0096-1523.8.2.177

Experiment 1: Metaphors of Brightness and Loudness
Objective: The purpose of this study is to examine the relationship of brightness, loudness, and pitch by examining the meanings of literal and metaphorical expressions. *Study sample:* Twenty individuals participated in the study (10 male and 10 female). All were native English speakers. *Method:* Each participant was presented with a set of sound words paired with visual nouns (e.g., murmur of sunlight) and a set of light words paired with auditory nouns (e.g., dim whisper). The participant was instructed to judge each expression on a scale of loudness (for the sound set) or brightness (for the light set). Each participant rated the level of loudness or brightness described by each expression via a slash on a rating line, with *very very dark* or *very very soft* at one end and *very very loud* or *very very bright* at the other end. Half of the participants judged the sound set first and then the light set, and half judged the light set first and then the sound set. *Results:* The correlation between loudness and brightness ratings was 0.269. *Conclusion:* Brightness adds loudness metaphorically when visual words modify sound words. Additionally, loudness adds brightness metaphorically when sound words modify visual words. Interestingly, modified words or phrases did not show any pattern for translating their loudness into brightness or their brightness into loudness. For example, *thunder* is much louder than a *whisper*, but was not judged to be brighter. *Relevance to the current work:* This study examined the relationship between brightness and loudness through the medium of expressions and metaphors. It is interesting to note that the same patterns of perception between brightness and loudness which have been found by direct matching studies were also found through the indirect medium of words. *Level of evidence:* Level IIIa.

Experiment 2: Metaphors of Brightness and Pitch
Objective: The purpose of this study is to examine the relationship of brightness, loudness, and pitch by examining the meanings of literal and metaphorical expressions. *Study sample:* Sixteen individuals participated in this study (eight males and eight females). *Method:* Each participant was presented with a set of sound words paired with visual nouns (e.g., murmur of sunlight) and a set of light words paired with auditory nouns (e.g., dim whisper). The participants were

instructed to judge each expression on a scale of pitch (for the sound set) or brightness (for the light set). Each participant rated the level of pitch or brightness described by each expression via a slash on a rating line, with *very very dark* or *very very low* at one end and *very very bright* or *very very high* at the other end. Each participant judged each set of stimuli twice. Half of the participants judged the sound set first and then the light set, and half judged the light set first and then the sound set. *Results:* For all 29 items, the correlation coefficient between the mean judgment of pitch and brightness was 0.969. *Conclusion:* Pitch is equivalent to brightness. The study determined that loudness does not always follow the same predictable pattern of loudness and brightness equivalence as pitch and brightness do. *Relevance to the current work:* This experiment concluded that brightness was more consistent in its alignment with pitch than it was with loudness. This will be interesting to keep in mind throughout the current study as I am examining the cognitive response to the relationship of brightness and loudness. This is also interesting considering that brightness and loudness both represent the level of intensity of their respective sensory modalities. *Level of evidence:* Level IIIa.

Experiment 3 and 4: Metaphors of Loudness, Pitch, and Luminosity
Objective: The purpose of this study was to determine the relationship of loudness and brightness in luminosity as opposed to brightness in surface brightness or lightness. *Study sample:* Experiment 3: Sixteen individuals participated (six men and 10 women). Experiment 4: Sixteen individuals participated (four men and 12 women). *Method:* Each participant was presented with a set of sound words paired with visual nouns (e.g., murmur of sunlight) and a set of light words paired with auditory nouns (e.g., dim whisper). Many of the words in the sets were similar to the sets presented in Experiments 1 and 2. However, any words from the previous sets that pertained to surface brightness (e.g., white) were changed to correspond with luminosity brightness (e.g., glow). Experiment 3: The participants were instructed to judge each expression on a scale of loudness (for the sound set) or brightness (for the light set). Each participant rated the level of loudness or brightness described by each expression via a slash on a rating line, with *very very dim* or *very very soft* at one end and *very very bright* or *very very loud* at the other end. Each participant judged each set of stimuli twice. Half of the participants judged the sound set first, followed by the light set. The other half judged the light set first, followed by the sound set. Experiment 4: The participants were instructed to judge each expression on a scale of pitch (for the sound set) or brightness (for the light set). Each participant rated the level of pitch or brightness described by each expression via a slash on a rating line, with *very very dim* or *very very low* at one end and *very very bright* or *very very high* at the other end. Each participant judged each set of stimuli twice. Half of the participants judged the sound set first, followed by the light set. The other half judged the light set first, followed by the sound set. *Results:* Experiment 3: Compared to Experiment 1 (which studied the relationship between loudness and surface brightness rather than loudness and luminosity brightness), the researchers found that the translation of loudness to brightness and of brightness to loudness was much richer than before. Experiment 4: Pitch translated directly to brightness and brightness directly to pitch. This is similar to the results seen in Experiment 2, which examined pitch and surface brightness rather than pitch and luminosity brightness. *Conclusion:* Pitch and brightness are steady and reliable correlates. High pitch is equivalent to bright in the sense of both surface brightness and

luminosity. Loudness and brightness are also good correlates, but it is more fickle than pitch and brightness are. Loudness was found to relate closely to brightness in the sense of luminosity, but not as closely in the sense of surface brightness. *Relevance to the current work:* This study determined that pitch is a more concrete match to brightness than loudness is. My study sought to measure cortical activation during a matching procedure of loudness and brightness. It was interesting to note how the participants of the present study correlated loudness with surface brightness. *Level of evidence:* Level IIIa.

