FACTOR ANALYSIS OF LATERALIZED AUDITORY

PERCEPTUAL RESOURCES

by

ERIC T. GREENLEE

DAVID B. BOLES, COMMITTEE CHAIR
MARCUS E. BROWN
EDWARD C. MERRILL
PATRICIA A. PARMELEE
BEVERLY ROSKOS

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Psychology
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2015

Abstract

The primary goal of this study was to identify independent, hemispherically lateralized auditory perceptual resources so that they could be used to expand the Multiple Resources Questionnaire (MRQ), an existing measure that assesses the demands that a task places upon multiple resources (Boles & Adair, 2001a). Researchers have demonstrated that the MRQ's subjective ratings of resource demand can be used to predict multi-task interference, and the measure has demonstrated advantages over other subjective measures of task demand (for review Boles & Dillard, in press). Yet, of the 13 perceptual resources represented by the MRQ, only two are auditory. This shortage of auditory resources in the MRQ prevents the accurate measurement of tasks presented within the auditory modality, and the diagnosticity of the MRQ would likely benefit from the addition of items representing auditory resources (Finomore et al., 2008).

The methods used to identify auditory resources in the present study were the same as those used to identify the bulk of the resources that are currently represented within the MRQ. A comprehensive survey of auditory perceptual research was conducted to identify the types of processing and tasks that appear to demand hemispherically lateralized perceptual resources. Based on this literature review, 13 tasks were selected for use in the current study. These tasks were administered as a test battery to 124 right-handed, nonmusicians. All significant, reliable performance asymmetries produced by these tasks were factor analyzed in order to identify underlying perceptual resources.

Exploratory factor analysis revealed evidence for a novel right-lateralized Auditory Spectral Pitch resource which is specialized for processing and perceiving pitch based on the harmonic content in complex sounds. Results also indicated the possible existence of a right-lateralized Auditory Intensity resource, which is specialized for the processing of perceived intensity (i.e. loudness). However, the existence and independence of this Auditory Resource is suggested cautiously, since the data used to infer the resource was relatively unreliable. Additionally, two previously identified resources were evident in the current results: the Auditory Linguistic and Visual Temporal resources. The theoretical implications and human factors applications of these findings are discussed.

List of Abbreviations and Symbols

AST   Asymmetrical Sampling in Time

dBA   'A' weighted decibels, a measure of perceived sound intensity

δ Delta: Parameter that controls the amount of obliqueness in factor analytic solutions

DL   Dichotic Listening

ERP   Event-Related Potential

FA   Factor Analysis

fMRI   Functional Magnetic Resonance Imaging

Hz   Unit of frequency: Cycles per second

ISI   Inter-Stimulus Interval, time between reference and comparison stimuli

ITD   Inter-aural time difference, the onset asynchrony between left and right ears

LC   Lateralization Coefficient: A measure of hemispheric asymmetry

LEA   Left-Ear Advantage

LH   Left Hemisphere

MEG   Magnetoencephalography

MRQ   Multiple Resources Questionnaire

ms   Milliseconds

N Sample size

p Probability of obtaining a test statistic as extreme as the observed value due to chance

r Pearson's correlation coefficient

r_{sb} Spearman-Brown corrected reliability estimate

RT   Reaction Time

REA   Right-Ear Advantage

RH   Right Hemisphere

SD   Standard deviation of the mean

t   Student's *t* test statistic

=   Equal to

\>   Greater than

<   Less than

Contents

List of Tables

List of Figures

Introduction

The performance of any task – mental or physical – requires engagement of neurocognitive resources. Mechanistically, resources are generally described as functional, limited capacity processors that are necessary for perception, cognition, and ultimately, task performance (Boles & Dillard, in press; Wickens, 1984). The limited capacity of a resource governs how much work may be accomplished simultaneously; and increased demand upon a resource reduces performance. Multiple resources have been identified (Boles, 1991, 1992, 1996, 1998b); and performance impairment has been demonstrated when tasks demand a great deal of processing by the same resource(s) rather than spreading demand among different resources (Boles, Bursk, Phillips, & Perdelwitz, 2007; Boles & Law, 1998). Thus, identification of independent resources allows the prediction of task performance. Such prediction would be valuable in military and industrial environments where maximization of task performance could be achieved by designing tasks predicted to minimize the demand placed upon any given resource. However, the utility of resource models is governed by comprehensiveness. Processing demand upon unidentified resources could introduce unforeseen detriments to task performance; therefore, comprehensive identification of resources is needed to maximize the utility of multiple resource models.

In order to provide a comprehensive resource view, the proposed study aims to expand upon an existing model of multiple resources that was created using factor analyses (Boles, 1991, 1992, 1996, 1998b). These factor analyses revealed a list of multiple independent resources; which was then used to create the Multiple Resources Questionnaire (MRQ, see Appendix A),

a subjective measure of resource demand or workload (Boles & Adair, 2001a). The MRQ has demonstrated reliability (Boles & Adair, 2001b); and criterion validity (Boles, Phillips, Perdelwitz, & Bursk, 2004). As referenced previously, the MRQ displays predictive validity for estimates of task interference (Boles, Bursk, Phillips, & Perdelwitz, 2007); and these estimates are superior to those of some other measures of task workload, namely the Global Resource Questionnaire and the Workload Profile (Phillips & Boles, 2004). Additionally, the MRQ has been shown to be more sensitive to workload demands than the NASA- Task Load Index (NASA-TLX) in multi-tasking conditions (Finomore, Shaw, Warm, Matthews, & Boles, 2013).

While the MRQ provides an index of demand across multiple resources, most of the included resources are visual in nature. Indeed, of the MRQ's 13 perceptual resources, ten are visual, and only two are auditory. This shortage of auditory resources in the MRQ prevents the accurate measurement of tasks presented within the auditory modality, and the diagnosticity of the MRQ would likely benefit from the addition of items representing auditory resources (Finomore et al., 2008). This is the purpose of the current study – to identify independent auditory resources that may then be added to the MRQ.

Factor Analysis of Asymmetric Resources

The identification of independent auditory resources was accomplished using methods that mirror those used by David Boles in his original factor analytic studies (Boles, 1991, 1992, 1996, 1998b; see also Boles & Pasquarette, 1996). In these studies, participants were presented with a battery of tasks that had reliable histories of asymmetry – meaning that performance is superior for one perceptual hemifield, compared to the other.

Behavioral asymmetry is explained by the fact that information from each sensory hemifield is processed predominantly by the contralateral hemisphere of the cortex, so a

behavioral hemifield advantage (e.g. faster RT) indicates that the resource required for the behavior is lateralized towards the contralateral hemisphere (Kimura, 2011 for a brief review). For example, a right hemifield behavioral advantage for syllable processing would suggest that the resource required for syllable processing is lateralized towards the left hemisphere.

Boles (1991, 1992, 1996, 1998b) factor analyzed the resulting behavioral asymmetries (e.g. a reaction speed advantage for the right visual field) for all tasks that demonstrated asymmetry. This method measured the relationships among all tasks within the battery, and determined which tasks loaded on independent factors. Each of the resulting factors was considered representative of a resource (e.g. visual temporal); and some of the resources were represented by multiple tasks.

Yet, the tasks used in these initial studies were primarily visual (Boles, 1991, 1992, 1996). Thus, the resulting resources that emerged from factor analysis were themselves primarily visual. However, similar to the previously examined visual tasks, performance and cortical asymmetries vary for multiple auditory tasks. It is reasonable to predict that there are also multiple orthogonal resources within the auditory domain, and that factor analysis would permit identification of these resources required for auditory processing.

The first step towards testing this prediction is the identification of behavioral tasks that recruit lateralized auditory resources and result in reliable performance asymmetries. Candidate processes were be drawn from previous investigations of hemispheric asymmetry within auditory perception. What follows is a brief, but comprehensive summary of these previous investigations of auditory laterality. All domains of auditory asymmetry are discussed.

Asymmetric Audition: A Literature Review

Verbal processing.

Linguistic. Research has provided a wealth of converging neurological and behavioral evidence for the left hemisphere lateralization of language processes. Early neurophysiological examinations of aphasic patients revealed that the loss of language was most typically associated with damage to the left hemisphere of the brain, as opposed to the right (see Farah & Feinberg, 2000 for review). Behavioral asymmetries, indicative of leftward lateralization of language, have been reliably observed using dichotic listening paradigms. In her pioneering work, Doreen Kimura (1961) used dichotic listening paradigms to demonstrate that when a different word is presented simultaneously to both ears, listeners are more likely to correctly report the word delivered to the right ear. Additionally, listeners often report stimuli presented to the right ear before reporting stimuli presented to the left ear (Boles, 1992; Kimura, 1961). These right ear advantages (REAs) for accuracy and report order are behavioral evidence that the contralateral hemisphere, the left hemisphere, is better able to process linguistic stimuli.

Boles (1996) found that a common resource underlies a right-ear advantage (REA) on a traditional dichotic words task (described above) and a dichotic syllables task. Dichotic words tasks likely require lexical processing (Boles 1991, 1992); yet, the common resource is labeled broadly as linguistic, because it also supports the phonetic processing of syllables.

Prosody. Prosody is another aspect of language that has shown evidence of behavioral asymmetry, but the reported asymmetries are inconsistent, unreliable, and even reversible (Blumstein & Cooper, 1974; Shipley-Brown, Dingwall, & Berlin, 1988; Zurif, 1974; see also Baum & Pell, 1999 for review). The qualities of prosody may predispose investigations to muddled and inconsistent results for a couple of reasons. First, prosody is a broad term that

encompasses multiple processes including linguistic and affective prosody, which are typically lateralized to differing degrees (Shipley-Brown, Dingwall, Berlin, Yeni-Komshian, & Gordon-Salant, 1988). Second, the perception of prosody appears to require multiple processes including discrimination of pitch, intensity, and temporal variables. Because of its nebulous nature, perception of prosody likely requires multiple resources, so interpretation of overall prosodic asymmetry in terms of localized resources is likely to yield mixed results.

However, the MRQ already contains an Auditory Emotional resource that was inferred based on results from an emotional prosody task. So, it is important to consider the direction of asymmetry that is most often found when tasks depend on the processing of emotional prosody.

Emotional prosody. Research has shown that the emotionality of auditory stimuli is predominantly processed within the right cerebral hemisphere. Evidence for this asymmetry has been provided by behavioral methods demonstrating a left-ear advantage (LEA) for accuracy of emotional identification (Boles, 1996; Bryden, Ley, & Sugarman, 1982; Erhan, Borod, Tenke, & Bruder, 1998; King & Kimura, 1972). Likewise, psychophysiological measures also indicate a right hemisphere neurological mechanism for processing auditory emotionality (Erhan, et al., 1998). The tasks used in such emotional prosody studies are typically dichotic listening procedures that require that vocal or tonal sounds be categorized based on the emotional quality of the stimuli.

Temporal processing. Processing of temporal information also appears to be lateralized towards the left hemisphere, as demonstrated by a broad range of behavioral tasks requiring perception of temporal duration, sequence, rhythm and other elements of auditory timing (see Nicholls, 1996 for review). Interestingly, a review of this literature reveals an apparent overlap between the lateralization of speech processing and the lateralization of temporal acoustic

processing; and experimental explorations of verbal-temporal relationships have indicated that the left hemisphere's superiority for verbal processing may be due, in part, to superiority for fine temporal discrimination.

For example, Pascal Belin and colleagues (1998) presented participants with unpronounceable, nonverbal auditory stimuli that were designed to mimic the temporal structure of consonant-vowel-consonant syllables, and the rate of formant transitions was manipulated. Formant transitions were either rapid 40 ms shifts that are most like the temporal characteristics of speech (Minifie, 1973), or they were slow 200 ms shifts. Positron emission tomography (PET) revealed bilateral processing symmetry for the stimuli consisting of slow formant transitions. In contrast, left hemisphere activation was greater during the processing of stimuli with rapid formant transitions. Reduced right hemisphere processing appears to account for the relative superiority of the left hemisphere for processing rapid formant transitions. The authors argue that the left hemisphere specialization for speech may have emerged from an earlier lateralized process necessary for detecting rapid changes in auditory stimuli (Belin, Zilbovicius et al., 1998); and this supports a previous evolutionary argument (Tallal, 1994).

Duration. Left hemisphere specialization for rapid acoustic information has also been demonstrated behaviorally. For example, Mills and Rollman (1979) presented participants with two tasks designed to examine perceptual asymmetries for the processing of auditory duration. For the first task, participants listened to monaural sequences of auditory clicks in which the duration of inter-click interval varied between sequences. Participants responded at the end of the sequence by pressing a key and their reaction times were recorded. Reaction times revealed a right-ear advantage (REA) when the inter-click interval was 50 ms or less, but no other asymmetries were observed. The second task presented participants with a brief binaural pulse

train. Each train consisted of 1ms clicks that were repeated every 20 ms for the duration of the train. After binaural presentation, a comparison train was presented to either the right or the left ear, and participants were tasked with determining whether the second, comparison stimulus was longer, shorter, or the same duration as the initial binaural stimulus. Participants showed a right-ear advantage (REA) for accuracy only when the comparison stimulus duration was greater than the initial binaural stimulus by 50 ms or less; demonstrating that the left hemisphere likely houses a specialized resource for the perception and discrimination of fine, rapid temporal information.

Left hemisphere laterality for duration discrimination has also been shown using a match-to-sample paradigm comparing the temporal processing of speech sounds to music tones (Brancucci, Anselmo, Martello, Tommasi, 2008). On each trial a reference stimulus was presented monaurally, followed to the same ear by a second, comparison stimulus; and participants were tasked with deciding whether the duration of the two stimuli were the same or different. A right-ear advantage (REA) was revealed, which is particularly interesting, because the differences in stimulus duration used in this study were quite large (150ms-350ms), well beyond the 50ms window critical for verbal perception. Brancucci and colleagues (2008) argue, generally, that the left hemisphere is specialized for temporal processing.

Others have made similar arguments for left hemisphere superiority for temporal processing, suggesting that it is dichotomously paired with right hemisphere superiority for spectral information (Zatorre, Belin, & Penhume, 2002). Yet, these arguments note that the left hemisphere superiority is a specialization for rapid, narrow temporal windows of about 20-50 ms. Others have gone further to suggest that the right hemisphere is actually specialized for long temporal windows of 150-250 ms (Poeppel, 2003). In short, many seem to agree on the left

7

hemisphere superiority for rapid temporal processing, but there is not a consensus on exact role of the right hemisphere in temporal processing. The lateralization of a resource for long, slow-changing temporal information is also unclear.

Results of previously mentioned studies have shown that the processing of long, slowly transitioning auditory stimuli is behaviorally and physiologically symmetrical (Belin et al., 1998, Mills & Rollman, 1979). Yet, other psychophysiological studies have shown increased right hemisphere activity for the temporal processing of these long, slowly changing auditory stimuli (Boemio, Fromm, Braun, & Poeppel, 2005). If accurate, this finding allows for a functional contrast between auditory temporal functions of the left and right hemispheres. Such a contrast implies that the resources used for short and long temporal windows differ. This model was considered when selecting temporal tasks for the current factor analytic research to facilitate comparisons between behavioral lateralization for short and long temporal windows.

Sequence and rhythm. The left hemisphere's specialty for rapid temporal processing has been shown to include recognition of auditory rhythm (Halperin, Nachshon, & Carmon, 1973; Papcun, Krashen, Terbeek, Remington, & Harshman, 1974, Robinson & Solomon, 1974); and reproduction of auditory sequence (Halperin, Nachson, & Carmon, 1973; Papcun, Krashen, Terbeck, Remmington, & Harshman, 1974).

Using a delayed match-to-sample paradigm, Michael Natale (1977) demonstrated a right-ear/left-hemisphere advantage for the accurate recognition of rhythmic sequences of a simple tone; and this right-ear advantage (REA) was maximized when rhythms were complex rather than simple. Similarly, reproduction accuracy for tonal sequences is more accurate when tones are initially presented to the right ear during dichotic listening; and this right-ear advantage (REA) is also maximized when the complexity of the sequence is increased (Halperin, Nachson,

8

& Carmon, 1973). These results indicate the resource(s) necessary to process rhythm are left lateralized.

Intensity processing. There is little research investigating asymmetries for the processing of auditory intensity, yet extant behavioral and physiological findings suggest that the right hemisphere is predisposed to more readily and accurately process auditory intensity (Belin, McAdams et al., 1998; Brancucci, Babiloni, Rossini, & Romani, 2005).

Brancucci and colleagues (2005) used a match-to-sample paradigm in a task based on speech sounds and a task based on tonal sounds. In both tasks participants were presented with a monaural reference stimulus with an intensity of 60, 70, or 80 dBA. A comparison stimulus was then presented to the same ear as part of a dichotic pair. The comparison stimulus was presented with an intensity of 60, 70, or 80 dBA, while a mask stimulus was presented simultaneously to the opposite ear with a constant intensity of 70 dBA. Participants were asked to judge whether the reference and comparison tones were of equivalent or different intensities. Results showed a left-ear advantage (LEA) for both accuracy and reaction times, indicating a right hemisphere lateralization for the discrimination of auditory intensity.

Pitch processing. For the perception of auditory pitch, research has provided extensive evidence for the importance of the right hemisphere. Specifically, during complex pitch processing, portions of Heschl's gyrus and the surrounding cortical tissue are more active than the homologous structures in the left hemisphere (Zatorre, 2000 for review). Much of the evidence for this asymmetry has been neurophysiological. Studies of patients with unilateral cortical lesions support the critical role of the right hemisphere in pitch processing (Sidtis & Volpe, 1988), as do neurophysiological studies of normal human brains (Wioland, Rudolf, Metz-Lutz, Mutschler, & Marescaux, 1999; Zatorre, Evans, & Meyer, 1994).

9

Behavioral evidence for a rightward hemispheric asymmetry has also been observed. The Complex Tone Test presents participants with a pair of dichotically presented complex tones followed by a binaural complex tone (Sidtis, 1980, 1981). Each member of the dichotic tone pair is presented with a different pitch, and participants are asked to decide whether the binaural tone matches either of the dichotic tones. Reaction time and accuracy data from this test indicated that there is a left-ear advantage (LEA) for the discrimination of complex tones. This left ear advantage increases as the frequency difference between the two dichotic tones is decreased. Sidtis (1981) argues that the neurological resources required for this task are asymmetrically distributed to the right hemisphere; and the greater the spectral overlap between the two tones, the greater the competition for right hemisphere resources. Increased competition for right hemisphere resources results in an increased advantage of the contralateral ear, hence the left-ear advantage (LEA).

Using the Complex Tone Test, Tenke, Bruder, Towey, Leite and Sidtis (1993) found that a behavioral left-ear advantage (LEA) correlated with increased rightward asymmetry of parietal and occipital event-related potentials (ERPs). Further, right hemisphere physiological laterality was evident only in individuals with significant behavioral left-ear advantage (LEA) – approximately 70% of the mostly right handed sample. Participants who did not demonstrate behavioral asymmetries for pitch discrimination also did not show any physiological asymmetry.

In a similar study, an oddball paradigm was employed in conjunction with magnetoencephalography (MEG) recording (Mathiak, Hertrich, Lutzenberger, & Ackermann, 2002). Tonal oddballs resulted in the increased bilateral physiological responses and faster contralateral onsets when presented to the left ear, compared to the right. Additionally,

responses were significantly faster and more accurate when oddballs were presented to the left ear.

Timbre processing. The American Standards Association (as cited in Moore, 1997, p. 246) describes timbre as "that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar." More concretely, timbre accounts for our ability to discriminate the sounds made by different musical instruments playing the same note with the same intensity.

Perception and discrimination of timbre seems to be based upon many tonal components including features of pitch, duration, and intensity. Examinations of asymmetries in timbre processing have identified two major classes of acoustic attributes that contribute to timbral perception: A *Temporal Component*, determined by intensity or frequency fluctuations within a tone across time (rise, fall, and fluctuations); and A *Steady-State Component*, determined by the constant, relative intensity contained within each of the tone's harmonics and the number of harmonics (Brancucci & San Martini, 1999; Samson, Zatorre, & Ramsay, 1997).

Several studies have created artificial tones in order to independently manipulate these two classes of timbral features and to circumvent verbal labeling of natural musical tones. Results from these studies using artificial tones indicate that processing both the steady state components and the fluctuating intensity components of timbre are lateralized towards the right hemisphere (Brancucci & San Martini, 1999, 2003; Samson & Zatorre, 1994; San Martini, Filetti, Marangon, & Tasin, 1994).

Neurophysiological evidence also indicates that timbral processing is lateralized towards the right hemisphere. Samson and Zatorre (1994) selectively manipulated the steady-state harmonic composition of tones in one task, and manipulated the temporal components of tone

11

intensity in another. They found that individuals with lesions to the right temporal cortex were less able to discriminate tonal timbre in either task, compared to individuals with left temporal lesions or control subjects.

Similarly, Brancucci and San Martini (1999, 2003) have shown behavioral evidence of right hemisphere superiority for timbral discrimination based upon the fluctuation of tone intensity. A monaural match-to-sample method was used in both studies. This method required that participants determine whether a comparison tone matched a preceding target tone. Tones varied by rise and decay times, as well as the rate of intensity fluctuation. A left-ear advantage (LEA) was evident for reaction times in both studies and for accuracy in the initial study.

The authors argue that rapid temporal variations in intensity that are characteristic of tone timbre introduce inharmonic qualities into the perception of frequency (Brancucci & San Martini, 2003). So, the processing of rapid temporal changes in intensity may be processed in the frequency domain rather than the temporal domain. They tested this hypothesis by adding tones with slowly changing intensities, and lateralization of these slowly fluctuating tones was compared to that of the previously described rapid fluctuating tones. Slow intensity fluctuations were expected to reduce or reverse the left-ear advantage (LEA) seen with rapid fluctuations, because only rapid fluctuations should create the perception of inharmonic spectral qualities. However, a left-ear advantage (LEA) remained even when the rate of intensity fluctuation was made slower than would be relevant to timbral quality (Brancucci & San Martini, 2003). The authors acknowledge that the role of the right hemisphere in intensity discrimination may be responsible for the rightward lateralization of both tasks.

Factor analytic methods can potentially address the ambiguous results of these studies. If the tasks used by Brancucci and San Martini (2003) are examined alongside tasks that selectively

and separately tap intensity discrimination and temporal discrimination, a factor analysis of perceptual laterality should reveal whether common resources are required to discriminate slowly fluctuating or rapidly fluctuating intensities.

Critically, the perception of timbre for naturally produced tones involves processing of both these temporal-intensity cues, as well as steady state harmonic information. Even if the two tasks used by Brancucci & San Martini (2003) are supported by a right lateralized intensity processor, it is possible that a separate resource is needed for the processing of the harmonic information; which has also been shown to be right lateralized (San Martini, et al., 1994).

Spatial processing. Extant literature on the neurology of auditory localization suggests that the right hemisphere contains resources that are qualitatively and quantitatively different from those represented by homologous left hemisphere structures. In summary, tasks requiring attention to space or localization within space typically result in neurological activity that is greater in the right hemisphere (Zatorre, Mondor, & Evans, 1999); damage to the right hemisphere is typically more detrimental to auditory spatial processing than damage to the left hemisphere (Spierer, Bellmann-Thiran, Maeder, Murray, & Clark, 2009); and localization accuracy in auditory free-field studies indicates a right hemisphere advantage (Butler, 1994; Ivarsson, De Ribaupierre & De Ribaupierre, 1980). Behavioral studies of localization are generally limited to such free-field methodologies.

Exceptions include studies that use head-related transfer functions (HRTFs) to create the illusion of auditory space. Head-related transfer functions can be used to filter digital sound in the same way that the head, shoulders, and pinnae of the ear filter natural sound; and this filtered sound can be presented via headphones to create virtual auditory space. Use of these methods has revealed that the discrimination of auditory motion direction is superior for the left

hemispace (Hirnstein, Hausmann, & Lewald, 2006). Like the previously mentioned research, this may indicate that the right hemisphere contains the dominant resources for auditory spatial processing. However, this study used artificially derived head-related transfer functions; meaning that the digital filters were based upon recordings of natural sounds measured using microphones contained within a mannequin bust.

It may seem strange to criticize a method of artificial measurement when the end goal is artificial sound space, but individual differences in head and ear shape result in differences in head-related transfer functions. Using nonindividualized head-related transfer functions could prohibit accurate measurement of hemispheric asymmetry. Any behavioral asymmetry could arguably be due to physical asymmetries of the head and ears, rather than asymmetry of the brain. Further, these nonindividualized head related transfer functions have been shown to result in inaccurate localization performance – at least prior to training – which is subject to large inter-subject variability (Mendonça et al., 2012; Middlebrooks, 1999). Direct comparisons of auditory motion perception also demonstrate that use of nonindividualized head-related transfer functions results in reduced neural responding and a reduced tendency to perceive sounds as externally located, compared to free-field stimuli (Getzmann & Lewald, 2010).

Individualized measurement of head-related transfer functions is possible; but like free field experimentation, this requires specialized equipment and facilities. Measurement of head-related transfer functions requires external speakers as well as small microphones that are placed within the ear (Middlebrooks, 1999). Free field stimulation requires multiple external speaker arrays in which speakers are generally concealed. Both of these methods also require anechoic testing space to ensure the spatial fidelity of presented stimuli. Unfortunately, I lacked the

apparatus necessary for these spatial methodologies, so the current study did not include spatial tasks.

Proposed Study

      Human factors application. As mentioned previously, the primary goal of this study was to identify orthogonal auditory resources so that they could be used to expand the Multiple Resources Questionnaire (MRQ), an existing measure of task workload (Boles & Adair, 2001a). This expansion would be useful in human factors research. For example, one vein of research within human factors psychology emphasizes the importance of thoughtful workstation and display design in order to maximize the accuracy and efficiency of human operators. In recent years, there has been a movement towards multimodal displays in which both visual and auditory information streams convey critical, task-relevant information. This research on multimodal displays has shown improved performance when task information is divided among modalities, rather than presented only to the visual system (e.g. Garcia, Finomore, Burnett, Baldwin, & Brill, 2012).

      These findings are unsurprising given that the separation of visual and auditory resources has long been a central theme of resource theory (Wickens, 2008 for review). However, resources are not only divided between perceptual modalities. Previous factor analyses have shown that multiple resources exist within a given modality (Boles, 1991, 1992, 1996). Within the visual domain, ratings of demand on these resources have been shown to be more predictive of dual-task performance than ratings of broad, modality-specific demand (Phillips & Boles, 2004). Previous studies have found that perceptual asymmetry varies depending on the type of auditory task. This suggests that there are multiple independent resources within the auditory

modality. If these resources were identified, they could likely be used to improve specificity and diagnosticity of workload measurement within the auditory modality.

If auditory information is to be used within human workstations, it is important that the demands of these auditory tasks are well-understood. Therefore, the ultimate goal of the present project was to modify the Multiple Resources Questionnaire (MRQ) to produce a measure capable of predicting the demands of multimodal and auditory tasks.

To this end, a list of tasks was extracted from the literature – tasks that exemplify potential auditory resources and demonstrate reliable asymmetry. Resulting asymmetries were analyzed using an exploratory factor analysis to extract and identify auditory resources.

Theoretical implications. Although the primary goal of this project was the application-oriented expansion of the MRQ's resource list, this study was also designed to clarify theoretical uncertainties about the lateralization and relationships of resources indicated by previous research. The review above describes several aspects of auditory perception that are reliably asymmetric (e.g. temporal processing, pitch processing, and verbal processing). Taken together, these findings suggest that there are multiple lateralized resources important to auditory perception and performance. Further, previous research provides grounds for predictions about the identities and relationships of these independent resources. The current study was proposed with the intention of assessing existing theoretical models of auditory perceptual asymmetry using confirmatory factor analysis.

Few formal models have been specified to account for relationships between auditory asymmetries. However, the Asymmetrical Sampling in Time (AST) hypothesis appears to account for many findings within the neuroimaging literature, and tasks were selected in order to allow confirmatory modeling of the AST hypothesis. While the AST model is the only formal

16

theoretical model that comprehensively describes the relationship between functional

asymmetries in auditory perception, two additional hypothetical models were also designed

based on the reviewed literature. These three models – described and considered in detail below

– were proposed to be tested using confirmatory factor analyses of the perceptual asymmetries

derived from the battery of tasks.

AST model: Three factor model. This model consists of three factors, each representing

a different lateralized perceptual resource. These three resources include a Fast Resource, a

Slow Resource, and an Intensity Resource; each is described in turn below.

The asymmetrical sampling in time (AST) hypothesis suggests that the left and right

cerebral hemispheres are predisposed for processing of fast and slow changing information,

respectively (Poeppel, 2003). Based primarily on neuroimaging and lesion literature, Poeppel

(2003) argues that the left hemisphere is better able to process acoustic information that must be

integrated within a very narrow time frame (20-40ms). This asymmetry, he suggests, explains

the superiority for the processing of verbal information due to the rapidity of formant transitions

in speech; and high pitches (> 2000Hz) are also proposed to be better processed within the left

hemisphere. Thus, the first factor in this three-factor model would be a left-lateralized Fast

Resource.

The second factor would be a right-lateralized Slow Resource, which is proposed to be

responsible for the processing of information which changes relatively slowly. Rightward

lateralization of emotional prosody was explained by the fact that the critical information for

identifying voiced emotion is slow-changing. This model also predicts that slowly changing

temporal information should be right lateralized, and rightward lateralization of low pitch

processing is also explained by this model.

No specific predictions were made for timbre or loudness in terms of their fit within the AST hypothesis. However, timbre is determined, in part, by spectral and temporal information. So, the inconsistency in lateralization of timbre perception could be due to irregularities in the speed of the critical information contained for discriminating these sounds. If the discriminating feature exists within a narrow window of time (e.g. a very high carrier frequency, or rapid onset); a left hemisphere superiority would be expected (i.e. the Fast Resource would be responsible). If timbre of two tones were discriminable based on a slow-changing, broad temporal window, the right hemisphere should be superior (i.e. the Slow Resource would be responsible).

The third and final factor in this model would represent an Intensity Resource for the processing of intensity information, such as auditory loudness. Asymmetries for loudness are not addressed within the asymmetrical sampling in time (AST) hypothesis, since loudness is a function of amplitude, independent of time.

However, this model also has weaknesses. First, behavioral research has often failed to show any lateralization for slow temporal information (e.g. Belin et al., 1998, Mills & Rollman, 1979); and in some cases, a leftward asymmetry is shown even for information that matches Poeppel's (2003) characterization of long temporal windows (e.g. Brancucci et al., 2008). Additionally, multiple studies have examined the laterality of pitch discrimination for varying frequencies; and the right hemisphere advantage for pitch discrimination seems consistent, regardless of the frequency range.

Studies have shown that the right-hemisphere advantage is more robust when the tones are complex rather than simple – meaning that a tone containing multiple harmonic pure tones produces more asymmetric responses than a pure sinusoidal tone (Sidtis, 1980). Further, the right hemisphere advantage is also amplified when dichotically presented tones are similar in

pitch (Divenyi, Efron, & Yund, 1977; Sidtis, 1981). As the masking tone is made lower or higher than the contralateral target tone, the ear advantage is reduced. Divenyi, Efron, and Yund (1977) demonstrated this effect with masking tones ranging from 378 Hz to 4580 Hz, and the reduced left ear advantage (LEA) appears to be due to the frequency separation between the masking tone and the contralateral target tone (1650 Hz or 1750 Hz in this case). There was no apparent effect of the frequency beyond this interference effect.

If the left hemisphere contained a separable resource for high pitched information as Poeppel (2003) suggests, a reduction in dichotic interference should be observed when a masking tone is above the 2000 Hz threshold and the target tone is below 2000 Hz. However, the asymmetric sampling in time (AST) hypothesis cannot account for reduced interference between two low frequency sounds, especially when this effect is considered in comparison to the reduced interference that occurs when sounds are target and masking tones are on separate sides of the 2000 Hz boundary specified by the AST. Since the model defined by the AST hypothesis is unable to account for previous research findings, alternate, hypothetical models were considered in hopes that they could better explain the perceptual asymmetries derived from the current battery of tasks.

A perceptual feature model: Six factor model. The second proposed model consisted of six orthogonal factors, each representing a different resource which is specialized for the processing of a single perceptual feature of sound (e.g. timbre, verbal content) – meaning that all of the lateralized processes discussed above in the literature review are modeled as if driven by independent perceptual resources, separate factors. These six feature-specific resources were defined as follows: Verbal Resource, Emotional Resource, Temporal Resource, Intensity Resource, Pitch Resource, and Timbre Resource.

19

This model is purely hypothetical, and is derived from literature review, rather than any formal theory. Statistical support for this model was not considered likely; in part, because previous research has indicated an overlap between the processing of verbal content and acoustic timing. Moreover, perception of timbre has been shown to be dependent upon the spectral content, timing and intensity of sound (Brancucci & San Martini, 1999, 2003: Samson, Zatorre, & Ramsay, 1997).

A physical feature model: Four factor model. This model was proposed as four factors, each representing a different resource: Fast Temporal/Verbal Resource, Slow Temporal Resource, Pitch Resource, and an Intensity Resource.

This four-factor model is similar to the previously described model in that it is based on literature review, rather than a formal theory; however this model was designed to account evidence indicating that tasks requiring the processing of perceptually distinct features of sound (e.g. a timbre discrimination task and a pitch discrimination task), may actually be facilitated by the same underlying resource(s). This model essentially merges a Verbal Resource with the Fast Temporal Resource, because evidence points towards an overlap in temporal processing (of rapid information) and verbal processing, which is thought to be dependent on processing changes in spoken stimuli that occur very quickly. Verbal processing is left lateralized, as is temporal processing is left lateralized when the critical information is rapid (50ms or less); whereas processing of slow temporal information often results in no asymmetry (e.g. Zatorre, Belin, & Penhume, 2002), and occasionally a right hemisphere asymmetry (Boemio, Fromm, Braun, & Poeppel, 2005). So, temporal processing for rapid information may use the same resource as the processing of verbal information, hence the proposal of the Fast Temporal/Verbal Resource.

However, processing of slowly changing temporal information is likely served by a separate resource, here dubbed the Slow Temporal Resource.

As with the previous model, the Pitch Resource is proposed to stand alone, orthogonal from the other resources and right lateralized. Auditory intensity also appears to be processed by a separate right-lateralized resource. Though few studies have reported on the asymmetry of intensity processing, there has been no evidence tying the lateralization of intensity to other aspects of acoustic processing; thus the independent Intensity Resource.

Of the perceptual features defining the previous, six-factor model, the lateralization and resources responsible for auditory emotional processing and timbre processing are the most uncertain due to conflicting and inconsistent results. This proposed model was designed to test the possibility that both are composites of processing by multiple independent resources. Perceptual research suggests that the processing of spectral pitch, intensity, and timing are critical for the perception of both timbre (Grey, 1977; Lakatos, 2000; Samson, Zatorre, & Ramsay, 1997); and auditory affect (Baum & Pell, 1999 for review). Therefore, asymmetries in perception of either timbre or emotion are likely to depend upon processing by spectral, temporal, and intensity resources. Therefore, tasks that have been previously described as perceptually timbral or emotional were to be specified as observed variables for all four of the factors in this model.

Method

Participants

Sample and demographics. Participants were 129 right handed students (29 males, 100 females; M_{age} = 18.22 years) recruited from recruited introductory psychology courses at the University of Alabama. Students participated in exchange for credit towards a course research requirement.

Restrictions. Participants were required to have normal or corrected vision, and normal hearing. Hearing ability was tested with a standard tonal hearing test, prior to engagement in experimental tasks. Self-reports of normal or corrected-to-normal vision were accepted. Individuals who did not meet normal criteria in either modality were excluded from the study. Following completion of the task battery, participants were also asked whether they had a head cold or congestion. If so, their data were to be excluded, because such a condition could affect hearing.

Previous research has shown that functional hemispheric asymmetries are affected by handedness (Peters, 1995 for review). Consequently, participants were also required to be right handed. Right-handedness was verified by explicit self-report and by measurement with the Edinburgh Handedness Inventory (Oldfield, 1971).

In addition to the confounding effects of handedness and detection threshold asymmetries, the effects of perceptual expertise were also a concern. Previous research has shown that musicians, especially those with early and extensive training, possess superior performance in auditory perceptual tasks (e.g. Wilson, Lusher, Wan, Dudgeon, & Reutens,

2009), which is not necessarily a concern since the current study is based on within-subject correlations of asymmetrical performance, not between subject differences in performance. However, previous research also indicates that highly trained musicians display altered patterns of brain activity and hemispheric asymmetry, compared to nonmusicians (Morais, Peretz, Gudanski, & Guiard, 1982; Vuust et al., 2005; Wilson et al., 2009; see Herholz & Zatorre, 2012 for review). For example, comparison of musicians and nonmusicians indicates that while pitch discrimination is typically right-lateralized in nonmusician samples, it typically recruits either bilateral or left hemisphere cerebral resources in musicians (e.g. Schlaug, Jancke, Huang, & Steinmetz, 1995).

Quantification of musical expertise was achieved using a self-report measure (see Appendix B). This measure assesses the quality and quantity of musical experience and is an excerpt from a measure that was designed, in part, to quantify the amount of experience and potential expertise with musical instruments (Greenlee, 2013). Participants were deemed musicians if they reported a history of formal musical training or regular (i.e. > 1 hour of practice per week) musical play in the last six months. Musicians' data were excluded from all statistical analyses because of the potential that they may have altered patterns of hemispheric asymmetry.

The self-report measure also assessed experience and expertise with video games, since previous research has shown that extensive video game experience can improve auditory perceptual performance (Greenlee & Boles, 2014). Video game expertise was not expected to affect lateralization, but was measured as a basic demographic variable. Less than three percent of the sample had notable video game experience as defined by Greenlee and Boles (2014), so this variable was not considered any further.

Materials, Apparatus and General Procedures

Participants were tested individually in a small room which contained the computer used for task presentation. The air conditioning system and computer equipment produced a constant level of background noise at a level of 40 dBA. This ambient noise measurement and all further reports of sound level are based on recordings using a Rion NA-27 Sound Level Meter, a 1/3 Octave Band Analyzer.

Unless otherwise specified, each task was computerized and displayed using a Dell personal computer and a 22 inch LCD monitor, and responses were recorded using a wired keyboard. During all tasks, participants were seated approximately 45 centimeters from the center of the screen. During all auditory tasks, this viewing distance was unrestrained, but participants were asked to maintain visual fixation on a white cross that was continuously displayed at the center of a gray screen. For all tasks that required keyboard responses, the keys to be used were aligned with the center of the screen and the participant's midline. Some tasks required that two keys be used to make same/different decisions. Participants were instructed to use their left index finger for one key, and their right index finger for the other. The hand assignments were balanced between participants. When a task required only a single key be used to respond, that key was the spacebar and participants were instructed to respond by pressing with their left and right index fingers simultaneously.