Marks, L. E., Szczesiul, R., & Ohlott, P. (1986). On the cross-modal perception of intensity. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 517-534. doi:10.1037/0096-1523.12.4.517

Objective: The purpose of this study was to explore the similarities of intensity in vision, hearing, and touch. The study explored absoluteness vs. relativity of cross modal matches, the effect of method on cross modal matches, and sensory scales that mediate cross modal equivalences. *Study sample:* Sixteen young individuals participated in this study. *Method:* This study consisted of two parts. The first was magnitude estimation. During the magnitude estimation procedure, the subjects were presented with various intensities of vibration stimuli and auditory stimuli and asked to assign each of them a number. The second part of the study was cross modal difference estimation task. During the cross modal task, the subjects were presented with pairs of stimuli consisting of vibration stimuli and auditory stimuli. They were asked to determine which was more intense and by how much. *Results:* The judgments of the vibration stimuli were the same, irrespective of whether the vibration stimuli and auditory stimuli alternated from low or high sound intensities. *Conclusion:* Absolute components do play a role in cross modal perception. However, there is also strong evidence to suggest a relativist component as well. Due to the intermediate nature of cross modality matching (it is partly relative and partly absolute), it could potentially be valuable in assessing intergroup differences using magnitude estimation. *Relevance to the current work:* Absolute vs. relativity of the results of cross modality matching were examined in this study. The present study used cross modality matching to examine the relationship of loudness and brightness. The study found that matches have both absolute and relative components. This was taken into account in the present study. *Level of evidence:* Level IIIa.

Marks, L. E. (1987). On cross-modal similarity: Auditory–visual interactions in speeded discrimination. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 384-394. doi:10.1037/0096-1523.13.3.384

Objective: The purpose of this study was to identify similarities between sensory attributes of vision and hearing through cross modality speeded discrimination. *Study sample:* The participants consisted of 40 young men and women. *Method:* Light and sound stimuli were presented to the participant simultaneously. The participant was instructed to respond to the stimulation by pressing one of two keys to indicate whether the light was dim or bright. Each participant responded to four blocks of 100 trials each per session. Each participant served in four sessions. Sixteen participants responded directly to the visual stimuli (black vs. white, gray background), 10 with normal and six with reversed assignment of keys to stimuli. Twelve participants responded directly to the visual stimuli (dim vs. bright, black background), six with normal and six with reversed assignment of keys to stimuli. Twelve subjects responded directly to sound (low vs. high pitch). *Results:* Luminance level affected response times to low and high frequency sounds. Also, frequency level differentially affected response times to low and high luminance. An ANOVA confirmed that when participants responded to sound, the overall sound level multiplied by the light level was significant. The individual interactions for lightness and brightness were also significant. *Conclusion:* Discrimination was faster on trials where the target stimulus was accompanied by matching rather than mismatching stimuli from the accompanying sensory modality. A wide range of sensory modalities are interlinked. Additionally, relationships between different attributes of visual and auditory stimuli permeate functional responses to sensory stimulation. *Relevance to the current work:* The relationship of auditory and sensory stimuli were examined in this study. Functional cross modal similarities in reaction and accuracy were found, implying that there is some commonality between them in the way the stimuli are processed by our brains. This is relevant to the current study as this study analyzed auditory and visual sensory integration, but without the electrophysiological component that the current study employed. *Level of evidence:* Level II.

Marks, L. E. (1989). On cross-modal similarity: The perceptual structure of pitch, loudness, and brightness. *Journal of Experimental Psychology: Human Perception and Performance, 15*(3), 586-602. doi:10.1037/0096-1523.15.3.586