All auditory stimuli were presented at an intensity of 70 dBA unless otherwise stated. A sampling rate of 44,100 Hz and 16 bit amplitude resolution were used. Auditory stimuli were presented using Sennheiser HD 439 headphones. These headphones attenuated ambient noise by 20 dBA. Both ear cups were tested to ensure that the total sound levels produced by each ear cup were equal and that the frequency response curves were also equal. Here equivalence was

24

defined as a difference less than 1 dBA. In other words, both ear cups produced equal loudness at all frequencies that were used in the current study.

To further ensure that any observed behavioral asymmetries were not artifacts of asymmetries in headphone sound production, the orientation of headphones was balanced within participant (i.e. headphones were rotated in the middle of each task), and the starting orientation was balanced between participants (i.e. 50% of participants began with the headphones in the reversed orientation).

Testing Procedure

Once in the laboratory, participants were tested to verify normal hearing. The hearing test was a computerized, pure tone test which was used to establish each individual's threshold of detection at specific frequencies (250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, and 4000 Hz). Design of this hearing test was based upon established standards of audiometric assessment (ASHA, 1978). A determination of normal hearing was made when a participant's average threshold of detection across tested frequencies was no more than 10 dB above established normal thresholds, and when the threshold difference between ears was 5 dB or less. Similar requirements have been used in previous psychophysical and psychophysiological studies of auditory asymmetry in order to avoid the confounding effects that asymmetries in hearing thresholds could have for the measurement of perceptual asymmetries (e.g. Brancucci et al., 2005).

The task battery consisted of 13 tasks, and lasted approximately 2.5 hours. The testing was divided across two sessions, which occurred on separate days. The average time between sessions was approximately 6 days (Range = 1 to 25 days, SD = 5 days). The order of task administration was controlled using a balanced Latin square procedure. Due to variations in task

length, participants completed between 5 and 7 tasks in the first session and the remaining tasks were completed in the second session.

Following completion of the task battery, participants were given the expertise questionnaire and the Edinburgh handedness questionnaire. Participants who did not complete the second session were contacted and were given the opportunity to complete the two surveys remotely. All participants completed both measures.

Match-To-Sample Procedure. Many of the tasks were structured using similar match-to-sample procedures. While the specific parameters (e.g. timing) vary among these tasks, the general procedure is consistent. Participants were initially presented with a reference stimulus presented to one ear. Following a brief silence, a comparison stimulus was presented to the same ear that received the reference. Participants were tasked with determining whether the comparison stimulus matched the reference stimulus. Only one aspect of the reference and comparison stimuli were varied in each task (e.g. if pitch was varied, duration and amplitude would remained constant). Thus, discrimination between reference and comparison stimuli was based purely on the manipulated sound component and resulting performance asymmetries can be interpreted based on underlying perceptual asymmetries.

Task List

Verbal.

Dichotic Words (6 minutes). Based on Boles (1992). Participants were presented with ten lists of four pairs of dichotically presented words that were said aloud by a female voice presented at an average intensity of 70 dBA. This is a taped procedure that was recorded and first used by Doreen Kimura (1961). Participants were instructed to pay equal attention to both ears. After each list, participants listed as many words as they could recall in any order that they

26

chose. After all 10 lists have been played, headphones were reversed, and the lists were

replayed. Participant responses were documented by the experimenter using a prepared answer

sheet to document. The dependent variables for this task were accuracy and order of report.

Order of report was simply recorded as the ear that heard the stimulus that was first reported by

the participant on each trial.

Emotional.

Dichotic Emotions (10 minutes). Based on Boles (1996). Stimuli were short sentences

read aloud by a male voice in one of four affective tones: happy, bored, distressed, or angry.

Twenty-four pairs of dichotic sentences were presented so that the emotional tone differed at

each ear. The peak stimulus intensity was 70 dBA. Participants were instructed to pay equal

attention to both ears, and were tasked with determining the emotionality of both sentences. On

each trial, they indicated their responses by circling the two heard emotions on a prepared

response sheet. After completing all 24 trials, headphones were reversed and the procedure was

repeated. Responses made before headphone rotation were not visible to participants after

headphone rotation, in order to prevent any bias in responding. The dependent variable was

accuracy.

Temporal.

Visual Temporal Onsets (10 minutes). Based on Boles (1996). The computer screen

was invisibly segmented into four equal quadrants. Each trial began with a 750 ms presentation

of a central fixation cross, followed by a 100 ms blank inter-stimulus interval. On each trial, an

"O" was presented in each of the four quadrants with 2.4 degrees of eccentricity (measured to the

point on the "O"s nearest the center of the screen). Each "O" occupied approximately 0.4 x 0.5

degrees of visual angle. The relative order of the top and bottom "O"s varied from trial to trial

so that on each side of the screen the top "O" could appear slightly before or slightly after the bottom "O". The onset difference could be 50, 67, or 83 ms; which was varied from trial to trial. A centrally presented arrow indicated to which half of the screen the participant should respond. The participants decided whether the top or bottom "O" appeared first on the target side of the screen. The top and bottom "O"s were separated by one degree of visual angle at their nearest points. Participants were instructed to respond as quickly and accurately as possible, by pressing one of two keyboard keys. The dependent variables were reaction time and accuracy.

This task was included for comparison with auditory temporal tasks to determine whether visual temporal and auditory temporal tasks are accomplished by a singular resource, or by separate resources.

Duration Fast Verbal (12 minutes). Based on Brancucci et al., 2008. In this match-to-sample task, each trial began with a brief presentation of a verbal Consonant-Vowel reference stimulus (i.e. /ba/) which as paired with a simultaneous verbal mask (i.e. /pa/) to the opposite ear. The reference stimulus could last 300, 320, or 350 ms, and the masking stimulus lasted 700 ms. After an 800 ms inter-stimulus interval (ISI), a Consonant-Vowel stimulus was presented to the same ear as the reference stimulus, which was again paired with a contralateral mask stimulus. The task was to determine whether the duration of the reference stimulus was the same or different than the duration of the comparison stimulus. The comparison and reference stimuli were the same duration on half of the trials. The participant responded by pressing one of two keys which were vertically aligned with the participant's midline. Participants were instructed to respond as quickly and accurately as possible. The dependent variables for this task were accuracy and reaction time.

Participants completed 96 trials which were separated into 16 blocks of 6 trials. Within each block the reference and comparison stimuli were always presented to the same ear (right or left). Between each block a high pitched (2000 Hz) pure tone was played in the ear that would receive the reference and comparison stimuli in the following block. Participants were instructed to pay attention only to the ear that heard the high pitched tone. The attended ear switched after each block. After block eight, the headphones were reversed. The trials presented in the first half of the task (blocks 1-8) were the same as those presented in the second half (blocks 9-16), though the order of trials within each half of the task was randomized.

Since the possible durations of the reference and comparison stimuli were 300 ms, 320 ms, and 350 ms, the difference in duration between the reference and comparison stimuli was 50 ms or less, or there was no difference. This task was designed to test for left lateralized processing of rapid temporal information.

Duration Fast Tonal (12 minutes). Based on Brancucci et al., 2008. This match-to-sample task required that participants discriminate tonal sounds based on their duration. The task procedure was identical to the procedure of the Duration Fast Verbal task, except all stimuli were tonal instead of verbal. Specifically, the tones used for reference and comparison stimuli were complex tones with a 500 Hz fundamental frequency and the following seven harmonics of the fundamental. Starting with the fundamental, the relative amplitudes of each harmonic component were as follows: 1, 0.7, 0.5, 0.3, 0.1, 0.03, 0.01, 0.005. The 700 ms contralateral mask stimulus was also a complex tone that used the same relative amplitude, but the tone was designed with the fundamental of 550 Hz and its harmonics. All tones had 50 ms rise and fall times. The reference and comparison stimuli were 300, 320, or 350 ms in length. So the potential duration difference was again 50 ms or less. This task was also designed to test for left

lateralized processing of rapid temporal information. Dependent variables were accuracy and reaction time.

Duration Slow Tonal (12 minutes). Based on Brancucci et al., 2008. This was a match-to-sample task that used exactly the same stimuli and procedures as the Duration Fast Tonal task, with one important exception. The possible durations of the reference and comparison stimuli were increased to 350 ms, 500 ms and 650 ms. The duration of the mask tone was unaltered and remained 700 ms. The increased durations of the reference and comparison tones increased the possible duration difference that participants were asked to discriminate. When the comparison and reference stimuli were different durations (50% probability), the possible difference was 150-300 ms. These longer stimuli and increased duration differences were employed to test the hypothesis that slowly changing temporal information may be processed bilaterally or even in the right hemisphere. Dependent variables were accuracy and reaction time.

Temporal Sequencing (8 minutes). Based on Halperin, Nachshon, and Carmon (1973) and Natale (1977). Rhythmic sequences of simple, sinusoidal tones were presented dichotically, such that each ear received a different rhythm. Tones were either long (400 ms) or short (200 ms), and short and long tones were combined to form different rhythmic sequences. Each sequence consisted of four tones, and the duration changed at least twice in each sequence. Eight unique sequences were created, varying in length from 1000-1400 ms. These sequences were then combined into twelve different dichotic pairs, so that a different sequence was presented simultaneously to each ear. Each sequence within a pair was the same total length, so that there were no differences in onset or offset to act as temporal cues.

Each trial consisted of a presentation of one dichotic pair of sequences. Trials were presented in eight blocks of six. Participants completed 48 trials in total. After the first 12 trials,

30

the assignment 500 Hz and 2600 Hz tones switched ears After the first 24 trials, the headphones were reversed. Between each block a high pitched (2000 Hz) pure tone was played in the ear that would receive the reference and comparison stimuli in the following block. Participants were instructed to pay attention only to the ear that heard the high pitched tone, meaning that they should ignore the unattended sequence. The attended ear switched after each block.

On each trial, participants were to listen to the sequence presented in the attended ear. They were then tasked with replicating that sequence of short and long tones by pressing the appropriate keyboard keys in order. One key represented short tones and one key represented long tones, so participants were to press each key to match the order of the previous sequence. Participants were instructed to be as accurate as possible. The dependent variable was accuracy. A response was only considered correct if it fully reproduced the order of the sequence.

Perceptual separation of the dichotic sequences was facilitated by using a different pitch in each ear. One ear received tonal sequences at a frequency of 2600 Hz, while the other ear received tones that were presented at 500 Hz. After 12 trials the frequencies switched ears, so that each ear heard sequences at high and low frequencies. The order of these pitch assignments was balanced between participants.

Intensity.

Intensity (12 minutes). Based on Brancucci et al. (2005). This match-to-sample task required the listener to compare the loudness of two stimuli that were presented sequentially to the same ear. The first, reference stimulus is presented monaurally (i.e. nothing is presented to the opposite ear); and after an interval of 1000 ms, the second, comparison stimulus was paired with a masking stimulus presented simultaneously to the opposite ear. The intensities of the reference and comparison stimuli were randomly selected from levels representing 60, 70, and

31

80 dBA, and the intensities of reference and comparison stimuli were matched on 50 percent of trials. The contralateral mask stimulus was presented at the same intensity on all trials, 70 dBA.

Participants were asked to judge whether the reference and comparison tones were of equivalent or different intensities. Reaction time and accuracy were the dependent variables.

Stimuli were tones. The reference and comparison stimuli were 500 ms complex tones consisting of a fundamental frequency of 260 Hz and the following seven harmonics of this frequency. In order of ascending frequency, these spectral components were presented at the following relative amplitudes: 1, 0.7, 0.5, 0.3, 0.1, 0.03, 0.01, and 0.005. Similarly, the masking tone consisted of the first eight harmonics of 290 Hz, and the relative amplitudes were the same as those used for the reference and comparison tones. All tones had 50 ms rise and fall times with steady-state components of 400 ms, resulting in tones lasting 500ms.

Participants completed 96 trials which were separated into 16 blocks of 6 trials. Within each block the reference and comparison stimuli were always presented to the same ear (right or left). Between each block a high pitched (2000 Hz) pure tone was played in the ear that would receive the reference and comparison stimuli in the following block. Participants were instructed to pay attention only to the ear that heard the high pitched tone. The attended ear switched after each block. After block eight, the headphones were reversed. The trials presented in the first half of the task (blocks 1-8) were the same as those presented in the second half (blocks 9-16), though the order of trials within each half of the task was randomized.

Pitch.

Complex Tone Test (21 minutes). Based on Sidtis (1980, 1981). This task used a match-to-sample procedure in which participants compared the pitch of tones. All stimuli were 80 dBA, complex, square-wave tones lasting 550 ms, including a 25 ms rise and 25 ms decay. The

32

tones were the eight notes on the major scale ranging from C_4 to C_5. In ascending order, the fundamental frequencies of these tones were: 264, 297, 330, 352, 396, 440, 495, and 528 Hz. These eight tonal stimuli were randomly combined to create 28 dichotic pairs.

Each trial began with presentation of a dichotic pair of two different tones, i.e. a different note was presented in each ear simultaneously. After a one second inter-stimulus interval a single tone was presented as a diotic comparison stimulus, i.e. one tone was presented to both ears simultaneously. Participants were tasked with determining whether the pitch of the second, diotic stimulus matched either member of the preceding dichotic pair of tones. Participants were instructed to pay equal attention to both ears and were asked to respond as quickly and accurately as possible by pressing one of two keyboard keys.

Trials were presented in blocks of 28; each dichotic pair was presented once in each block. Within each block, 14 of the trials contained diotic tones that matched one of the preceding dichotic tones. Four blocks were presented, and trial order was randomized within each. The trials were designed so that each member of all dichotic pairs was matched once by a diotic stimulus. After the fourth block, headphones were reversed and participants completed another four blocks which used the same trial stimuli in a newly randomized order. A five second inter-trial interval was employed.

Tonal Spectral Oddball (9 minutes). Based on Mathiak et al. (2002). This task utilized an oddball procedure in which participants were tasked with determining whether a rare pitch shift had occurred in either ear. All stimuli were complex square wave tones, which lasted for 90 ms (10 ms rise and fall times).

On each trial, a different tone was presented simultaneously to each ear. Usually (on 80% of trials) one ear was presented with a 350 Hz tone and the other heard a 500 Hz tone. These

tones were the neutral stimuli to which participants were instructed not to respond at all. Occasionally (20% of trials), a tone would be presented that was slightly higher or slightly lower pitched than the standard, neutral stimulus. The change in pitch could be small (2% change from neutral frequency) or large (4% change from neutral frequency). These pitch changes represented the deviant stimuli. Only one ear could receive an deviant tone on a given trial. Upward and downward shifts were equally likely, as were small and large shifts.

Trials were blocked into four blocks of 120 trials. Before each block participants were instructed to only respond to one direction of pitch change (i.e. either upward shifts, or downward shifts). They were told to ignore pitch changes in the opposite direction. Thus, participants were only asked to respond during half of the deviant trials (10% of all trials). In other words, the oddball stimuli represented only half of the deviant pitch shifts. Participants were instructed to pay equal attention to both ears and to respond as quickly as possible by pressing the spacebar when they detected the pitch shift in the correct direction.

The direction to which participants were asked to attend switched between each block. The pitch of the neutral tone was also switched between ears at this point. In other words, if a participant had received the 350 Hz tone to the left ear for the first block, they received the 350 Hz tone to the right ear for the second block.

After two blocks (240 trials) headphones were reversed and the procedure was repeated in blocks 3-4. Because the attended shift direction and the pitch-ear assignments were changed between blocks, the pairing of these variables was balanced between participants. For example, one participant would hear the left lateralized 350 Hz tone when being asked to detect downward changes in either ear, while instructions to detect upward changes in either ear would be paired with a 500 Hz tone in the left ear; other participants received the opposite pairings of shift

directions and tone-ear assignments. The order of each of these variables was also balanced between participants. The dependent variables were reaction time and hit rate, i.e. percentage of

Timbre. The tasks designed to require processing of auditory timbre utilized artificially constructed tones. Timbre is perceived based upon two major classes of tonal components: A temporal components and steady-state components. The tasks used in the current study allowed for independent manipulation of these two components of timbre. Only one component was manipulated in each task, while the other components were held constant. The Timbre Slow and Timbre Fast tasks were designed to test processing of temporal aspects of timbre; specifically only temporal fluctuations in intensity were manipulated. While the Timbre Steady task was designed to test processing for steady-state features of timbre; specifically, only the relative intensity of harmonics was manipulated.

Timbre Slow (12 minutes). Based on Brancucci and San Martini (2003). This task used a match-to-sample procedure. Stimuli were three complex tones that were identical in frequency spectrum, pitch and intensity. The tones were created by the summation of the first 8 harmonics of the fundamental of 500 Hz. The relative amplitudes of the spectral components were: 1, 0.7, 0.5, 0.3, 0.1, 0.03, 0.01, and 0.005. The amplitude envelopes of each of the tones differed, but average and peak amplitude were held constant between tones. The three complex tones were modulated to be 'slow'. This was achieved by regular, gradual, smooth changes in amplitude. The amplitude envelope of one stimulus was gradually increasing, another was gradually decreasing, and the envelope of another first gradually increased then gradually decreased. All tones had durations of one second and were presented with a peak intensity of 70 dBA.

On each trial, one of these amplitude modulated tones was presented monaurally as a reference stimulus. After a one second inter-stimulus interval, a second amplitude modulated tone was presented to the same ear as a comparison stimulus. A white noise burst was presented

The task contained 96 trials, divided into blocks of 32 trials. Stimuli will be presented to only one ear in each block. Two seconds will separate each trial. Each trial will begin with a monaural tone lasting 1 second. After a 1 second ISI, a second monaural tone will be presented 50 ms before and lasted until 50 ms after the reference tone. Participants were tasked with determining whether the comparison stimulus sounded the same as the reference stimulus. Dependent variables were reaction time and accuracy.

Participants completed 96 trials which were separated into 16 blocks of 6 trials. Within each block the reference and comparison stimuli were always presented to the same ear (right or left). Between each block a high pitched (2000 Hz) pure tone was played in the ear that would receive the reference and comparison stimuli in the following block. Participants were instructed to pay attention only to the ear that heard the high pitched tone. The attended ear switched after each block. After block eight, the headphones were reversed. The trials presented in the first half of the task (blocks 1-8) were the same as those presented in the second half (blocks 9-16), though the order of trials within each half of the task was randomized.

Timbre Fast (12 minutes). Based on Brancucci and San Martini (2003). The procedure was the same as the procedure used for the Timbre Slow task, except the amplitude envelopes of the three tones were modulated to create 'rapid' changes. In one tone, the amplitude envelope included a rise time of 65 ms, sawtooth amplitude fluctuations of 6.67 Hz, and a fall time of 200 ms. Another tone involved a rise of 70 ms, fluctuations of 40 Hz, and a decay of 200 ms. Another tone consisted of a 10ms rise, a 560ms steady intensity, and a 430 ms decay.

Timbre Steady (12 minutes). Based on San Martini et al. (1994). This task also used a match-to-sample procedure. Each trial began with a one-second presentation of a monaural reference tone; and after a 500 ms inter-stimulus interval, a comparison tone was presented to the same ear for one second while white noise is presented to the contralateral ear. The reference and comparison stimuli were selected from three complex tones. All three tones consisted of the first 12 harmonics of 100 Hz and were presented at peak intensities of 70 dBA and equal average intensities. The three tones were only distinguished by the amplitudes of harmonic components. In all stimuli, four harmonic components were presented with high relative amplitudes of 1.0, while the other 8 harmonic components were presented with amplitudes that were halved (0.5). The high amplitude harmonics were harmonics 1-4, harmonics 5-8, or harmonics 9-12; thus, the high intensity harmonics differed in each stimulus. The number of trials and blocking procedure were identical to the previously described match-to-sample tasks. Accuracy and reaction time were the dependent variables.

Results

Preliminary Data Preparation

Prior to any statistical analyses, each participant's screening data were checked for evidence of abnormal hearing, left handedness and extensive musical experience. Four participants were identified as musicians and their data were excluded from subsequent analyses. One participant was found to be left-handed and this participant's data was also excluded from all analyses. These five exclusions resulted in a final sample of 124 right-handed, nonmusicians.

While no participant indicated hearing loss or generally poor hearing in terms of average hearing thresholds or inter-ear differences in hearing thresholds, some participants did demonstrate increased thresholds in specific frequency bands. While this could have been an artifact of the abbreviated audiometric testing, a conservative approach was taken to ensure that task performance was not contaminated by abnormal hearing. A threshold difference between the two ears would be especially problematic, since this could potentially produce performance asymmetries even where there may be no hemispheric asymmetries. If a participant's hearing threshold at a specific frequency was more than 5 dB different between the ears or more than 10 dB above normal in both ears, the tasks utilizing that frequency were removed from that participant's data. These methods of audiometric assessment and exclusionary criteria are similar to those used in previous studies of auditory asymmetry (e.g. Brancucci, Franciotti, Anselmo, della Penna, & Tommasi, 2011; Brancucci et al., 2005).

This task exclusion procedure, in addition to the fact that some participants did not complete all tasks, caused the sample size to vary from task to task. Analyses involving more

than one variable excluded cases pairwise, so that all intact tasks were used. Table 1 indicates

how many participants were missing for each task due to either attrition or hearing test results,

and it shows how many of the 124 participants produced useable data on each of the 13 tasks.

Table 1

Final sample size for each task and explanations for missing data for each task

	Missing Data: Causes and Counts		
Task	Not Complete or Non Compliant	Tonal Hearing Test	Final Sample Size (N)
Complex Tone Test	8	3	113
Dichotic Emotions	18	0	106
Dichotic Words	10	0	114
Duration Fast Speech	10	0	114
Duration Fast Tones	17	18	89
Duration Slow Tones	12	23	89
Intensity	10	8	106
Spectral Oddball	8	3	113
Temporal Sequencing	9	7	108
Timbre Fast	20	14	90
Timbre Slow	15	17	92
Timbre Steady	10	8	106
Visual Onsets	7	0	117

Note. Compare to a total sample size of 124 participants who completed at least one session (i.e.

approximately half of the task battery).

Failure to complete a task was typically caused by failure to return for the second session

of the study, in which case a participant completed approximately half of the task battery. The

13 participants who did not return for the second session accounted for 90 of the 154 missing

cells, and another five individuals failed to complete 1-3 tasks each (11 total) because they were

late to the session, they were generally slow to complete tasks, or a computerized task crashed

during the experimental session. The above-described issues account for approximately 65% of

the missing tasks.

The remaining portion of missing data is explained by participant noncompliance. Participants occasionally failed to rotate their headphones during the task, reported responding in confusion because they had misunderstood the task instructions, or had been nonresponsive throughout the task. Despite the apparent disparity in missing cells between tasks, attrition and noncompliance appear to have occurred randomly and led to missing cells that were dispersed across all orders of task presentation. In contrast, the exclusion of certain tasks based on an individual's frequency-specific hearing thresholds was not entirely random and resulted in missing more of some tasks than others.

Performance data from the participants were converted into values representing the relative performance in the right perceptual field compared to the left. For measures of accuracy, there are many ways to calculate performance asymmetry (Bryden, 1982). Often, the difference in accuracy between the right and left perceptual field is used as the measure of asymmetry. However, these difference scores have a statistical shortcoming; when performance is near ceiling or floor levels, the potential for performance asymmetry is constrained, compared to when performance of either ear is middling (i.e. near 50%). To correct for this limitation, lateralization coefficients (LCs) were computed from the accuracy data using the formulas below shown in Figure 1. For further discussion of the merits of LCs versus raw difference scores in the evaluation of accuracy asymmetries see Boles, Barth and Merrill (2008) and Boles and Barth (2011).

When mean accuracy is greater than 50 percent:
LC = (Right % Correct – Left % Correct)/(Right % Error + Left % Error)

When mean accuracy is less than 50 percent:
LC = (Right % Correct – Left % Correct)/(Right % Correct + Left % Correct)

Figure 1. Formulas used for the computation of Lateralization Coefficients (LCs). Right and Left refer to the right and left perceptual fields.

These formulas produce LC values that range from -1.0 to +1.0, where negative values indicate a left side (right hemisphere) advantage and positive values indicate a right side (left hemisphere) advantage in terms of mean accuracy.

For reaction time data, the median reaction time was computed for each perceptual hemifield, for each participant; then right hemifield RT was subtracted from left hemifield RT, producing a difference score where a negative value indicates a left side (right hemisphere) advantage and positive values indicate a right side (left hemisphere) advantage for median reaction time. Justification for use of RT side differences is twofold. First, unlike accuracy data, reaction time data is not likely to be limited by floor or ceiling effects, since as Boles and Barth (2008) point out, reaction times can range without limit. Second, side differences such as these have been the standard index of reaction time asymmetry in previous factor analytic research (Boles 1991, 1992, 1996); and there is no generally accepted alternate index of hemispheric asymmetry for reaction time data (see Bryden, 1982, p. 37 for a brief discussion).

Analyses of Asymmetry

After computing the side differences and LCs, each index of asymmetry was tested for significance using a one sample t-test ($\alpha = .05$, two-tailed), in which mean asymmetry scores were compared to zero (i.e. no asymmetry). To be included in subsequent factor analyses, a task asymmetry index was required to be at least marginally significant ($p < .10$).

41

Estimates of reliability were also calculated and considered prior to factor analysis. All reliability estimates were computed by either split-half or odd-even procedure. In either case, this involved calculation of the correlation (r) of performance in two halves of a given task. If the correlation was positive, the Spearman-Brown correction was applied to estimate reliability.

Negative correlations between halves were treated differently. Since reliability measures are fundamentally based on an estimate of correspondence between a measurement and the true score that is being measured, the minimum theoretical value for reliability is zero (Spearman, 1904, 1910). A reliability of zero indicates that the measured values have no relationship with the true values (Thompson, 2003). A negative reliability estimate would imply the theoretical impossibility that observed scores and true scores somehow have less than nothing to do with each other. So, an assumption for the use of the formula is that the two halves being examined are positively correlated (Webb, Shavelson, & Haertel, 2006). Thus, a negative correlation between halves was taken as a clear indicator that the data from a measure were not reliable, and no further reliability calculations were made for that measure. Instead, when correlations between split halves were negative, the measurements were considered to have zero reliability, and were tabled as such.

Before delving into factor analysis, it is important to consider which tasks actually produced significant measures of asymmetry, whether asymmetries are in the predicted direction, and whether there is an explanation for why some tasks may have failed to produce the predicted asymmetry. Table 2 depicts the results of these preliminary significance and reliability tests for measures of asymmetry produced from each task.

Table 2

Mean asymmetry scores, significance and Spearman-Brown corrected reliability estimates (r_{sb})

for all recorded task measures

| Task | Measure | N | Asymmetry | | Reliablility | |
			Mean	p	Type	r_{sb}
Complex Tone Test	**Accuracy(LC)**	**113**	**-.07**	**= .025**	**odd-even**	**.374**
Complex Tone Test	RT(SD)	113	-11 ms	= .169	odd-even	.343
Dichotic Emotions	**Accuracy(LC)**	**106**	**-.07**	**< .001**	**odd-even**	**.031**
Dichotic Words	**Accuracy(LC)**	**114**	**+.40**	**< .001**	**split-half**	**.511**
Dichotic Words	**Order(LC)**	**114**	**+.34**	**< .001**	**split-half**	**.315**
Duration Fast Speech	Accuracy(LC)	114	.00	= .880	odd-even	.000
Duration Fast Speech	RT(SD)	114	0 ms	= .986	odd-even	.444
Duration Fast Tones	Accuracy(LC)	89	.00	= .687	odd-even	.000
Duration Fast Tones	RT(SD)	89	+9 ms	= .510	odd-even	.428
Duration Slow Tones	Accuracy(LC)	89	-.01	= .313	odd-even	.000
Duration Slow Tones	RT(SD)	89	+1 ms	= .937	odd-even	.000
Intensity	Accuracy(LC)	106	-.03	= .133	odd-even	.000
Intensity	**RT(SD)**	**106**	**-21 ms**	**= .019**	**odd-even**	**.240**
Spectral Oddball	**Accuracy(LC)**	**113**	**-.08**	**< .001**	**split-half**	**.101**
Spectral Oddball	RT(SD)	113	-10 ms	= .169	odd-even	.302
Temporal Sequencing	Accuracy(LC)	108	+.05	= .228	odd-even	.261
Timbre Fast	Accuracy(LC)	90	.00	= .941	odd-even	.000
Timbre Fast	RT(SD)	90	+12 ms	= .403	odd-even	.614
Timbre Slow	Accuracy(LC)	92	-.04	= .294	odd-even	.000
Timbre Slow	RT(SD)	92	0 ms	= .976	odd-even	.051
Timbre Steady	**Accuracy(LC)**	**106**	**-.12**	**= .044**	**odd-even**	**.094**
Timbre Steady	RT(SD)	106	-24 ms	= .479	odd-even	.819
Visual Onsets	**Accuracy(LC)**	**117**	**+.01**	**= .066**	**odd-even**	**.566**
Visual Onsets	RT(SD)	117	+5 ms	= .652	odd-even	.402

Note. Bold text indicates tasks that are at least marginally significant ($p < .10$).

Significant asymmetry measures. As can be seen in Table 2, eight measures produced significant asymmetries. They included the accuracy (LC) measures for Visual Onsets, Dichotic Words, Complex Tone Test, Spectral Oddball, Steady State Timbre Discrimination, and the Dichotic Emotions tasks. There was also a significant asymmetry for the order of report (LC) during the Dichotic Words task. The Intensity Discrimination task was the only task to produce

a significant asymmetry for reaction time. Each of these significant asymmetries is in the predicted direction, replicating the ear and visual field advantages reported in previous research.

Further, where one measure from a given task (e.g. accuracy LC) was significant and the other (e.g. RT side difference) was not, the nonsignificant measure showed an asymmetry that was descriptively in the predicted direction. For example, the accuracy LC measure indicated a significant LEA (right hemisphere) for the performance of the Steady State Timbre Discrimination task, and the counterpart RT measure for that task also indicated a notable, but nonsignificant LEA of 24 milliseconds. This correspondence between asymmetry measures suggests that the significant asymmetries observed here are due to true differences in hemispheric processing, rather than randomly occurring artifacts. This is encouraging since it is the significant measures that were included in subsequent factor analyses.

Nonsignificant asymmetry measures. In contrast, the results of the wholly nonsignificant tasks are somewhat more varied. Yet, over seventy percent of the nonsignificant measures produced asymmetries that trended in the predicted direction. The tasks that failed to produce any significant measures fall into two groups: Temporal discrimination tasks and Timbre discrimination tasks. Possible explanations for task nonsignificance are discussed here, and the discussion section contains recommendations for avoiding similar problems in future research on perceptual asym   metries.

Temporal discrimination. Temporal Sequencing produced a nonsignificant asymmetry in the predicted direction, towards a REA, for the only measured variable, accuracy (LC). Of the other auditory temporal tasks, the Duration Slow Tones task produced a REA for reaction time and a LEA for accuracy, though the magnitude of asymmetry was miniscule in both cases. In

retrospect, this result is not entirely surprising, given the conflicting accounts of the laterality of temporal processing of slow signals.

For instance, Brancucci and colleagues (2008) observed a REA for each variable, but as previously discussed, researchers often fail to find any performance or physiological asymmetries when temporal stimuli must be discriminated based on relatively large differences in duration (> 50 ms). In some cases, researchers even find a reversed, LEA for the processing of slowly occurring temporal information, which implies a right hemisphere lateralization (Belin et al., 1998; Boemio et al., 2005; Mills & Rollman, 1979). The Duration Fast Speech task did not produce any significant asymmetries. The Duration Fast Tones task resulted in a reaction time difference that trended towards the predicted REA, while accuracy LC produced no asymmetry. Theoretically, it is more surprising that these fast duration tasks failed to produce significant evidence for left-hemisphere lateralization for processing of rapid temporal information, given that plenty of behavioral and neurophysiological evidence exists in support of this asymmetry (e.g. Mills & Rollman, 1979; Poeppel, 2003). However, the nonsignificance of these tasks may have more to do with methodology than with underlying laterality.

The stimuli were based upon the stimuli used by Brancucci et al. (2008), but they were modified before being implemented in these tasks. Specifically, the speech and tone stimuli were shortened so that the stimuli on each trial differed by no more than 50 ms. This modification was made in order to ensure that the temporal discrimination would be defined by the fast, narrow temporal window for which the left hemisphere seems to be specialized (Mills & Rollman, 1979; Poeppel, 2003). This was also done to allow comparison with the Slow Tone task and to permit testing of the hemispheric dichotomy proposed by the AST hypothesis (Poeppel, 2003). However, the task appears to have been too difficult, since the average

45

accuracy was near chance (50%) for both the tonal and verbal versions of the fast duration discrimination tasks (54.97% and 59.68%, respectively). This poor performance may indicate that participants were often unable to discriminate between stimulus durations and were forced to guess more often, which would reduce the potential for meaningful measurement of true hemispheric asymmetry.

   Timbre discrimination. The Fast Timbre task and the Slow Timbre task were used to test asymmetry in the processing of temporal features of timbre; RT and accuracy were recorded for each task. The Slow Timbre task produced a nonsignificant, negligible LEA for the accuracy measure, and no asymmetry was evident in the RT data. A LEA is the predicted direction of asymmetry based on previous research using this task (Brancucci & San Martini, 2003). No asymmetry was evident in the accuracy data for the Fast Timbre task, but a nonsignificant REA was evident in the reaction time data. This is opposite the predicted direction.

Exploratory Factor Analyses

   Two pairs of factor analyses were conducted. Between each pair of analyses, the only difference was the degree of conservatism used for determining adequate reliability for entry into factor analysis. The reliability criterion for entering factor analysis was reduced slightly from the first pair of analyses to the second pair. Reducing the reliability criterion increased the number of variables entered into factor analysis and the resultant factor solution. Within each pair, the first analysis used Kaiser's traditional eigenvalue criterion to determine the number of factors extracted (Kaiser, 1960, 1961), and the second analysis used Cattell's (1966) scree test to determine the number of factors extracted.

Table 3 represents the correlations among all significant measures of perceptual asymmetry; all subsequent factor analyses were driven by the relationships depicted in this correlational matrix.

Table 3

Correlation matrix for all significant measures of performance asymmetry

	VO	DWA	DWO	CTT	I	SO	TS	DE
Visual Onsets Accuracy (VO)		+.09	+.08	-.03	+.07	-.04	+.16	+.21*
Dichotic Words Accuracy (DWA)			+.86**	+.04	-.03	-.03	-.06	+.10
Dichotic Words Order (DWO)				+.07	-.02	+.08	-.02	+.11
Complex Tone Test Accuracy (CTT)					-.05	+.30**	+.12	+.11
Intensity RT (I)						+.05	+.13	-.01
Spectral Oddball Accuracy (SO)							+.07	+.11
Timbre Steady Accuracy (TS)								+.22**
Dichotic Emotions Accuracy (DE)								

* $p < .05$
** $p < .01$

FA1: Traditional reliability criterion with Kaiser's criterion. Here, as in previous factor analytic studies of perceptual asymmetry (e.g. Boles, 1998b), a variable was accepted for factor analysis if performance asymmetry was at least marginally significant ($p < .10$) and reliable, as indicated by Spearman-Brown corrected reliability estimates ($r \geq .30$). As shown in Table 2, accuracy LCs from the Visual Onsets task, the Dichotic Words task, and the Complex Tone Test task, each met this dual significance-reliability criterion; as did the LC of report order from the Dichotic Words task. An initial exploratory factor analysis was conducted using these four variables.

The exploratory factor analysis employed Principle Components extraction using Kaiser's criterion to extract factors only when the associated Eigenvalue was greater than one. In this and all subsequent factor analyses, missing task data was excluded on a pairwise basis, meaning that if a participant did not complete a specific task, the rest of their data was still

useable. Adequacy for factor analysis was determined using the Kaiser-Meyer-Olkin (KMO)

measure of sampling adequacy (KMO = .503), and Bartlett test for sphericity ($p < .001$).

Two factors were extracted, which accounted for a cumulative 73% of total variance

(Factor 1 = 47% and Factor 2 = 26%, approximately). These factors were then rotated using the

Direct Oblimin rotation method, which permits correlations between factors. Delta (δ), a

statistical parameter which controls the amount of inter-factor correlation, or obliqueness, was

systematically varied until the rotated factor solution was reached in a minimum number of

iterations. This is a method that was recommended by Gorsuch (1983), which was used in

previous factor analyses of perceptual asymmetries (e.g. Boles, 1998b). In this analysis a rotated

factor solution required a minimum of two iterations (δ = 0.2). This rotated factor solution is

presented as a structure matrix in Table 4.

Table 4

Structure matrix of extracted and rotated factors for factor analysis 1 with Kaiser's Criterion

Factor 1	
Dichotic Words Accuracy	+.959
Dichotic Words Order	+.957
Factor 2	
Complex Tone Test Accuracy	+.752
Visual Onsets Accuracy	-.680

Note. All loadings ≥ .30 are shown.

Factor 1 consists solely of the two measures taken from the Dichotic Words tasks.

Given that these two measures both indicate a left-hemisphere advantage in the processing of

auditory linguistic information and that both measures positively loaded on Factor 1, it is

reasonable to conclude that Factor 1 represents a resource for Auditory Linguistic processing.

This resource has been identified in previous factor analytic studies (e.g. Boles, 1991). Factor 2

represents loadings from the remaining two tasks: Visual Onsets and the Complex Tone Test. These two tasks do not appear to represent a single resource. Visual Onsets elicited a left hemisphere accuracy advantage, while a right hemisphere advantage was apparent for accuracy during the Complex Tone Test. Further, these two measures load inversely on Factor 2 – Visual Onsets loading negatively and the Complex Tone Test positively. Thus, it appears that Factor 2 represents two distinct perceptual resources: A Visual Temporal resource and an Auditory Spectral Pitch resource, the latter being a novel discovery and the former a replicated resource previously found by Boles (1996).

The relationship between Factor 1 and Factor 2 was assessed by testing the factor inter-correlations for significance. A t-test was used in which the degrees of freedom were based upon the mean sample size of all possible measure pairings between Factor 1 and Factor 2. Since two measures loaded on Factor 1 (Dichotic Words Accuracy and Dichotic Words Order) and two measures loaded on Factor 2 (Complex Tone Test Accuracy and Visual Onsets Accuracy), four pairwise comparisons were possible between Factors. These pairwise comparisons were Dichotic Words Accuracy vs. Complex Tone Test Accuracy ($n = 105$), Dichotic Words Accuracy vs. Visual Onsets Accuracy ($n = 108$), Dichotic Words Order vs. Complex Tone Test Accuracy ($n = 105$), Dichotic Words Order vs. Visual Onsets Accuracy ($n = 108$). The average sample size of these four pairwise comparisons was 106.5 participants, so the degrees of freedom ($n - 2$) were conservatively set to 104 to test the inter-factor correlation for significance. This *t*-test revealed that the correlation ($r = -.036$) between Factors was not significant, $t(104) = -0.37$, $p > .05$. The result of this factor analysis is two uncorrelated factors: one which represents a pure Visual Linguistic resource, and another which consists of a Visual Temporal resource as well as an Auditory Spectral resource.