Objective: The purpose of this study was to explore the relationship of pitch and loudness to brightness. To do this, three questions were asked. First, how do loudness and pitch interact in the process of determining the similarities of sounds to lights? Second, what are the individual differences in the way that people use pitch or loudness in cross modal judgment? Third, how absolute are the cross modal associations? *Study sample:* The study sample consisted of 16 individuals. *Method:* In the first experiment, the participants identified which of two lights had a higher resemblance to 16 tones. In the second experiment, eight of the participants from Experiment one rated the similarity of lights to lights, tones to tones, and lights to tones. *Results:* Experiment one: There were clear individual differences regarding whether the participants relied more heavily on pitch to relate to brightness or loudness to relate to brightness. About half of the participants relied largely on pitch. About one fourth of the participants relied largely on loudness. About one fourth of the participants relied on both pitch and loudness. Experiment two: Two perceptual dimensions, loudness and pitch, were revealed by multidimensional scaling. Brightness was common to both dimensions. *Conclusion:* The visual stimuli of brightness has at least two structural and functional correlates in auditory stimuli. These are pitch and loudness. They both correlate to the level of brightness in predictable ways. Bright lights are more likely to be associated with high pitch sounds and louder sounds. Dim lights are more likely to be associated with low pitch sounds and softer sounds. Thus, there are at least two types of auditory stimuli that structurally and functionally correlate to visual brightness. *Relevance to the current work:* This study supports the conclusion that loudness and brightness are correlates of one another. *Level of evidence:* Level IIIa.

Marks, L. E., Ben-Artzi, E., & Lakatos, S. (2003). Cross-modal interactions in auditory and visual discrimination. *International Journal of Psychophysiology, 50*(1–2), 125-145. doi: 10.1016/S0167-8760(03)00129-6

Objective: The purpose of this study was to determine whether and how cross modal congruence relations affect auditory and visual discrimination. *Study sample:* Six participants, two men and four women, participated in the first experiment. Seven participants, two men and five women, participated in the second experiment. Sixteen participants participated in the third experiment. *Method:* Experiment 1: The participants performed a one-interval confidence-rating procedure in which they pressed a key labeled *low* or *high* for a low or high pitch or brightness, depending on the dimension tested. The participants also pressed a key to indicate their degree of confidence in their response. This was done using a three-point scale where one indicated they were very sure, two indicated they were sure, and three indicated they were not very sure. Experiment 2: The procedure was the same as that used in Experiment 1. However, in this experiment, loudness was adjusted rather than pitch. Experiment 3: The participants participated in a two-interval same-different procedure in which they indicated whether visual and auditory stimuli were the same or different. *Results:* Experiment 1: An ANOVA revealed significant differences in sensitivity between congruent and incongruent trials and between baseline and incongruent trials, but not between baseline and congruent trials. Experiment 2: When discriminating loudness, five out of six participants showed poorest performance on incongruent trials. Additionally, six of the six participants showed a congruence effect by performing better on incongruent trials. Experiment 3: An omnibus ANOVA showed no significant effect of modality, a nearly significant effect of condition, and a significant interaction between the two. Individual ANOVAs showed significant effects of condition for both pitch and brightness. *Conclusion:* Cross modal interactions pervade perceptual processing and experience. Additionally, interactions observed in Experiments 1 and 2 arose from decision biases, which were not evident in Experiment 3. *Relevance to the current work:* The methods and stimuli of this study are similar to those which were used in the present cross modality matching study. Additionally, the authors discussed past research using event related potentials, which were also analyzed in the present study. *Level of evidence:* Level IIIa.

McPherson, D. L. (1975). Loudness and brightness: A study on cross modality matching. *Journal of Auditory Research, 15,* 65-72.

Objective: The purpose of this study was to investigate how a participant perceives the intensity of one stimulus (lightness or brightness) as it relates to the other. *Study sample:* Five normal-hearing adults, with no history of middle ear pathology, participated in the study. *Method:* The study employed a cross modality matching procedure of brightness and loudness. Each participant was presented with a set of auditory stimuli and asked to match the brightness of a light to the loudness of the sound. The task was then reversed and a set of light stimuli were presented and the participant was asked to match the loudness of a tone to the brightness of the light. *Results:* As the intensity of the auditory stimuli increased the subjective brightness response increased as well. Additionally, as the brightness stimuli increased, so did the subject auditory loudness response. The exponents observed for brightness and loudness were plotted as a regression lines and compared with the regression line reported by Stevens (1961). The two lines would have been almost equal, had the present study calculated the exact exponents Stevens calculated. *Conclusion:* Cross modality matching of brightness and loudness can be expressed by a power law which expresses the relationship between physical and psychological intensity. *Relevance to the current work:* This study observed the psychological relationship of auditory and visual (brightness) intensity. *Level of evidence:* Level IIIa.

McPherson, D. L., Ballachanda, B. B., & Kaf, W. (2007). Middle and long latency auditory evoked potentials. In Roeser R. J., Valente M., & Hosford-Dunn H. (Eds.), *Audiology, diagnosis* (p. 443-477). New York, NY: Thieme.