49

While this three-resource model is clearly supported by the rotated structure matrix (Table 4), it is important to check the structure matrix against the original correlation matrix (Table 3) to make sure that the factor structure is a good representation of the correlations within the data. This comparison reveals that Visual Onsets Accuracy and Complex Tone Test Accuracy are uncorrelated, yet they were forced to load together on Factor 2. Examination of the scree plot from this analysis (Figure 2) shows that while Kaiser's criterion led to only two factors being extracted, a third factor is only marginally below the Eigenvalue ≥ 1 criterion. Further, this third factor would pass the visual scree test, which bases factor extraction on the scree plot. In short, factors are accepted for extraction if they are above the lowest point of inflexion, or elbow, of the scree plot (Cattell, 1966; Field, 2013; Thompson, 2004).
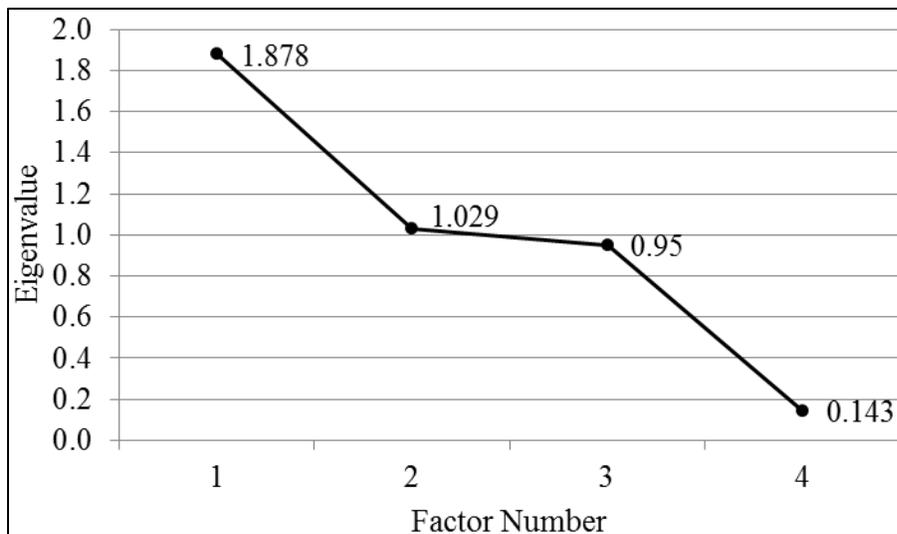
Figure 2. Scree plot from factor analysis 1.

FA1: Reanalysis using scree test extraction. This secondary factor analysis followed the same procedures, but rather than using Kaiser's criterion that an Eigenvalue must be at least 1, the scree-test was used to justify extraction of a third factor. The three factors accounted for approximately 47%, 26%, and 24% of the variance (96% cumulatively). Four iterations were needed to reach a rotated factor solution ($\delta = 0$). The structure matrix is presented in Table 5.

50

Table 5

Structure matrix of extracted and rotated factors for factor analysis 1 with Scree test

Factor 1	
Dichotic Words Accuracy	+.963
Dichotic Words Order	+.963
Factor 2	
Complex Tone Test Accuracy	+1.000
Factor 3	
Visual Onsets Accuracy	+1.000

Note. All loadings ≥ .30 are shown.

As expected, extraction of a third factor led Complex Tone Test Accuracy and Visual Onsets Accuracy to split into two separate pure factors, each representing a single resource. Tests of the correlations between factors indicated that these three factors are uncorrelated ($p > .05$, in each case), here meaning that the Auditory Linguistic, Auditory Spectral Pitch, and Visual Temporal resources are uncorrelated. The factor structure produced by this model is an accurate depiction of the correlations in the underlying data (see Table 5 and Table 3). Critically, despite the improved correspondence between the correlation matrix and the factor structure, the identities of the resources inferred from this secondary analysis are no different from those of the initial factor analysis.

FA2: Reduced reliability criterion with Kaiser's criterion. For this factor analysis the reliability criteria were loosened to allow any measure with a Spearman-Brown corrected estimate of at least .2 into the analysis. The methods of extraction, methods of rotation, and appropriateness of factor analysis were unchanged from the previous analysis. Compared to the previous factor analysis, relaxation of the reliability criterion led to the addition of one measure: Intensity Reaction Time. The structure matrix is presented in Table 6 and described below.

Table 6

Structure matrix of extracted and rotated factors for factor analysis 2 with Kaiser's Criterion

Factor 1	
Dichotic Words Order	+.958
Dichotic Words Accuracy	+.967
Factor 2	
Intensity Reaction Time	+.678
Visual Onsets Accuracy	+.609
Complex Tone Test Accuracy	-.517

Note. All loadings $\geq$ .30 are shown.

A rotated two-factor solution was produced in which Factor 1 and Factor 2 explained approximately 38% and 22% of the variance, respectively (60% cumulatively). Measures of Auditory Linguistic asymmetry were again the sole representatives of Factor 1. Asymmetries measured from the Complex Tone Test and the Visual Onsets task, and the Intensity task all loaded on Factor 2, which again appears to be comprised of multiple resources. As discussed previously, the opposing directions of factor loadings and hemispheric asymmetries indicate that Complex Tone Test and the Visual Onsets performances are reliant on different lateralized resources. Similar comparisons indicate that the Intensity task relies on an auditory processing resource that is distinct from that of other Factor 2 measures. Specifically, the right hemisphere advantage for the Intensity task is opposite that of the Visual Onsets task; and while both the Intensity Task and the Complex Tone Test are right lateralized, the two tasks load inversely on Factor 2, indicating that they too represent two distinct resources.

The correlation between Factor 1 and Factor 2 was again found to be nonsignificant, $r = -.013$, $t(103) = -.13$, $p > .05$. Thus, it appears that inclusion of the Auditory Intensity task led to a factor solution indicative of four distinct perceptual resources.

Comparison of the structure matrix and the correlation matrix (Table 6 and Table 3, respectively) indicates that Factor 2 is again a hodgepodge of uncorrelated measures; and a quick view of the scree plot for this analysis indicates that two more Factors lie just below the surface of the Kaiser criterion, waiting to be extracted (see Figure 3).
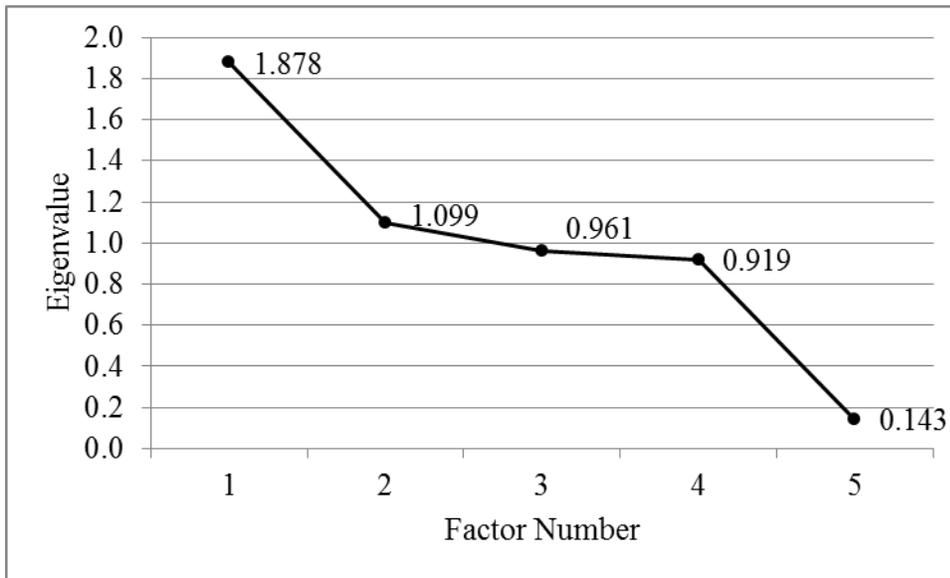
Figure 3. Scree plot from factor analysis 2.

FA2: Reanalysis using scree test extraction. A secondary factor analysis was conducted to explore the explanatory utility of adding these two factors. Four factors were extracted accounting for 38%, 22%, 19%, and 18% of the variance (97% cumulatively). Five iterations were needed to reach a rotated factor solution ($\delta = 0.05$). The structure matrix is presented in Table 7.

Table 7

Structure matrix of extracted and rotated factors for factor analysis 2 with Scree Test

Factor 1	
Dichotic Words Order	+.963
Dichotic Words Accuracy	+.963
Factor 2	
Intensity Reaction Time	+1.000
Factor 3	
Complex Tone Test Accuracy	+1.000
Factor 4	
Visual Onsets Accuracy	-1.000

Note. All loadings $\geq$ .30 are shown.

As this structure matrix shows, Intensity Reaction Time, Complex Tone Test Accuracy and Visual Onsets Accuracy now load on separate pure factors. Follow-up tests of inter-factor correlations indicated no significant correlations, so these four factors appear to represent four uncorrelated asymmetrical resources. Again, despite the change in factor structure, the conclusions regarding resource identities are unchanged from the analysis using Kaiser's criterion that resulted in only two factors, rather than four.

Reliability: Implications for Factor Analyses

Since the first pair of factor analyses (i.e. FA1) used only reliable measures of asymmetry, the Auditory Linguistic, Auditory Spectral and Visual Temporal resources that these analyses revealed can be considered legitimate. The relaxation of the reliability criterion in the second pair of factor analyses (i.e. FA2) revealed what appeared to be an additional independent resource, the Auditory Intensity resource. Although loosening the reliability requirements revealed evidence for one additional resource, the existence of this resource is also uncertain due to the unreliable performance measure that represented auditory intensity processing. If

unreliable measures are included in factor analyses, factor solutions may be rendered invalid by two types of problems, namely dubious relationships and dubious nonrelationships.

Dubious relationships. As discussed previously, if reliability is zero, measured scores do not account for any of the variance in the true scores and any correlations that exist between the unreliable measurement and another measurement must also be due to sampling error. Since factor analytic methods are based upon the correlations between multiple measures, inclusion of unreliable measures can produce spurious correlations that may in turn produce spurious factors.

This does not appear to be a problem in the case of the current factor analyses, since the most unreliable of the measures analyzed (from the Intensity task) was uncorrelated with any other measure. However, this could have been a problem had I continued to decrease the reliability criterion for entry into factor analyses. Dichotic Emotions, Timbre Steady, and Spectral Oddball produced the three significant measures that were excluded from all factor analyses due to poor reliability. Correlational analyses did indicate that there were significant relationships involving these and other variables. Yet, with such poor reliability, these correlations are questionable and could arguably be due to sampling error. Likewise, if these measures had been included in the factor analyses, the factors would have likely represented these correlations whether or not they are valid.

Dubious nonrelationships. Further, the utility of factor analysis for the identification of perceptual resources is dependent on the ability to trust that uncorrelated measures represent uncorrelated resources. If a measured asymmetry is heavily biased by error, that unreliable measure must be less likely to correlate with other measures than if it were reliable. This means that the inclusion of unreliable measures may lead to a failure to detect correlations that may

exist between true scores – a difference that could be detectable if the variable's scores were reliable.

This again is a reason for not including the tasks that were the source of three measures that had very poor reliability: Dichotic Emotions, Timbre Steady, and Spectral Oddball. Even if these measures indicated a novel resource that was separate from the previously identified lateralized perceptual resources, it would be impossible to say for certain that the processes underlying these unreliable tasks and other tasks are truly separate -- given the increased influence of error in the unreliable measures.

This could theoretically be a problem for the resource model specified by the second pair of factor analyses, since it included the marginally unreliable Intensity RT measure. This measure from the Intensity task was uncorrelated with any other measure, and consequently the factor structure indicated that processing asymmetry for the intensity task was dissociated from all other tasks. However, the relative unreliability of the Intensity task necessitates extra caution before concluding that there truly is no relationship and that there is an orthogonal Auditory Intensity resource. A deeper discussion of the likelihood of such an orthogonal resource is deferred to the discussion section, where relevant literature is reviewed to determine whether the past research corresponds with the current finding that there may be an independent, right lateralized Auditory Intensity resource.

Exclusion of Confirmatory Models

While the primary purpose of this project was the identification of auditory resources using exploratory factor analyses, a secondary goal was to examine existing theoretical models of auditory processing asymmetries using confirmatory factor analyses. Confirmatory factor analysis was proposed to be used to determine whether the current data were well-explained by

the three theoretical models. Unfortunately, many of the asymmetry measures needed for these confirmatory analyses did not indicate significant perceptual processing asymmetry. Here, as with the exploratory factor analyses, inclusion of nonsignificant measures of hemispheric asymmetry would not be useful for the examination of any model of hemispheric asymmetry.

In the absence of these measures, there are too few observed variables to act as indicators for the theoretical resources (i.e. latent factors). For example, all three of the to-be-tested theoretical models contained an intensity processing resource, which would have been indicated by two or more observed variables had all variables yielded significant asymmetries. Disappointingly, there was only one possible observed variable for the Intensity resource that could serve as an indicator variable in any of the models: Intensity Task RT. A minimum of two observed variables are required (more are recommended) to indicate each factor in a multifactor confirmatory factor analysis, otherwise the model parameters will not be identified, and the model will not be able to run (Kline, 2013). Other theoretical resources share a similar lack of significant observed variables, making the identification of any of the confirmatory models a statistical impossibility. For this reason, no confirmatory analyses were conducted. The planned models are tabled in Appendix C in terms of the observed variables that would have been used if the necessary measures had been significant.

Discussion

Consideration of Possible Resources

Collectively, the results of these factor analyses appear to support the initial hypothesis, that multiple, lateralized auditory resources exist which are distinct from those that have been identified in previous research. However, the reliability issue needs to be considered before summary conclusions can be made regarding the inferred resource structure.

The identification of an independent resource for the processing of Auditory Spectral pitch represents a novel finding in factor analytic research of this kind. The factor analytic results indicate that auditory perception of spectral pitch is separate from independent resources required for the processing of Visual Temporal information and Auditory Linguistic information. The measures that defined the Visual Temporal, Auditory Linguistic, and Auditory Spectral Pitch resources all demonstrated adequate reliability, which provides confidence that these resources are independent from one another as the factor analyses indicate. In contrast, because of the reduced reliability of the sole measure of auditory intensity processing, the independence – and even the existence – of the Auditory Intensity resource is uncertain.

Review of extant research within the perceptual domains of visual temporal, auditory linguistic, auditory spectral pitch, and auditory intensity allows for comparisons of the neurological mechanisms that are reportedly involved in each type of processing. These comparisons were conducted in order to determine whether previous research findings reaffirm the current inference of resource independence or call it into question.

Of the resources detected, both the Visual Temporal resource and the Auditory Linguistic resource have been identified previously in studies that also employed the Dichotic Words task and the Visual Onsets task as representative measures of each of these asymmetric resources, respectively (Boles 1992, 1996, 1998b). The re-emergence of these resources from among a new set of tasks should be considered further support for the legitimacy of the Auditory Linguistic and Visual Temporal resources.

Auditory Linguistic processing. Evidence from past and present factor analytic research indicates that the Auditory Linguistic resource is lateralized to the left cerebral hemisphere and is predominantly responsible for the perceptual processing of phonetic and lexical information contained within spoken language. The left lateralization of this resource coincides with the countless studies that have documented the left lateralization of language processing. More specifically, neuroimaging research points to the left medial and left superior temporal gyri as sites of linguistic processing – brain regions that correspond with Brodmann areas (BA) 21 and 22, Wernicke's area (Tervaniemi et al., 2000).

Visual Temporal processing. The Visual Temporal resource also appears to be left lateralized based on the right visual field advantage found in the current study and previous behavioral studies using visual temporal order discrimination tasks (Boles, 1996; Brandeis & Babkoff, 1984). The neurological underpinnings of temporal order perception are not as well understood as those of language perception, but research in this area has identified cerebral regions that may house the Visual Temporal resource. Davis, Christie and Rorden (2009) observed that temporal order judgments elicit activation of the temporal parietal junction (BA 39) that appears to be greater within the left cerebral hemisphere than in the homologous area of the right hemisphere.

Auditory Linguistic vs. Visual Temporal processing. The reviewed literature indicates that while the Auditory Linguistic task and Visual Temporal task are both left-lateralized, they are most likely dependent on different structures within the left hemisphere. Two processes that are dependent on orthogonal cortical resources should be uncorrelated, so the factor analysis appears to have demonstrated the resource independence that would be predicted based on functional neuroimaging.

Auditory Spectral Pitch processing. For pitch processing, converging evidence of right-hemisphere lateralization comes from multiple studies employing diverse research methods including studies of focal lesions, neuroimaging, and behavior (e.g. Sidtis & Volpe, 1988; Wioland, Rudolf, Metz-Lutz, Mutschler, & Marescaux, 1999; Zatorre, Evans, & Meyer, 1994). While the current research methods also implicate the right hemisphere as the source of pitch processing, the exact cortical localization cannot be inferred. Previous research provides clues regarding potential neural mechanisms that may be supporting pitch processing in the current study.

The Complex Tone Test was the spectral pitch task used in the current factor analyses. It required participants to discriminate between spectrally complex tones and decide whether they were the same or different. Previous research indicates that pitch discrimination is dependent on right hemispheric areas of the brain (for review: Stewart, von Kriegstein, Warren & Griffiths, 2006; Walker, Bizley, King, & Schnupp, 2011). Neuroimaging research indicates that the right planum temporale (BA 22) is especially critical for pitch discrimination (Hyde, Peretz, & Zatorre, 2008). The right planum temporale is homologous to Wernicke's area of the left hemisphere, and it has also been shown to be central for spectrally complex pitch processing even when the task utilizes speech stimuli (Gandour et al., 2004).

The specialty of this right-lateralized resource for pitch processing may be limited to the resolution of spectrally complex sounds. Previous research using the Complex Tone Test has shown that the LEA only occurs when there is harmonic information contained within a sound; while both hemispheres appear to be equipotent for the processing of pure tones, i.e. tones containing only a fundamental frequency (Sidtis, 1980). Hence, the pitch processing resource indicated in the current factor analyses appears to be resource which is specialized for processing the pitch of spectrally complex tones.

Speculation about the exact function of this right lateralized resource for complex, spectral pitch perception requires an understanding of the way frequency is represented in the brain. Frequency is tonotopically represented in the primary auditory cortex in both hemispheres of the brain (Kolb & Whishaw, 2009; Merzenich, Knight, & Roth, 1975). The tonotopic organization is essentially spatial, with different frequencies having different place codings that relate to their locations along the basilar membrane. This means that a pure tone is represented as activity in a specific place within the tonotopic map. Given previous findings that there are no asymmetries in pure tone perception, perception and discrimination of these place codes appears to be executed equally well by both hemispheres.

In contrast, spectrally complex tones consist of multiple frequencies and are represented by activity in multiple areas of the tonotopic map. Yet, even when a sound is made up of multiple harmonic frequencies, a single pitch is perceived which matches the pitch of the fundamental frequency of that sound (Plomp, 1967). Two perceptual processes have been proposed as explanations for how the auditory system resolves the pitch of complex tones. One possibility is that the perception of pitch is driven by the processing of the fundamental frequency. An alternate explanation is that pitch perception is driven by processing of the

spectral harmonic components. Behavioral research supports the latter explanation, that pitch perception is determined by the spectral features of a complex sound (Plomp, 1967). Neurologically, researchers believe that resolution of this spectral pitch is achieved through pattern analysis of the tonotopic map, and that a resource in the right hemisphere is specialized for this process (e.g. Sidtis, 1980).

This conclusion is supported by research that has examined pitch perception when the fundamental frequency is absent from a complex tone, leaving only the harmonic information. Even when the fundamental frequency is absent, pattern analysis of the harmonic information can be used to determine the pitch of a sound (e.g. Schneider et al., 2005). Zatorre (1988) studied participants who had undergone procedures to excise portions of their right temporal lobes. Compared to normal control participants and participants with left temporal lesions, participants with right temporal lesions were impaired in their ability to discriminate pitch when the fundamental was missing from complex tones. This is further evidence that the right hemisphere houses a specialized resource for the processing of the spectral content of complex tones.

Thus, it is likely that the currently inferred resource for complex pitch perception is actually a right-lateralized Spectral Pitch resource which is specialized for the processing of pitch based upon harmonic information contained within complex sounds. Given that most sounds in the environment are spectrally complex and that pitch for these complex sounds is primarily determined by processing of spectral information, it is likely that this right-lateralized Spectral Pitch resource would be demanded by most tasks that require pitch perception – unless artificially created pure tones are employed. For the remainder of this discussion, references to

pitch and pitch processing relate to complex, spectral pitch; while pitch processing for pure tones

will not be discussed further.

Auditory Spectral Pitch vs. Auditory Linguistic and Visual Temporal processing.

Evidence for the independence of the Auditory Spectral Pitch resource can be inferred in part

from the factor analytic results, which indicate no significant correlations between the processing

of Auditory Spectral information and either Auditory Linguistic or Visual Temporal information.

The measures from each respective resource are uncorrelated. Also, as the current measures of

asymmetry indicated, Auditory Spectral Pitch processing is lateralized towards the right

hemisphere, while the resources that underlie Auditory Linguistic and Visual Temporal

processing are each lateralized within the left hemisphere. Thus, these uncorrelated,

hemispherically separated processes appear to each be driven by orthogonal resources.

Auditory Intensity processing. Compared to the mechanisms of spectral pitch

perception the nature of auditory intensity perception has received far less attention, both in

terms of behavioral studies and investigations of the neurology of intensity perception. The

recorded localization of intensity processing resources is also variable, compared to the

previously reported asymmetries which are reportedly stable.

Several studies indicate that mechanisms within the right hemisphere are primarily

responsible for the processing of perceptual loudness when discrimination is required (Belin,

McAdams et al., 1998; Brancucci et al., 2005). Neuroimaging has highlighted the importance of

regions within the right parietal cortex for the discrimination of auditory intensity (Jancke, Shah,

Posse, Grosse-Ryuken & Muller-Gartner, 1998). More specifically, Belin, McAdams and

colleagues (1998) showed that the right dorsal inferior parietal lobule (BA 40) is involved in

discrimination of auditory intensity. In addition, these researchers observed what appears to be a

right-lateralized network for loudness discrimination which includes the posterior superior temporal gyrus (a.k.a. the planum temporale: BA 22/42), as well as the right precentral sulcus and right inferior frontal operculum (BA 6 and BA 45, respectively). The activated tissue within the temporal cortex was located slightly posterior to Heschl's gyrus (BA 41), and Belin and colleagues argue that this is the brain structure that is specifically responsible for the processing of intensity. In contrast, they argue that the activity in frontal/parietal structures represents attentional processes that are not specific to perception of auditory intensity. Jancke and colleagues (1998) also found that intensity processing activated the planum temporale, with greater activation in the right hemisphere. This imaging-based account of right-lateralized resources coincides with the results of a focal lesion study by Milner (1962); where excision of the right temporal lobe hindered intensity discrimination, whereas removal of the left temporal lobe did not. The LEA demonstrated by behavioral studies also corresponds with a probable right hemisphere superiority for the discrimination of auditory intensity (Brancucci et al., 2005; Doehring, 1972)

However, despite a preponderance of evidence implicating the right hemisphere as the source of intensity processing, there are some researchers that offer conflicting arguments. These researchers have also employed auditory discrimination tasks and neuroimaging, but found that intensity discrimination was processed predominantly within the left auditory cortex – including the planum temporale and portions of Heschl's gyrus (Angstein & Brechmann, 2013; Reiterer, Erb, Grodd, & Wildgruber, 2008). This is the reverse of the asymmetry found in the current study and findings reported above, so there is clearly some uncertainty about the neurology of intensity discrimination.

Critically, however, the left hemisphere lateralization reported in these studies is purely based on functional imaging. Angstein and Brechmann (2013) even found a confusing left ear advantage for accuracy during intensity discrimination. Although this would typically be taken as evidence for right hemispheric processing, they attempt to dissociate the performance from the brain activity they observe by arguing that participants put more effort into the left ear presentations to compensate for the inferiority of the right hemispheric resources. It seems equally likely that it is the neural activity that is compensatory, rather than the performance. Perhaps the left hemispheric resources appear more active, because they are less well equipped for the task of intensity discrimination and must be worked harder than the dominant resources in the right hemisphere. This explanation would fit better with the previously cited studies of behavior, imaging, and lobectomy.

However, this explanation also challenges a basic, oft unstated assumption of neuroimaging research, that degree and extent of activation correlates perfectly with the importance of that tissue for processing. Researchers have cautioned against such assumptions and argued that the contrast between imaging-based inferences and lesion-based inferences indicate that neuroimaging may not always provide a valid measure of hemispheric processing asymmetries (Ross, 2010; Sidtis, 2007). As Boles (2011, p. 56) suggested, behavioral measures of functional asymmetry may actually be more sensitive than neuroimaging measures of functional asymmetry. If so, when disagreements arise between behavioral evidence and neuroimaging evidence in terms of lateralized functions (e.g. auditory intensity processing), the behavioral results may provide a more accurate model.

In summary, there is still some disagreement among researchers over which hemisphere is dominant for intensity processing. However, researchers generally agree that regions of the

planum temporale are critical for the processing of sound intensity. The results of the current study agree with the dominant view on intensity lateralization, that the requisite resource is primarily a right lateralized resource. Yet, due to the unreliability of the intensity measure, the independence of this resource remains uncertain.

Auditory Intensity processing vs. other identified processes. The lateralization of the Auditory Intensity resource appears to be lateralized to the opposite hemisphere as the resources underlying Visual Temporal processing and Auditory Linguistic processing. So, it is unlikely that they overlap. The major question is whether the right lateralized Auditory Spectral Pitch processing and the right lateralized Auditory Intensity processing are driven by orthogonal resources. Research indicates that both types of processing are dependent on areas of the secondary auditory cortex within the temporal lobe (Belin, McAdams, 1998; Hyde, Peretz, & Zatorre, 2008). More specifically, both processes appear to depend upon regions of the planum temporale. The right planum temporale serves functions other than pitch and intensity perception, including the control of auditory attention (Hirnstein, Westerhausen, & Hugdahl, 2013), and the processing of unattended auditory spatial information (Deouell, Heller, Malach, D'Esposito, & Knight, 2007). Given the diversity of functions served by the right planum temporale, it may be that intensity and spectral pitch processes depend on different parts of this structure. More research is needed using direct comparisons of the two types of processing in order to resolve this uncertainty. However, there is not enough evidence against the independence of these resources to reject the Intensity resource outright; instead it should be treated cautiously until more research can be conducted.

Inferred Resources

In summary, three resources can be inferred from these factor analyses with confidence. They are the Auditory Linguistic resource, the Visual Temporal resource, and the Auditory Spectral Pitch resource. A fourth resource, the Auditory Intensity resource, remains questionable. Although there is evidence for its existence, the evidence for the independence of the Auditory Intensity resource is lacking. Table 8 indicates the inferred hemispheric lateralization of each resource.

Table 8

Resources inferred from current factor analyses

Resource Specialization	Resource Lateralization
Auditory Linguistic	Left Hemisphere
Visual Temporal	Left Hemisphere
Auditory Spectral Pitch	Right Hemisphere
Auditory Intensity?	Right Hemisphere

These findings have theoretical implications for the broad field of research on perceptual asymmetry. This is the first factor analytic research study to consider pitch processing or intensity processing, and the current results agree with the view that auditory spectral processing of pitch, the auditory linguistic processing of language, and the visual temporal processing of order are each driven by a separate orthogonal resource. Again though, the independence of an Auditory Intensity resource is uncertain. So, it should be considered with caution, until future research can either confirm or deny its separation from the other auditory resources.

Unanswered Questions

The current study suffered from a loss of data due to nonsignificant and unreliable measures of asymmetry. The loss of these measures meant that three domains of asymmetric auditory processing could not be examined using factor analysis. The auditory emotional task,

all auditory timbre tasks, and all auditory temporal tasks produced measures that were nonsignificant and/or unreliable. The ramification of these missing measures is an uncertainty about the number of auditory perceptual resources and the relationships between them. Further, resources and resource relationships that might be predicted based on existing literature were untested in the current study, due to the loss of measures.

Resource(s) for emotional processing. Of these three untested perceptual domains, only auditory emotional processing has been considered in previous correlational and factor analytic research (Boles, 1996; Boles & Pasquarette, 1996). This previous research also used the Dichotic Emotions task that was used in the current study. These previous investigations revealed evidence for the existence of an Auditory Emotional resource that is independent from the resource for Auditory Linguistic processing, as well as from multiple nonvisual perceptual resources. These previous investigations have also found the data from the Dichotic Emotions task to be adequately reliable ($r_{sb} = .30$, as reported in Boles, 1998b). Unfortunately, the current data from the Dichotic Emotions task did not achieve this level of reliability.

While there is no need to question the Auditory Emotional resource in terms of its independence from the Auditory Linguistic and nonauditory resources, it is possible that auditory emotional processing is not independent from the Auditory Spectral Pitch and Auditory Intensity resources that were evidenced by the current study. This concern is based on previous research, which indicates that pitch and intensity are important cues for the perception and discrimination of auditory emotions (e.g. Lehiste, 1970). Researchers have suggested that the demand for spectral pitch and intensity processing can explain the right hemisphere lateralization that is often observed for emotional prosody tasks (Van Lancker & Sidtis, 1992). If this is the case, then the rightward asymmetry that is typically observed during the performance of the Dichotic

68

Emotions task may be due to the processing asymmetries of the Spectral Pitch resource and/or the Intensity resource, rather than due to the asymmetry of a resource that is uniquely dedicated to the processing of emotional prosody.

Van Lancker and Sidtis (1992) proposed that the perception of emotional prosody is indeed driven by the processing of relatively basic acoustic features, spectral pitch and intensity. They also demonstrated the importance of a third perceptual feature, duration, for the perception of emotional prosody. These researchers studied auditory emotional perception in participants with unilateral brain damage, and they found that individuals with left hemisphere damage relied primarily on pitch for discrimination. In contrast, individuals with right hemisphere damage relied upon temporal duration cues for the discrimination of emotion. Critically however, damage in either hemisphere resulted in reduced ability to accurately perceive emotional prosody, indicating that normal participants may be utilizing resources in both hemispheres to process emotional content.

If both hemispheres are involved in emotional perception, why does the Dichotic Emotions task show a LEA? Perhaps the lateralization of emotional processing varies depending on the degree to which a task demands discrimination based on spectral pitch, intensity, or temporal cues. If so, the right hemisphere advantage that is typically observed on the Dichotic Words task indicates that the stimuli are predominantly discriminated based on spectral pitch and/or intensity cues. If emotional stimuli were selected or redesigned to force discrimination based on duration cues, a left hemisphere advantage might be expected.

If the perception of emotional prosody is driven solely by spectral pitch, intensity, and/or temporal processes, there may not be an independent resource that is specialized for auditory emotional processing. Here, it is important to keep in mind that the previously identified

Auditory Emotional resource was deemed independent based on statistical evidence of independence from the other processes that were represented in past research (Boles, 1996; Boles & Pasquarette, 1996). The independence of these processes from each other was and is also supported by cognitive neuroscience research, e.g. the separation of auditory emotional processing and auditory linguistic processing is well-supported (e.g. Ley & Bryden, 1982). However, auditory emotional processing may overlap or depend upon multiple, previously unconsidered auditory processes (i.e. spectral pitch, intensity, & duration processes). This means that once measures of spectral pitch, intensity and duration processes are examined and compared with measures of emotional processing, it may become clear that there is no independent auditory emotional resource.

This is a problem that factor analysis is well suited to solve, since the relationship between multiple processes can be determined simultaneously. However, given the nonsignificance of some of the measures needed for these comparisons, this remains an unsolved problem that could be addressed with future research of this kind.

Resource(s) for timbre processing. Likewise, future factor analytic explorations of timbre processing are needed. Like auditory emotional processing, timbre processing may require collaborative engagement of multiple resources. Variations in spectral pitch, intensity, and temporal information are all considered to be important for timbral and prosodic processing (Brancucci & San Martini, 1999, 2003; Goydke, Altenmuller, Moller, & Munte, 2004; San Martini et al., 1994). So, it is possible that timbre is not represented by a unique resource. Instead, it may be driven by the resources that process spectral pitch, intensity, and temporal information. Future research should be conducted to determine whether timbre perception is driven by separate feature-specific resources. Multiple resources would be predicted which are

each specialized for the processing steady state spectral information or the temporally fluctuating information (i.e. changes in spectral pitch and intensity).

Resource(s) for auditory temporal processing. Finally, the inclusion of temporal tasks was intended to test a theoretical proposal made by many researchers, that a common left lateralized resource underlies the processing of linguistic information and rapid temporal information. While the current findings indicate that auditory linguistic processing is left lateralized, no conclusions can be made about the relationship of that Auditory Linguistic resource with the processing of rapid temporal information.

The temporal tasks used within the current study were also strategically selected to allow for a contrast between processing of fast temporal information and slow temporal information, two types of temporal information that researchers have hypothesized to the left and right hemisphere, respectively (Poeppel, 2003). Since, both types of temporal tasks failed to show significant asymmetries, no conclusions can be made regarding the functional dichotomy proposed by the AST hypothesis. This is unfortunate, since direct tests of the AST hypothesis have been primarily based upon contrasts of functional neural activity, without consideration of performance asymmetries.

Suggestions for Use and Improvement of Future Factor Analytic Research

The uncertainty about Temporal, Timbre, Prosody, and Intensity resources provides a potential path forward to future factor analytic research of auditory perceptual asymmetries. Factor analysis of behavioral data has advantages and is able to supply information that is not available or would be difficult to acquire through more direct observation of underlying resources (e.g. neuroimaging). However, like all behavioral methods, a researcher's ability to find meaningful results depends upon the quality of data produced by one or more measures.

The following sections contain suggestions for selecting and developing asymmetry measures so that useful data will be more likely – but first a discussion of why researchers should bother, an argument for the merits of behavior-based factor analysis for the identification of perceptual resources.

Strengths of Factor Analytic Methods. First, the use of factor analysis permits the within-subject comparison of multiple asymmetric processes, which allows for a direct comparison of the lateralization of multiple tasks. In contrast, previous investigations of these processes have typically employed separate research studies to examine the separate neural mechanisms that appear to support each process. While comparisons of separate findings can serve to elucidate the mechanisms responsible for different types of processing, it is not possible to determine the relationship of these separately measured processes without more direct, within-subject functional contrasts.

Second, factor analyses of behavioral data can alleviate concerns over sampling error that arise due to the small sample sizes that are often used within imaging experiments. There are individual differences in degree and even direction of lateralization (e.g. Boles & Barth, 2011; Savel, 2009). So, the smaller the sample size the greater the potential that a random sample will misrepresent the population's average processing asymmetry, due to sampling error. A large sample size is required to meet the statistical demands of factor analysis, and a benefit of this increased sample size is increased confidence in the representativeness of the sample's performance asymmetries and the modeled independence between asymmetric resources.

Finally, factor analyses of behavioral measures have the advantage of indicating resources that are based on human performance. In some cases, the use of behavioral data can serve to confirm the resource relationships that have been proposed by researchers based on

other behavioral studies and neuroimaging data. However, it is clear that behavioral asymmetries do not always agree with the functional asymmetries measured via neuroimaging, so factor analyses may also serve to amend theoretical models of auditory asymmetry. In either case, factor analyses of this kind provide an additional tool for the examination of comprehensive models of perceptual resources.

Suggestions for Selecting and Developing Asymmetry Tasks.

Select Historically Significant and Reliable Tasks. The history of laterality research has no shortage of conflicting findings and failed replications. This is part of the reasoning for using pre-proven tasks in the current study – measures that have been shown to reliably detect the expected hemispheric asymmetry – typically through multiple previous replications since reports of statistical reliability are rare.

Although all of the current tasks were designed based on previously used tasks, some were modified slightly, which may have attributed to their unexpected failure as measures of hemispheric asymmetry. There are situations in which modifications may be needed to test a specific hypothesis, but pilot testing is recommended when any changes are made.

Pilot test new or modified tasks. In the present study, several tasks were modified for time and two were modified to test the relationship between fast temporal processing and slow temporal processing. While almost all of the tasks produced asymmetries in the predicted direction, the resulting effects were not significant and in many cases unreliable. Pilot testing was conducted to verify that the modified tasks were producing results that replicated the expected asymmetries. However, it is possible that the truncated tasks resulted in more within subject variability in performance. Such measurement error may explain the lack of significance, and would also reduce the reliability of the measurement.

The tasks that were modified to test theoretical assumptions about temporal processing proved to be quite difficult for the participants. These tasks were also piloted, and the pilot sample's performance was significantly above chance and indicated trends towards the expected asymmetries. Yet overall performance in the full study was quite poor for these tasks.

Future researchers should take additional care during pilot testing to ensure that asymmetries produced by modified tasks are stable. This may mean recruiting a sample size that is larger than may typically be used for pilot testing to be certain that asymmetries are not only significant, but also highly reliable.

Pilot test old, unmodified tasks. If an auditory task is being adopted from another researcher's work or is being implemented on new equipment, it is very important to carefully measure the stimulus properties and to pilot that task. Most measures of auditory asymmetry employ dichotic stimulation, meaning that the presence and magnitude of asymmetry is often dependent on the relationship between stimuli in the two ears.

For example, behavioral asymmetry of pitch perception varies depending on the pitches that are presented to each ear (Sidtis, 1981). When dichotic tones are close in fundamental frequency, larger asymmetries arise than when tones are further apart in pitch. Different computer equipment, headphones, and speakers will produce different spectral properties, so it is critical that researchers check the fidelity of the sound using sound testing equipment. Sound testing equipment such as sound pressure level meters can also be used to ensure that the sounds are being produced at the desired intensity at all presented frequencies. Research has also shown that ear advantages are affected by the amplification of sound in one ear relative to the other (Hugdahl, Westerhausen, Alho, Medvedev, & Hamalainen, 2008).

Finally, pilot testing should be conducted to make sure that expected asymmetries are evident and that task difficulty appears to be at the desired level. The relative intensity of contralateral masking stimuli can be manipulated to make the detection of the target stimuli easier. These manipulations may not always be reported in the literature, so it is important that researchers check for these performance issues prior to full data collection.