Objective: The purpose of this work was to provide practitioners with an introduction to middle latency auditory evoked potentials (MLAEP) and long latency auditory evoked potentials (LAEP). *Discussion:* The following specific MLAEPs and LAEPs were studied in this chapter: P1, P300, and MMN. The P1 is one of four components of the long latency auditory evoked potentials (LAEP). The P1 occurs between 55 and 80 ms. It is generally an exogenous potential, it is primarily generated by the physical characteristics of the stimulus and it is a response to perception of sensory stimuli. It changes with the physical features of the stimuli. The P1 is present whenever a stimulus is recognized. The P300 is a cognitive auditory ERP that occurs at a higher level of cognitive processing associated with stimulus recognition and novelty. The P300 is an endogenous ERP, it is produced after internal processing of the stimulus. Therefore, the amplitude is affected by level of attention (unlike the MMN). The P300 occurs between 220 and 380 ms. A physically deviant stimulus, in a sequence of homogeneous stimuli, serves to elicit the MMN. The most common parameters to measure in the MMN are amplitude and latency. Amplitude is measured between the positive peak and corresponding negative trough. Latency is measured from the time of stimulus onset to the initial peak of the MMN waveform. *Relevance to the current work:* The P1, P300, and MMN were evoked potentials that were considered for analysis in the present study using quantitative electrophysiological techniques. This work provided a brief background of the significance of these three event related potentials, as well as how they are elicited and measured. *Level of evidence:* Level IV.

Ohara, S., Lenz, F. A., & Zhou, Y. (2006). Modulation of somatosensory event related potential components in a tactile–visual cross-modal task. *Neuroscience, 138*(4), 1387-1395. doi: 10.1016/j.neuroscience.2005.12.005

Objective: The purpose of this study was to determine whether the event related potential N140 would be modulated during a tactile-visual delayed cross modality matching task. *Study sample:* Ten participants took part in the study. Data from two of the participants was excluded due to excessive eye blinking of one subject and excessive artifacts of the other. Data from eight participants was included in the final analysis (six male and two female, 19-47 years old). *Method:* The participants first participated in a unimodal matching task in which they determined whether a pair of tactile stimuli were equal or unequal in intensity. Next, the participants completed a delayed cross modal matching task in which they indicated whether the brightness of a light was equal to or unequal to the intensity of a vibration. Event related potentials (ERPs) were recorded using a standard electroencephalogram (EEG) recording system. A control task was performed for both the unimodal and cross modal paradigms in which the participant was presented with a pair of stimuli (tactile-tactile or tactile-visual) and instructed to not pay attention to the second sensation in the stimulus pair, but to use it as a go signal to indicate that they are to begin a task of whether the initial stimulus was a high or low frequency. *Results:* The N140 amplitude in the cross modal task was significantly higher than that in the midline task, which was revealed by post hoc analysis. The enhancement of the N140 was noted in the cross modal control task as well. *Conclusion:* Analysis of the results reveals that tactile-visual cross modal relationship affects tactile sensory-perceptual processes. *Relevance to the current work:* This study used EEG to measure changes in ERPs during a cross modality matching task, a unimodal matching task, and control tasks for both. It is interesting to note that changes were identified between the cross modal and unimodal task, but not between the cross modal task and the cross modal control task (in which participants were not asked to match the stimuli presented to them). *Level of evidence:* Level IIIa.

Pepermans, R. G., & Corlett, E. N. (1983). Cross-modality matching as a subjective assessment technique. *Applied Ergonomics, 14*(3), 169-176. doi: 10.1016/0003-6870(83)90078-9

Objective: The purpose of this work was to compare various forms of cross modality matching procedures as subjective assessment techniques and to outline limitations of each. This work also emphasized the application of cross modality matching in ergonomics. *Discussion:* This work introduced Fechner's law and its revised version by Stevens in his power law. The relationship between many different sensory modalities has been studied using cross modality matching. Cross modality matching can be applied to ergonomics to better understand how individuals perceive environmental conditions. There are a number of problems with the application of cross modality matching. These include: difficulty in allowing subjects to control the stimuli, varying frames of reference among subjects, bias due to range effects, the use of subjective measures, and potential cognitive restrictions of the subjects. *Relevance to the current work:* This work discussed several factors to consider when implementing cross modality matching. All potential problems were important to consider in order to perform a cross modality matching study with high validity and reliability. *Level of evidence:* Level I.

Root, R. T., & Ross, S. (1965). Further validation of subjective scales for loudness and brightness by means of cross-modality matching. *The American Journal of Psychology, 78*, 285-289.

Objective: The purpose of this study was to determine whether the slope of the equal-sensation function for brightness and loudness can be predicted with a knowledge of the two exponents. *Study sample:* The study sample consisted of 10 male undergraduates from the University of Maryland. *Method:* Each participant was asked to match the apparent intensity of the auditory stimuli with the intensity of the visual stimuli (which was under the participant's control).

Results: The matched loudness and brightness levels were plotted and the best fitting line through the points was obtained using the method of least squares. The slope of the line was 0.908. The slope of the line was expected to be 0.909, calculated from the exponents for the subjective magnitude functions for brightness and loudness. *Conclusion:* The results of the study were extremely close to the expected value. The log-log plot created from the results display a linear function for brightness and loudness. The close correspondence between the expected slope and the observed linear plot attests to the validity of the exponents 0.30 for loudness and 0.33 for brightness. *Relevance to the current work:* This study validates the relationship between brightness and loudness stimuli and the exponents used to represent these stimuli. The relationship between these two sensory modalities is integral to the present study. The present study examined the brain's response to the matching of sensory stimuli which correspond to one another in a previously established pattern. *Level of evidence:* Level IIIa.

Spence, C. (2011). Crossmodal correspondences: A tutorial review. *Attention, Perception, & Psychophysics, 73*, 971-995. doi: 10.3758/s13414-010-0073-7

Objective: The purpose of this work was to review current research which corroborates cross modal correspondences. This evidence was used to support the view that there may be several qualitatively different kinds of cross modal relationships. This information was used to determine where cross modal correspondences occur in the human brain. *Discussion:* Cross modal correspondences may be occurring in the polysensory areas in the temporal cortex. These areas have been found to respond with more force to cross modally congruent auditory and visual stimuli. The question remains as to whether the same cortical area would be activated with cross modal integration of basic stimuli. It is known that increases in stimulus intensity generally causes increased neural firing. This might be suggestive of a neural correspondence which supports the relationship between brightness and loudness. *Relevance to the current work:* This work reviewed current studies regarding neural components of cross modal relationships between sensory stimuli. This is relevant as cortical response to sensory integration was examined in the present study. *Level of evidence:* Level I.

Stevens, J. C., & Marks, L. E. (1965). Cross-modality matching of brightness and loudness. *Proceedings of the National Academy of Sciences of the United States of America, 54*(2), 407-411.

Objective: The purpose of this study was to use a cross modality matching procedure to determine whether brightness and loudness would produce an equal-sensation function whose exponent is the ratio of the exponents previously determined for the two sense modalities. *Study sample:* The study consisted of 10 participants. *Method:* Each individual participated in two sessions of the experiment. Before each session the participant's eyes were dark-adapted with red goggles for 10 minutes. All sessions were done in a dark room. The stimulus was presented to the participant, a band of noise and flash of light were presented simultaneously. The duration of the noise was 0.95 seconds and the light was 0.45 seconds. The participant was presented with a sequence of 16 paired stimuli for each session (each light luminance level was presented twice).

After the stimulus was presented, the participant was to turn a knob to adjust the loudness of the sound until they perceived it as equal to the brightness of the light. In the second session, the participants varied the brightness of the light to match the loudness of the sound. Five of the participants adjusted the sound levels first and five adjusted the light levels first. A second experiment was done using the same procedure, except the participant was allowed to control the onset and offset of both stimuli. In this experiment, seven stimulus levels were matched in each session. *Results:* The average slope for Experiment 1 and Experiment 2 was 1.0. The ratio of the exponents governing brightness and loudness should approximate unity, when plotted. *Conclusion:* The cross modality functions generated from the data have the form predicted by the psychophysical power law of sensory magnitude. Additionally, the psychophysical functions relating brightness and loudness to the level of stimulus energy have approximately the same exponents. *Relevance to the current work:* This study used cross modality matching to quantify the relationship between brightness and loudness. This is the same area of interest as the present study, which used cross modality matching of brightness and loudness to evaluate the cortical response to sensory integration. *Level of evidence:* Level IIIa.

Stevens, S. S. (1957). On the psychophysical law. *Psychological Review, 64*(3), 153-181. 10.1037/h0046162

Objective: The purpose of this work was to corroborate a general psychophysical law which relates subjective magnitude to stimulus magnitude. According to Stevens, this law requires equal stimulus ratios to result in equal subjective ratios. *Discussion:* This work drew on multiple studies to conclude that the form of the psychophysical law is a power function for prothetic continua. The basic principle is that equal stimulus ratios tend to produce equal sensation ratios. Various studies have documented relative consistency of ratio scaling for particular stimuli. These studies provide evidence that sensation is proportional to the stimulus raised to a power. This work also discusses methods for ratio scaling, outlining ratio estimation, ratio production, magnitude estimation, and magnitude production as four principal methods, with sub-varieties of each. *Relevance to the current work:* This work outlined the psychophysical law. It also detailed various methods for ratio scaling. The present study employed a sub-variety of magnitude production as the method of research. *Level of evidence:* Level I.