Select as many tasks as time will allow. One of the ways to prevent a process from being untestable in factor analytic research is make sure there are ample measures that could produce reliable asymmetries. In the current study, some processes (e.g. emotional prosody, intensity) were measured by no more than a pair of variables. In areas with tasks that are tried and true (e.g. auditory linguistic processing) this may be adequate, but task over-selection may be warranted in areas where asymmetries are less predictable. If a strategy of over-selection is adopted, it should be more likely that an asymmetric process will be represented by one or more measures of asymmetry, even in cases where some measures may fail.

Implications of Current Findings for the MRQ

Consideration of the suggestions listed above should lead to success in the factor analytic research that is needed to untangle various domains of auditory perceptual processing. Despite the remaining uncertainty about the relationship between the discussed resources, the current findings represent a step towards identifying all independent auditory resources. The knowledge of the Auditory Spectral Pitch resource and the possibility of the Auditory Intensity resource both have implications for the assessment of task workload and the prediction of task performance.

If Auditory Spectral Pitch processing and Auditory Intensity processing are driven by independent cortical resources, Multiple Resource Theory would predict that demands upon

these resources are also mostly independent – "mostly" because there is often a small performance cost that is incurred in dual-task situations regardless of task combinations, perhaps due to the need to coordinate between tasks or to a general resource (Boles et al., 2007). However, the performance costs of dual-task engagement would be reduced when concurrent tasks require different independent resources, e.g. in the case of a spectral pitch discrimination task and an intensity discrimination task (Just et al., 2001; Klingberg & Roland, 1997).

This means that performance on a task that demands processing from one resource (e.g. Auditory Spectral Pitch resource) should be less affected by engagement in a second task that utilizes a different resource (e.g. Visual Temporal resource) compared to a dual-task situation in which both tasks place demands upon the same resource. The resource separations indicated by factor analytic research were the basic foundation for the creation of the multiple resources questionnaire (MRQ: Boles & Adair, 2001a). Each item in the MRQ represents a resource which is specialized for a unique type of processing.

If the Auditory Spectral Pitch resource and the Auditory Intensity resource are independent from the resources currently represented in the MRQ, completeness of the questionnaire would be improved by the addition of items to measure the demands upon these resources. However, the utility of these additions is uncertain, because the independence of spectral pitch processing and intensity processing is uncertain.

While all current evidence indicates that the Auditory Spectral Pitch resource is independent from the currently modeled resources, there is one resource that is already represented in the MRQ which could theoretically demand Auditory Spectral Pitch processing. This resource is the Auditory Emotional resource, which allows for the processing and discrimination of auditory emotional information. If Auditory Emotional processing is

dependent on the Auditory Spectral Pitch resource, as some researchers have suggested, subjective rating of demand upon each of these survey items are also likely to be interdependent. Determining whether or not these processes are separate is a critical step towards determining what sort of modification needs to be made to the MRQ to have a complete survey of independent auditory perceptual resources.

Likewise, the uncertainty surrounding the Auditory Intensity resource also needs to be resolved before an item is formally added to the MRQ to represent the demands of processing auditory intensity. Additionally, solving the mysteries of timbre and auditory temporal perception may also reveal cause to further modify the auditory portion of the MRQ.

The resolution of these uncertainties offers a clear path forward for future research. The relationship between these processes could be clarified using by using one or more of a variety of research methods. With more reliable data, the factor analytic method would be one way to determine whether these processes are independent. Another option would be to employ dual task methods and determine whether performance on one type of task (i.e. emotional) interferes with performance of a concurrent task of another type (i.e. spectral pitch).

Conclusion

In summary, the current study found evidence for the existence and independence of two novel auditory perceptual resources: an Auditory Spectral Pitch resource, and an Auditory Intensity Resource. However, the reliability of the measure thought to represent intensity processing was questionable, and the existence of several theoretically plausible resources and resource relationships could not be tested because respective measures were nonsignificant and/or unreliable. The Auditory Spectral Pitch resource and the Auditory Intensity resource should be considered for addition to the multiple resources questionnaire (MRQ), but further

research should be conducted to confirm the independence of these resources and to determine whether further additions or modifications are warranted in order to fully represent the resources responsible for auditory perceptual processing.

Future research should aim to explore the resource structure that underlies perceptual processing for timbre, temporal information, emotional prosody, spectral pitch, and intensity. Further, if multiple processes are believed to drive timbre and emotional perception, it may be worthwhile to select tasks so that each demands a specific type of processing. For example, timbre tasks can be designed so that discrimination must be made based on intensity information or pitch information. Factor analytic methods would be ideal if these multiple processes are to be compared simultaneously. If fewer tasks are selected, the above-described dual task methodology could be utilized to determine whether task-pairings result in performance interference; relatively noninterfering tasks may be driven by independent resources. Dual-task methodology is also a viable option to examine the resource(s) required for auditory spatial processing. Since the asymmetry of auditory spatial perception is not easily tested, a dual-task study may be used to test for the independence of auditory spatial processing from other types of auditory processing.

References

American Speech-Language-Hearing Association (1978). Guidelines for manual pure-tone threshold audiometry. *Asha, 20*, 297-301.

Angenstein, N., & Brechmann, A. (2013). Division of labor between left and right human auditory cortices during the processing of intensity and duration. *NeuroImage, 83,* 1-11.

Baum, S. R. & Pell, M. D. (1999). The neural bases of prosody: Insights from lesion studies and neuroimaging. *Aphasiology, 13*(8), 581-608.

Belin, P., McAdams, S., Smith, B., Savel, S., Thivard, L., Samson, S., & Samson, Y. (1998). The functional anatomy of sound intensity discrimination. *The Journal of Neuroscience, 18* (16), 6388-6394.

Belin, P., Zilbovicius, M., Crozier, S., Thivard, L., Fontaine, A., Masure, M., & Samson, Y. (1998). Lateralization of speech and auditory processing. *Journal of Cognitive Neuroscience, 10*(4), 536-540.

Blumstein, S. & Cooper, W. E. (1974). Hemispheric processing of intonation contours. *Cortex, 10*, 146-158.

Boemio, A., Fromm, S., Braun, A., & Poeppel, D. (2005). Hierarchical and asymmetric temporal sensitivity in human auditory cortices. *Nature Neuroscience, 8*(3), 389-395.

Boles, D. B. (1991). Factor analysis and the cerebral hemispheres: Pilot study and parietal functions. *Neuropsychologia, 29,* 59-91.

Boles, D. B. (1992). Factor analysis and the cerebral hemispheres: Temporal, occipital and frontal functions. *Neuropsychologia, 30,* 963-988.

Boles, D. B. (1996). Factor analysis and the cerebral hemispheres: "Unlocalized" functions. *Neuropsychologia, 34,* 723-736.

Boles, D. B. (1998a). Relationships among multiple task asymmetries I. A critical review. *Brain and Cognition, 36,* 253-267.

Boles, D. B. (1998b). Relationships among multiple task asymmetries II. A large-sample factor analysis. *Brain and Cognition, 36,* 268-289.

Boles, D. B. (2011). Socioeconomic status, a forgotten variable in lateralization development. *Brain and Cognition, 76,* 52-57.

Boles, D. B. & Adair, L. P. (2001a). The Multiple Resources Questionnaire (MRQ). *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 45*, 1790-1794.

Boles, D. B. & Adair, L. P. (2001b). Validity of the Multiple Resources Questionnaire (MRQ). *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 45*, 1795-1799.

Boles, D. B. & Barth, J. M. (2011). Does degree of asymmetry relate to performance? A critical review. *Brain & Cognition, 76*, 1-4.

Boles, D. B., Barth, J. M., & Merrill, E. C. (2008). Asymmetry and performance: Towards a neurodevelopmental theory. *Brain and Cognition, 66*, 124-139.

Boles, D. B., Bursk, J. H., Phillips, J. B., & Perdelwitz, J. R. (2007). Predicting dual-task performance with the Multiple Resources Questionnaire (MRQ). *Human Factors: The Journal of the Human Factors and Ergonomics Society, 49*, 32-45.

Boles, D.B., & Dillard, M. (in press). The measurement of perceptual resources. In *Cambridge Handbook of Applied Perception Research*.

Boles, D. B. & Law, M. B. (1998). A simultaneous task comparison of differentiated and undifferentiated hemispheric resource theories. *Journal of Experimental Psychology: Human Perception and Performance, 24*(1), 204-215.

Boles, D. B. Phillips, J. B., Perdelwitz, J. R., & Bursk, J. H. (2004). Application of the Multiple Resources Questionnaire (MRQ) to a complex gaming environment. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 48*, 1968-1972.

Brancucci, A., D'Anselmo, A., Martello, F., & Tommasi, L. (2008). Left hemisphere specialization for duration of musical and speech sounds. *Neuropsychologia,46*, 2013-2019.

Brancucci, A., Babiloni, C., Rossini, P. M., & Romani, G. L. (2005). Right hemisphere specialization for intensity discrimination of musical and speech sounds. *Neuropsychologia, 43*, 1916-1923.

Brancucci, A., Franciotti, R., D'Anselmo, A., della Penna, S., & Tommasi, L. (2011). The sound of consciousness: Neural underpinnings of auditory perception. *The Journal of Neuroscience, 46*, 16611-16618.

Brancucci, A. & San Martini, P. (2003). Hemispheric asymmetries in the perception of rapid (timbral) and slow (nontimbral) amplitude fluctuations of complex tones. *Neuropsychology, 17*(3), 451-457.

Brancucci, A. & San Martini, P. (1999). Laterality in the perception of temporal cues of musical timbre. *Neuropsychologia, 37*, 1445-1451.

Brandeis, R. & Babkoff, H. (1984). Sorting of hemifield presented temporal and spatial stimuli. *Cortex, 20*, 179-192.

Bryden, M. P. (1982). *Laterality: Functional asymmetry in the intact brain*. New York, NY: Academic Press.

Bryden, M. P., Ley, R. G., & Sugarman, J. H. (1982). A left-ear advantage for identifying the emotional quality of tonal sequences. *Neuropsychologia, 20*(1), 83-87.

Butler, R. A. (1994). Asymmetric performances in monaural localization of sound in space. *Neuropsychologia, 32*(2), 221-229.

Cattell, R. B. (1966). The Scree test for the number of factors. *Multivariate Behavioral Research, 1*, 245-276.

Doehring, D. G. (1972). Ear asymmetry in the discrimination of monaural tonal sequences. *The Canadian Journal of Psychology, 26*, 106-110.

Davis, B., Christie, J., & Rorden, C. (2009). Temporal order judgments activate temporal parietal junction. *The Journal of Neuroscience, 29*(10), 3182-3188.

Deouell, L. Y., Heller, A. S., Malach, R., D'Esposito, M., & Knight, R. T., (2007). Cerebral responses to change in spatial location of unattended sounds. *Neuron, 55*, 985-996.

Erhan, H., Borod, J. C., Tenke, C. E., & Bruder, G. E. (1998). Identification of emotion in a dichotic listening task: Event-related brain potential and behavioral findings. *Brain and Cognition, 37,* 286-307.

Farah, M. J., Feinberg, T. E. (2000). A historical perspective on cognitive neuroscience. In *Patient-based approaches to cognitive neuroscience* (pp. 1-20). Cambridge, MA: MIT Press.

Field, A. (2013). *Discovering Statistics Using IBM SPSS Statistics*. London: SAGE Publications.

Finomore, V. S., Shaw, T. H., Warm, J. S., Matthews, G., Boles, D. B. (2013). Viewing the workload of vigilance through the lenses of the NASA-TLX and the MRQ. *Human Factors, 56* (1), 1-22.

Finomore, V. S., Shaw, T. H., Warm, J. S., Matthews, G., Riley, M. A., Boles, D. B., & Weldon, D. (2008). Measuring the workload of sustained attention: Further evaluation of the Multiple Resources Questionnaire. *Proceedings of the Human Factors and Ergonomics Society, 52*, 1209-1213.

Gandour, J., Tong, Y., Wong, D., Talavage, T., Dzemidzic, M., Xu, Y., … Lowe, M. (2004). Hemispheric roles in the perception of speech prosody. *NeuroImage, 23*, 344-357.

Garcia, A., Finomore, V., Burnett, G., Baldwin, C., & Brill, C. (2012). Individual differences in multimodal waypoint navigation. *Proceedings of the Human Factors and Ergonomics Society, 56*, 1538-1543.

Getzmann, S., & Lewld, J. (2010). Effects of natural versus artificial spatial cues on electrophysiological correlates of auditory motion. *Hearing Research, 259*, 44-54.

Gorsuch, R. L. (1983). *Factor analysis* (2nd ed.). Hillsdale, NJ: Ericbaum.

Goydke, K. N., Altenmuller, E., Moller, J., Munte, T. F. (2004). Changes in emotional tone and instrumental timbre are reflected by mismatch negativity. *Cognitive Brain Research, 21,* 351-359.

Greenlee, E. T., & Boles, D. B. (2014). Multimodal spatial discrimination in the face of uncertainty: The effects of action video game expertise. *Proceedings of the Human Factors and Ergonomics Society, 58*, 1419-1423.

Halperin, Y., Nachshon, I., & Carmon, A. (1973). Shift of ear superiority in dichotic listening to temporally patterned nonverbal stimuli. *Journal of the Acoustical Society of America, 53*, 46-50.

Herholz, S. C. & Zatorre, R. J. (2012). Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron, 76*, 486-502.

Hirnstein, M., Hausmann, M., & Lewald, J. (2006). Functional cerebral asymmetry in auditory motion perception. *Laterality, 12* (1), 87-99.

Hirnstein, M., Westerhausen, R., Hugdahl, K. (2013). The right planum temporale is involved in stimulus-driven auditory attention – Evidence from Transcranial Magnetic Stimulation. *PLoS ONE, 8*(2), e57316.

Hugdahl, K., Westerhausen, R., Alho, K., Medvedev, S., & Hamalainen, H. (2008). The effect of stimulus intensity on the right ear advantage in dichotic listening. *Neuroscience Letters, 431*, 90-94.

Hyde, K. L., Peretz, I., & Zatorre, R. J. (2008). Evidence for the role of the right auditory cortex in fine pitch resolution. *Neuropsychologia, 46*, 632-639.

Ivarsson, C., De Ribaupierre, Y., & De Ribaupierre, F. (1980). Functional ear asymmetry in vertical localization. *Hearing Research, 3*, 241-247.

Jancke, L., Shah, N. J., Posse, S., Grosse-Yruken, M., & Muller-Gartner, H. W. (1998). Intensity coding of auditory stimuli: An fMRI study. *Neuropsychologia, 36*, 875-883.

Just, M. A., Carpenter, P. A., Keller, T. A., Emery, L., Zajac, H., & Thulborn, K. R. (2001). Interdependence of nonoverlapping cortical systems in dual cognitive tasks. *Neuroimage, 14,* 417–426.

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Education and Psychological Measurement, 20*, 141-151.

Kaiser, H. F. (1961). A note on Guttman's lower bound for the number of common factors. *British Journal of Psychology 14*, 1-2.

Kimura, D. (2011). From ear to brain. *Brain and Cognition, 76*, 214-217.

Kimura, D. (1961). Cerebral dominance and the perception of verbal stimuli. *Canadian Journal of Psychology, 15*, 617-618.

King, F. L. & Kimura, D. (1972). Left-ear superiority in dichotic perception of vocal nonverbal sounds. *Canadian Journal of Psychology, 26*(2), 111-116.

Klingberg, T. & Roland, P.E. (1997). Interference between two concurrent tasks is associated with activation of overlapping fields in the cortex. *Cognitive Brain Research, 6*, 1-8.

Kline, R. (2013). Exploratory and confirmatory factor analysis. In Y. Petscher, C. Schatschneider, & D. L. Compton (Eds.). *Applied quantitative analysis in education and the social sciences* (171-207). New York, NY: Routledge.

Kolb, B. & Whishaw, I. Q. (2009). *Fundamentals of Human Neuropsychology,* 6th edition. New York, NY: Worth Publishers.

Ley, R. G. & Bryden, M. P. (1982). A dissociation of right and left hemispheric effects for recognizing emotional tone and verbal content. *Brain and Cognition, 1*, 3-9.

Luks, T. L., Nusbaum, H. C., & Levy, J. (1998). Hemispheric involvement in the perception of syntactic prosody is dynamically dependent on task demands. *Brain and Cognition, 65*, 313-332.

Mathiak, K., Hertrich, I., Lutzenbergerm, W., & Ackermann, H. (2002). Functional cerebral asymmetries of pitch processing during dichotic stimulus application: A whole-head magnetoencephalography study. *Neuropsychologia, 40*, 585-593.

Mendonça, C., Campos, G., Dias, P., Vieira, J., Ferreira, J. P., & Santos, J. A. (2012). On the improvement of localization accuracy with nonindividualized HRTF-based sounds. *Journal of the Audio Engineering Society, 60* (10): 821-830.

Merzenich, M. M., Knight, P. L., and Roth, G. L. (1975). Representation of cochlea within primary auditory cortex in the cat. *Journal of Neurophysiology, 38*(2), 231-249.

Middlebrooks, J. C. (1999). Individual differences in external-ear transfer functions reduced by scaling in frequency. *Journal of the Acoustic Society of America, 106* (3), 1480-1492.

Mills, L. & Rollman, G. B. (1979). Left hemisphere selectivity for processing duration in normal subjects. *Brain and Language, 7,* 320-335.

Minifie, F. (1973). Speech acoustics. In F. Minifie, T. Hixon, and F. Williams (Eds.) *Normative aspects of speech, hearing, and language.* Englewood Cliffs, NJ: Prentice-Hall.

Moore, B. C. J. (1997). *An introduction to the psychology of hearing* (4th ed.). London: Academic Press.

Morais, J., Peretz, I., Gudanski, M., & Guiard (1982). Ear asymmetry for chord recognition in musicians and nonmusicians. *Neuropsychologia, 20* (3), 351-354.

Natale, M. (1977). Perception of nonlinguistic auditory rhythms by the speech hemisphere. *Brain and Language, 4*, 32-44.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97-113.

Papcun, G., Krashen, S., Terbeek, D., Remington, R., & Harshman, R. (1974). Is the left hemisphere specialized for speech, language, and/or something else? *Journal of the Acoustical Society of America, 55*, 319-327.

Peters, M. (1995). Handedness and its relation to other indices of cerebral lateralization. In R.J. Davidson & K. Hugdahl (Eds.), *Brain asymmetry* (pp. 183-214). Cambridge, MA: MIT Press.

Phillips, J. B. & Boles, D. B. (2004). Multiple resources questionnaire and workload profile: Application of competing models to subjective workload measurement. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 48*, 1963-1967.

Plomp, R. (1967). Pitch of complex tones. *The Journal of the Acoustical Society of America, 41*(6), 1526-1533.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as 'asymmetric sampling in time'. *Speech Communication, 41*, 245-255.

Reiterer, S., Erb, M., Grodd, W., & Wildgruber, D. (2008). Cerebral processing of timbre and loudness: fMRI evidence for a contribution of Broca's area to basic auditory discrimination. *Brain Imaging and Behavior*. DOI: 10.1007/s11682-007-9010-3

Robinson, G. M., & Solomon, D. J. (1974). Rhythm is processed by the speech hemisphere. *Journal of Experimental Psychology, 1*, 508-511.

Ross, E. D. (2010). Cerebral localization of functions and the neurology of language: Fact versus fiction or is it something else? *The Neuroscientist, 16*(3), 222-243.