Stevens, S. S. (1971). Issues in psychophysical measurement. *Psychological Review, 78*(5), 426-450. doi: 10.1037/h0031324

Objective: The purpose of this work was to review several sensory matching procedures; especially those which are used to determine the power functions that govern the growth of sensation magnitude. *Discussion:* Cross modality matching is one type of magnitude matching. This magnitude matching procedure is ideal when the stimulus continuum can be varied by the participant. This way the participant can easily adjust one sensory modality until it matches another. Stevens noted that in typical behavior the participant has a tendency to shorten the range of the variable he controls, this tendency has been named the regression effect. Therefore, in an ideal scenario, the participant would complete two separate trials (adjusting one sensory modality in the first trial and the other modality in the second trial). Other types of sensory estimation methods include various forms of magnitude estimation, magnitude production, ratio matching, cross modal ratio matching, ratio estimation, and ratio production. Additionally, the psychophysical power law has been influenced by various forms of interval matching. Types of interval matching include cross modal interval matching, interval estimation, interval production, and sum production. This article also discussed averaging of data. It advised researchers using cross modality matching to use the geometric mean, not the arithmetic mean when averaging data. *Relevance to the current work:* This work discussed the research method of cross modality matching, providing insight into the best use of the method and the most valid ways of averaging data collected from this method. It also discusses potential errors with the cross modality matching method and ways to avoid the errors (i.e., avoiding range effects). *Level of evidence:* Level I.

Susini, P. (2000). Psychophysical validation of a proprioceptive device by cross-modal matching of loudness. *Acta Acustica United with Acustica, 86*(3), 515-525.

Objective: The authors of this study introduced a new proprioceptive estimation device for continuous unidimensional judgment of nonstationary sounds. The purpose of this study was to establish an individual calibration method and the loudness scale of pure tones (1000Hz) through a cross modal matching procedure using the new device. *Study sample:* Ten participants took part in all tests in the study. They consisted of eight men and two women, all between the ages of 25 and 30 years old. Ten additional participants (five men and five women, age 25-39) took part in a magnitude estimation of proprioceptive sensation and the cross modal matching task. *Method:* The method for Experiment six involved a cross modal matching procedure. Prior to the procedure, the proprioceptive device was calibrated to the individual participant. Stimuli consisted of eight one-kHz pure tones at 40, 45, 55, 60, 65, 70, 80, and 85 dB SPL. Each sound was presented for one second. Upon pushing a button, the participant was presented with a sound of consistent level every two seconds. The subject displaced the lever of the device until the apparent force was equal to the loudness of the sound. While holding the lever in that position, they pressed the letter *V* to indicate a response. This procedure was repeated for each sound level. The experiment was then repeated with the starting point of the lever at a 90 degree angle. Ten participants performed the experiment by a pushing effort first and then by a retaining effort. This order was reversed for the other 10 participants. *Results:* Functions obtained in both the pushing or retaining modes were straight lines with slopes of 0.30 and 0.28, respectively. This gives the exponent an average of 0.29. *Conclusion:* Loudness and proprioception can be described by a power function. It was also confirmed that the slope 0.29 of the matching function obtained directly by cross modality matching was very close to the slope that would be predicted from the power functions obtained in the previous experiments for loudness and proprioception independently. This slope validated the proprioceptive device used in the study and the matching method for evaluating loudness scaling. *Relevance to the current work:* This study employed a cross modality matching procedure; the same type of procedure used in the present study. This study noted that the cross modality matching procedure was particularly baffling to the participants. However, after a few trials the participants adapted to this paradigm. The participants also noted that they were able to respond instinctively while participating in cross modality matching. *Level of evidence:* IIIa.

Tsubomi, H., Ikeda, T., & Osaka, N. (2012). Primary visual cortex scales individual's perceived brightness with power function: Inner psychophysics with fMRI. *Journal of Experimental Psychology: Human Perception & Performance, 38*(6), 1341-1347. doi: 10.1037/a0030025

Objective: The purpose of this study was to determine how neural activation levels in the visual cortex scale an individual's subjective brightness. This was done using Stevens' power function and fMRI recordings. *Study sample:* The study consisted of nine participants, all of whom were neurologically normal, college students, and in the age range of 22-32 years old. *Method:* Participants were positioned supine in the fMRI scanner. To begin the session, participants were presented with a standard luminance level and told it equaled 10. They were also presented with the lower and upper luminance limits. Participants were presented with five different levels of luminance and asked to rate each compared to the standard level. Participants were presented with the five luminance levels at 10 repetitions each, 50 trials total. In trials with the fMRI scan, the participants were presented with each luminance level, eight times each. Participants were not asked to rate the levels. Three sessions were conducted, resulting in 24 repetitions of each luminance. *Results:* The results of the behavioral data show that participants provided consistent brightness ratings before and after the fMRI scans. The results of the fMRI scans show that activity in the primary visual cortex and the calcarine sulcus increased log-linearly with increase in luminance. The average power exponent was calculated to be 0.32 in the left hemisphere and 0.27 in the right. *Conclusion:* An individual's subjective brightness can be scaled by the primary visual cortex activation. This is in agreement with Stevens' power law. *Relevance to the current work:* Stevens' power function has been corroborated by cross modality matching tasks of brightness and loudness. Perceived loudness can also be described by a power function. This is significant because the purpose of the present study was to examine how neural activation differs when brightness and loudness match or are unmatched. *Level of evidence:* Level IIIa.

Walker, P. (2012). Cross-sensory correspondences and cross talk between dimensions of connotative meaning: Visual angularity is hard, high-pitched, and bright. *Attention, Perception, & Psychophysics, 74*, 1792-1809. doi: 10.3758/s13414-012-0341-9

Objective: The purpose of this series of studies was to determine if cross-sensory correspondences have a semantic basis during a speeded classification task. Three experiments were employed. The first examined if congruity effects were present between angularity of a shape and connotative hardness of a word. The second experiment examined the relationship between angularity and pitch. The third experiment examined congruity between angularity and brightness. The third experiment will be the focus of this bibliography. In this experiment, words were classified according to the level of brightness that they imply. *Study sample:* The third experiment in this series of studies examined 17 participants, all of whom were undergraduate students at Lancaster University. Ten participants were males and seven were females. Ages ranged from 19 to 24 years old. *Method:* Participants were presented with test words and shapes. Some shapes were angular and some were curved. The participants were asked to determine whether each word, presented inside a shape, was indicative of something bright or dim. This was done within a speeded classification design. *Results:* There was no significant impact on accuracy between words presented within angular shapes or non-angular shapes. However, participants responded more quickly on congruent trials (bright words paired with angular shapes, or dim words paired with non-angular shapes) than on incongruent trials (bright words paired with non-angular shapes, or dim words paired with angular shapes). *Conclusion:* Words are more easily classified as bright or dim when they appear concurrently with shapes with congruent connotations of brightness based on their angularity. That is, words suggesting brightness are classified relatively quickly when they appear in an angular shape and words suggesting darkness are classified more quickly when they appear in a curved shape. *Relevance to the current work:* This study observed the relationship between connotative meaning of shapes (angular vs. curved) and brightness. The results of the study indicate that there is a predictable relationship between the two sensory stimuli. This corroborates the suggestion that sensory stimuli can have predictive relationships with other sensory stimuli. It also illustrates additional connotative meaning to brightness, which had already been found to be associated with higher pitch. *Level of evidence:* Level IIIa.

Walker, P., & Walker, L. (2012). Size–brightness correspondence: Crosstalk and congruity among dimensions of connotative meaning. *Attention, Perception, & Psychophysics, 74*, 1226-1240. doi: 10.3758/s13414-012-0297-9

Objective: This study was designed for the purpose of examining the perceptual correspondence between size and brightness. *Study sample:* The study consisted of 76 Lancaster University students. Of the participants, 14 were males and 62 were females between the ages of 18 and 34 (mean age = 19.75 years). All but four participants were right handed. *Method:* A speeded classification task was administered to all participants. Visual stimuli consisted of six solid circles which were 4.5 cm in diameter. The circles varied in brightness from white through black; they were presented on a computer screen with a gray background. The response key was made up of two round spheres, one was 2.5 cm in diameter and the other was 7.5 cm in diameter. The spheres were each mounted on micro switches. The spheres were then covered with a thick black cloth, the participants never saw them. Participants grasped the top half of each key with the thumb and first two fingers of each hand. When a circle appeared on the computer screen, the participants classified it as *bright* or *dark* (relative to the background) by pressing one of the two keys. Half the participants were instructed to press the right key for brighter and left key for darker; the other half of the participants were instructed to press the left key for brighter and right key for darker. At the end of each trial, the experimenter switched the left and right keys without telling the participant. When participants pressed the small key for bright and the large key for dark, the condition was congruent. When the participants pressed the small key for dark and the large key for bright, the condition was incongruent. Experimenters measured the accuracy of brightness vs. darkness discrimination and the reaction time of each participant. *Results:* The congruent trials resulted in p(correct) = 0.99. The incongruent trials resulted in *p*(correct) = 0.98, p <.001. The overall mean correct reaction time was 733 ms. *Conclusion:* Participants responded more quickly and with fewer errors when the size of the key being pressed was congruent with the brightness of the visual stimulus being classified. This was the case, even though the size of the key was task irrelevant. This supports the prediction that size and brightness are correlated. *Relevance to the current work:* This is a cross modality matching study, testing the idea that size and brightness have a perceptual correlation. Past studies have found that people correlate higher frequency sounds with brighter light and smaller. Thus it seeks to determine if people correlate brighter light with smaller size. The methods and background research of this study are particularly significant to the present study. *Level of evidence:* Level IIIa.

Appendix B

Informed Consent to Act as a Human Research Subject

David L. McPherson, Ph.D.
Communication Science and Disorders
Brigham Young University
(801) 422-6458

Name of Participant: ______________________________________

Purpose of Study
The purpose of the proposed research project is to identify whether or not there is a brain response when matching differing intensities of light and sound. This will be accomplished by measuring brain activity during a matching procedure of the brightness of light with the loudness of sound.

Procedures
You have been asked to participate in this study by Tawnya Coates, B.S., a student conducting research under the direction of David L. McPherson, Ph.D. The study will be conducted in room 111 of the John Taylor Building on the campus of Brigham Young University. The testing will consist of one to three sessions, including orientation and testing, and will last for no more than 3.5 hours. You may ask for a break at any time during testing. Basic hearing tests will be administered during the first half-hour of the first session.

Surface electrodes (metal discs about the size of a dime) will be used to record electrical activity of your brain. These discs will be applied to the surface of the skin with a liquid. They are easily removed with water. Blunt needles will be used as a part of this study to help apply the electrode liquid. They will *never* be used to puncture the skin.

Brain processing of hearing and vision will be measured using an electrode cap, which simply measures the electrical activity of your brain and *does not* emit electricity; no electrical impulses will be applied to the brain. These measurements of the electrical activity are similar to what is known as an EEG or brain wave testing. These measurements are of normal, continuous electrical activity naturally found in the brain.

You will wear the electrode cap while you match varying intensities of a sound with varying intensities of a light. You will be asked to determine whether the sound intensity and light intensity are equal, and press a button to indicate your response. During the time of your responses, the electrical activity of your brain will be recorded on a computer. The sound will be presented through insert earphones and will not exceed a comfortable listening level. The light will be presented through a grayscale screen and will not exceed a comfortable brightness level. You will be seated comfortably in a sound treated testing room. You will be asked to give responses during the hearing test and portions of the electrophysiological recording by pressing a series of buttons.

The procedures used to record the electrophysiological responses of the brain are standardized and have been used without incident in many previous investigations. The combination of tones and lights presented is experimental, but the recording procedure is not.

You may be asked to participate in an MRI scan of your brain. This procedure is not experimental and is done to create a map of the brain, by which the responses from the electrode cap can be overlaid.

Risks/Discomforts
There are very few potential risks from this procedure, and these risks are minimal. The risks of this study include possible allergic reactions to the liquid used in applying the electrodes. Allergic reactions to the liquid are extremely rare. There is also a possibility for an allergic reaction to the electrodes. If any of these reactions occur, a rash would appear.

Treatment would include removing the electrodes and liquid and exposing the site to air, resulting in removal of the irritation. If there is an allergic reaction, testing procedures would be discontinued. Another unlikely risk is a small abrasion on the scalp when the blunt needle is used to place electrode gel. Treatment would also include removing the electrode and gel, exposing the site to air and testing procedures would be discontinued.

Risks associated with the MRI procedure are few and minimal as there is no x-ray exposure from MRI. Participants who participate in MRI will be required to be free of any metallic materials (e.g., artificial joints, metallic bone plates, heart pace maker, insulin pumps) as the magnets from the MRI may disrupt any metal materials. A claustrophobic sensation is a possible adverse side effect due to the closed area inside the machine that the participant must lie in. If at any time during the scan the claustrophobic sensation becomes too great, notify the nearby MRI staff and they will immediately end the scan.

Benefits
You will receive a copy of your hearing assessment at no charge. You will be notified if any indications of hearing loss are found in this area. The information from the study may help further the understanding of sensory integration, which will be beneficial to professionals in the corresponding field.

Confidentiality
All information obtained from testing is confidential and is protected under the laws governing privacy. All identifying references will be removed and replaced by control numbers. Data collected in this study will be stored in a secured area accessible only to personnel associated with the study. Data will be reported without individual identifying information.

Compensation
You will be given $10 compensation at the completion of this portion of the study; you will receive this compensation whether or not you complete the study in its entirety.

Participation
Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without affecting your standing with the University.

Questions about the Research
If there are any further questions or concerns regarding this study, you may ask the investigator or contact David McPherson, Ph.D., Communication Science and Disorders, at (801) 422-6458; Taylor Building Room 129, Brigham Young University, Provo, Utah 84602; e-mail: david_mcpherson@byu.edu.

Questions about your Rights as a Research Participant
If you have questions regarding your rights as a research participant, you may contact the BYU IRB Administrator at (801) 422-1461; A-285 ASB, Brigham Young University, Provo, UT 84602; e-mail: irb@byu.edu.

Other Considerations
There are no charges incurred by you for participation in this study. There is no treatment or intervention involved in this study.

The procedures listed above have been explained to me by: ______________________________ in a satisfactory manner and any questions relation to such risks have been answered.

I understand what is involved in participating in this research study. My questions have been answered and I have been offered a copy of this form for my records. I understand that I may withdraw from participating at any time. I agree to participate in this study.

Printed Name:___________________________

Signature:______________________________

Date:_________________________________