Samson, S., Zatorre, R. J., Ramsay, J. O. (1997). Multidimensional scaling of synthetic musical timbre: Perception of spectral and temporal characteristics. *Canadian Journal of Experimental Psychology, 51*(4), 307-315.

Savel, S. (2009) Individual differences and left/right asymmetries in auditory space perception I. Localization of low-frequency sounds in free field. *Hearing Research, 255*, 142-154.

San Martini, P., Filetti, F., Marangon, L., Tasin, N. (1994). Hemispheric asymmetries in the perception of timbre: Dichotic advantage for synthetic stationary tones with different spectral compositions. In: XIII National Congress of basic research in Psychology (S.I.Ps.), *Rivista di Psicologia*, 36-37.

Schlaug, G., Jancke, L., Huang, Y., & Steinmetz, H. (1995). In vivo evidence of structural brain asymmetry in musicians. *Science, 267*, 699-701.

Schneider, P., Sluming, V., Roberts, N., Scherg, M., Goebel, R., Specht, H. J.,…Rupp, A. (2005). Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference. *Nature Neuroscience, 8*(9), 1241-1247.

Shipley-Brown, F., Dingwall, W. O., Berlin, C. I., Yeni-Komshian, G., & Gordon-Salant, S. (1988). Hemispheric processing of affective and linguistic intonation contours in normal subjects. *Brain and Language, 33*, 16-26.

Sidtis, J. J. (1980). On the nature of cortical function underlying right hemisphere auditory perception. *Neuropsychologia, 18*, 321-330.

Sidtis, J. J. (1981). The complex tone test: Implications for the assessment of auditory laterality effects. *Neuropsychologia, 19,* 103-112.

Sidtis, J. J. (2007). Some problems for representations of brain organization based on activation in functional imaging. *Brain and Language, 102*, 130-140.

Sidtis, J. J. & Volpe, B. T. (1988). Selective loss of complex-pitch or speech discrimination after unilateral lesion. *Brain and Language, 34*, 235-245.

Spearman, C. E. (1904). The proof and measurement of association between two things. *American Journal of Psychology, 15*, 72-101.

Spearman, C. E. (2010). Correlation calculated from faulty data. *British Journal of Psychology, 3*, 271-295.

Spierer, L., Bellmann-Thiran, A., Maeder, P., Murray, M. M., & Clarke, S. (2009). Hemispheric competence for auditory spatial representation. *Brain, 132,* 1953-1966.

Stewart, L., von Kriegstein, K., Warren, J. D., & Griffiths, T. D. (2006). Music and the brain: Disorders of musical listening, *Brain, 129*, 2533-2553.

Tallal, P. (1994). In the perception of speech time is of the essence. In G. Buzsaki, R. Llinas, W. Singer, A. Berthoz, & Y. Christen (Eds.), *Temporal coding in the brain* (pp. 291–299). Berlin Heidelberg: Springer-Verlag.

Tenke, C. E., Bruder, G. E., Towey, J. P., Leite, P., & Sidtis, J. J. (1993). Correspondence between brain ERP and behavioral asymmetries in a dichotic complex tone test. *Psychophysiology, 30*, 62.70.

Tervaniemi, M., Medvedev, S. V., Alho, K., Pakhomov, S. V., Roudas, M. S., van Zuijen, T. L., & Naatanen, R. (2000). Lateralized automatic auditory processing of phonetic versus musical information: A PET study. *Human Brain Mapping, 10*, 74-79.

Thompson, B. (2003). Understanding reliability and coefficient alpha really. In B. Thompson (Ed.), *Score Reliability: Contemporary Thinking on Reliability Issues*, 3-23.

Thompson, B. (2004). *Exploratory and confirmatory factor analysis: Understanding concepts and applications*. Washington, DC: American Psychological Association.

Van Lancker, D. & Sidtis, J. J. (1992). The identification of affective-prosodic stimuli by the left- and right-hemisphere damaged subjects: All errors are not created equal. *Journal of Speech and Hearing Research, 35*, 963-970.

Vuust, P., Pallesen, K. J., Bailey, C., van Zuijen, T. L., Gjedde, A., Roepstorff, A., Ostergaard, L. (2005). To musicians, the message is in the meter: Pre-attentive neuronal responses to incongruent rhythm are left-lateralized in musicians. *NeuroImage, 24*, 560-564.

Walker, K. M. M., Bizley, J. K., King, A. J., Schnupp, J. W. H. (2011). Cortical encoding of pitch: Recent results and open questions. *Hearing Research, 271*, 74-87.

Warren, J. D., Jennings, A. R., & Griffiths, T. D. (2004). Analysis of the spectral envelope of sounds by the human brain. *NeuroImage, 24*, 1052-1057.

Webb, N. M., Shavelson, R. J., & Haertel, E. H. (2006). Reliability coefficients and generalizability theory. *Handbook of Statistics, 26*, 1-44.

Wickens, C. D. (1984). *Engineering psychology and human performance* (1st ed.). Columbus, OH: Charles E. Merrill.

Wickens, C. D. (1991). Processing resources and attention. In D. L.Damos (Ed.), *Multiple-task performance* (pp. 3-34). London: Taylor & Francis.

Wickens, C. D. (1992). *Engineering psychology and human performance* (2nd ed.). New York: Harper Collins.-

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science, 3*(2), 159-177.

Wickens, C. D. (2008). Multiple resources and mental workload. *The Journal of the Human Factors and Ergonomics Society, 50*, 449-455.

Wilson, S. J., Lusher, D., Wan, C. Y., Dudgeon, P., & Reutens, D. C. (2009). The neurocognitive components of pitch processing: Insights from absolute pitch. *Cerebral Cortex, 19*, 724-732.

Wioland, N., Rudolf, G., Metz-Lutz, M. N., Mutschler, V., & Marescaux, C. (1999). Cerbral correlates of hemispheric lateralization during a pitch discrimination task: An ERP study in dichotic situation. *Clinical Neurophysiology, 110*, 516-523.

Zatorre, R. J. (1988). Pitch perception of complex tones and human temporal-lobe function. *Journal of the Acoustical Society of America, 84*(2), 566-572.

Zatorre, R. J, Belin, P., & Penhume, V. B. (2002). Structure and function of auditory cortex: Music and speech. *TRENDS in Cognitive sciences, 6*(1), 37-46.

Zatorre, R. J., Evans, A. C., & Meyer, E. (1994). Neural mechanisms underlying melodic perception and memory for pitch. *The Journal of Neuroscience, 14*(4), 1908-1919.

Zatorre, R. J., Mondor, T. A. & Evans, A. C. (1999). Auditory attention to space and frequency activates similar cerebral systems. *NeuroImage, 10*, 544-554.

Zurif, E. B. (1974). Auditory Lateralization: Prosodic and syntactic factors. *Brain and Langauge, 1*, 391-404.

Appendix A

MULTIPLE RESOURCES QUESTIONNAIRE   for task_____

The purpose of this questionnaire is to characterize the nature of the mental processes used in the task with which you have become familiar. Below are the names and descriptions of several mental processes. Please read each carefully so that you understand the nature of the process. Then rate the task on the extent to which it uses each process, using the following scale.

No Usage	Light Usage	Moderate Usage	Heavy Usage	Extreme Usage
0	25	50	75	100
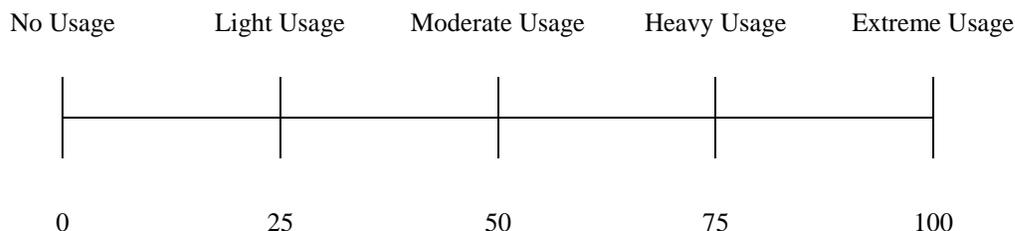
Important:

All parts of a process definition should be satisfied for it to be judged as having been used. For example, recognizing geometric figures presented visually should **not** lead you to judge that the "Tactile figural" process was used, just because figures were involved. For that process to be used, figures would need to be processed tactilely (i.e., using the sense of touch).

Please judge the task as a **whole**, averaged over the time you performed it. If a certain process was used at one point in the task and not at another, your rating should **not** reflect "peak usage" but should instead reflect **average** usage over the entire length of the task.

Auditory emotional process -- Required judgments of emotion (e.g., tone of voice or musical mood) presented through the sense of hearing.   ____

Auditory linguistic process -- Required recognition of words, syllables, or other verbal parts of speech presented through the sense of hearing.   ____

Facial figural process -- Required recognition of faces, or of the emotions shown on faces, presented through the sense of vision.   ____

Facial motive process -- Required movement of your own face muscles, unconnected to speech or the expression of emotion.   ____

Manual process -- Required movement of the arms, hands, and/or fingers.   ____

Short term memory process -- Required remembering of information for a period of time ranging from a couple of seconds to half a minute.   ____

Spatial attentive process – Required focusing of attention on a location, using the sense of vision.   ____

Spatial categorical process – Required judgment of simple left-versus-right or up-versus-down relationships, without consideration of precise location, using the sense of vision.   ____

Spatial concentrative process -- Required judgment of how tightly spaced are numerous visual objects or forms.   ____

Spatial emergent process -- Required "picking out" of a form or object from a highly cluttered or confusing background, using the sense of vision.   ____

Spatial positional process -- Required recognition of a precise location as differing from other locations, using the sense of vision.   ____

Spatial quantitative process -- Required judgment of numerical quantity based on a nonverbal, nondigital representation (for example, bargraphs or small clusters of items), using the sense of vision.   ____

Tactile figural process -- Required recognition or judgment of shapes (figures), using the sense of touch.   ____

Visual lexical process -- Required recognition of words, letters, or digits, using the sense of vision.   ____

Visual phonetic process -- Required detailed analysis of the sound of words, letters, or digits, presented using the sense of vision.   ____

Visual temporal process -- Required judgment of time intervals, or of the timing of events, using the sense of vision.   ____

Vocal process -- Required use of your voice.   ____

Experience, Expertise, and Hobbies Questionnaire

Instructions: *Please provide the following information regarding your hobbies and experiences. If you have any questions please ask the experimenter.*

Please specify your sex_____

Please specify your age_____

- Do you play any video games? yes/no
    - *If yes please answer the following questions. If no, please skip to next bullet point*

1.) At what age did you begin playing video games?_____

2.) How recently have you played video games? Please give a numeric answer with units (e.g. 1 day ago) unless the answer is today. _____

3.) Indicate your whether you agree or disagree with the following statements
   (*1= Strongly Disagree, 2=Disagree, 3=Neither Agree Nor Disagree, 4=Agree, 5=Strongly Agree*)

   a. Since I started playing video games, I have played continuously ever since_____

   b. I play videogames with others, either online or in-person, with the deliberate attempt to improve my performance_____

   c. I try to earn accomplishments within games that are not necessarily tied to pleasure (e.g. trophies, achievements, kill-to-death ratio) _____

4.) Estimate the average number of hours per week you have spent… *(Circle One)*
   a. playing video games during the time in your life when you played them the most
       0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

   b. playing videogames in the past 2 years
       0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

   c. Researching strategy for video game play within the last two years (e.g. watching instructional videos, reading strategy guides or articles)

0-1   2-4   5-7   8-10   11-13 14-16 17-19 20+

d. Playing videogames in the past 6 months
0-1   2-4   5-7   8-10   11-13 14-16 17-19 20+

e. Researching strategy for video game play within the last 6 months (e.g. watching instructional videos, reading strategy guides or articles)
0-1   2-4   5-7   8-10   11-13 14-16 17-19 20+

f. Playing video games on a phone or other mobile device in the last 6 months
0-1   2-4   5-7   8-10   11-13 14-16 17-19 20+

g. Playing video games on a console, PC, or MAC in the last 6 months
0-1   2-4   5-7   8-10   11-13 14-16 17-19 20+

5.) Please consider video game-play **within the last 6 months** and fill out the chart below.

Game Categories	How many hours per week? (Average Hours)	How Many Games?	Versus Online Play? (hours per week)	Which Is Your Favorite Category? (Checkmark)	Which Are You Best At? (Checkmark)
Adventure & Fantasy (e.g. Mario, WoW)					
Flight & Racing (Ace Combat, Need For Speed)					
Puzzle (e.g. Tetris, Bust-A-Move)					
Shooters (e.g. Call of Duty, Gears of War)					
Sports & Fighting (FIFA, Mortal Kombat)					
Real-Time Strategy (e.g. Starcraft)					
Other					

6.) Please rate the degree to which you enjoy playing videogames (0=Extremely Dislike, 4=Neither Like Nor Dislike, 8= Extremely Like)

0   1   2   3   4   5   6   7   8

7.) Please rate your level of expertise playing video games in general (0=Novice, 4=Intermediate, 8=Expert)

0   1   2   3   4   5   6   7   8

7.) When you play video games, what type of sound equipment do you use? (*Circle One*)

TV speakers   Headphones   2 Stereo Speakers   Surround Sound   No Sound

8.) When you play video games how often do you feel sound helps you to win or do well in the game? (0=Never, 4= Half the time, 8= Always)

0   1   2   3   4   5   6   7   8

- Do you play any musical instruments? yes/no
  - *If yes please answer the following questions. If no, please skip to next bullet point*

1.) At what age did you begin playing musical instruments?_____

2.) How recently have you played a musical instrument? Please give a numeric answer with units (e.g. 1 day ago) unless the answer is today.

   _____

3.) Indicate your whether you agree or disagree with the following statements
   (*1= Strongly Disagree, 2=Disagree, 3=Neither Agree Nor Disagree, 4=Agree, 5=Strongly Agree*)

   a.   Since I started playing musical instruments, I have played continuously ever since_____

   b.   I play instruments with others, cooperatively or competitively, with the deliberate attempt to improve my performance_____

   c.   I try to earn accomplishments with music that are not necessarily tied to pleasure (e.g. awards, perfecting a musical piece) _____

4.) Estimate the average number of hours per week you have spent… *(Circle One)*
   a.   Playing a musical instrument during the time in your life when you played them the most
        0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

   b.   playing musical instruments in the past 2 years
        0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

   c.   Researching for musical instrument play within the last two years (e.g. watching instructional videos, reading about techniques, Instruction from others)
        0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

   d.   Playing a musical instrument in the past 6 months
        0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

   e.   Researching for musical instrument play within the last 6 months (e.g. watching instructional videos, reading about techniques, Instruction from others)
        0-1   2-4   5-7   8-10   11-13   14-16   17-19   20+

5.) Please consider instrument play **within the last 6 months** and fill out the chart below.

Instrument Categories	How many hours per week? (Average Hours)	How Many songs played?	Do you play with others? (average hours per week)	Which Is Your Favorite Category? (Checkmark)	Which Are You Best At? (Checkmark)
Brass (e.g. Trumpet, Tuba)					
Keys (e.g Keyboard, Piano)					
Percussion (e.g. Drums)					
Strings (e.g. Guitar, Violin)					
Woodwinds (Clarinet, Saxophone)					
Other					

6.) Please rate the degree to which you enjoy playing musical instruments (0=Extremely Dislike, 4=Neither Like Nor Dislike, 8= Extremely Like)

0   1   2   3   4   5   6   7   8

7.) Please rate your level of expertise playing musical instruments in general (0=Novice, 4=Intermediate, 8=Expert)

0   1   2   3   4   5   6   7   8

8.) Have you ever received formal musical training or taken lessons? If so, during what ages did you take lessons, and for how many hours per week?

9.) Can you identify a note played or sung without any reference? In other words, if someone sang or played a note would you be able to say what that note was with certainty? yes/no

10.) Can you identify a note played or sung <u>with</u> a reference? In other words, if someone played or sang a note while you are able to hear a tuning note (a note that you know), would you be able to identify the note being played or sung? yes/no

Appendix C

Proposed Confirmatory Models

Table 9

Confirmatory factor model for the asymmetrical sampling in time (AST) hypothesis, a three

factor model

Latent Resource Identity	Resource Lateralization	Observed Variables	
		Task	Measures
Fast Resource	Left Hemisphere	Dichotic Words	Accuracy (LC), Order (LC)
		Visual Onsets	Accuracy (LC), RT
		Duration Fast Tones	Accuracy (LC), RT
		Duration Fast Speech	Accuracy (LC), RT
		Timbre Fast	Accuracy (LC), RT
Slow Resource	Right Hemisphere	Spectral Oddball	Accuracy (LC), RT
		Complex Tone Test	Accuracy (LC), RT
		Temporal Sequencing	Accuracy (LC)
		Timbre Steady	Accuracy (LC), RT
		Timbre Slow	Accuracy (LC), RT
		Duration Slow Tones	Accuracy (LC), RT
		Dichotic Emotions	Accuracy (LC)
Intensity Resource	Right Hemisphere	Intensity	Accuracy (LC), RT

Table 10

Confirmatory factor model for the perceptual feature model, a six factor model

Latent Resource Identity	Resource Lateralization	Observed Variables	
		Task	Measures
Verbal Resource	Left Hemisphere	Dichotic Words	Accuracy (LC), Order (LC)
Emotional Resource	Right Hemisphere	Dichotic Emotions	Accuracy (LC)
Temporal Resource	Left Hemisphere	Visual Onsets	Accuracy (LC), RT
		Temporal Sequencing	Accuracy (LC)
		Duration Fast Tones	Accuracy (LC), RT
		Duration Fast Speech	Accuracy (LC), RT
		Duration Slow Tones	Accuracy (LC), RT
Intensity Resource	Right Hemisphere	Intensity	Accuracy (LC), RT
Pitch Resource	Right Hemisphere	Complex Tone Test	Accuracy (LC), RT
		Spectral Oddball	Accuracy (LC), RT
Timbre Resource		Timbre Slow	Accuracy (LC), RT
		Timbre Steady	Accuracy (LC), RT
		Timbre Fast	Accuracy (LC), RT

Table 11

Confirmatory factor model for the physical feature model, a four factor model

Latent Resource Identity	Resource Lateralization	Observed Variables	
		Task	Measures
Temporal Fast & Verbal Resource	Left Hemisphere	Dichotic Words	Accuracy (LC), Order (LC)
		Temporal Sequencing	Accuracy (LC)
		Duration Fast Tones	Accuracy (LC), RT
		Duration Fast Speech	Accuracy (LC), RT
Temporal Slow Resource	Left Hemisphere	Visual Onsets	Accuracy (LC), RT
		Duration Slow Tones	Accuracy (LC), RT
Pitch Resource	Right Hemisphere	Complex Tone Test	Accuracy (LC), RT
		Spectral Oddball	Accuracy (LC), RT
		Dichotic Emotions	Accuracy (LC)
		Timbre Steady	Accuracy (LC), RT
Intensity Resource	Right Hemisphere	Timbre Slow	Accuracy (LC), RT
		Timbre Fast	Accuracy (LC), RT
		Intensity	Accuracy (LC), RT

Appendix D

May 6, 2014

Office for Research

Institutional Review Board for the
Protection of Human Subjects

THE UNIVERSITY OF
ALABAMA
RESEARCH

Eric Greenlee
Department of Psychology
College of Arts and Sciences
Box 870348

Re: IRB # 14-OR-161, "Sounds of Psychology"

Dear Mr. Greenlee:

The University of Alabama Institutional Review Board has granted
approval for your proposed research.

Your application has been given expedited approval according to 45 CFR
part 46. You have also been granted the requested waiver of informed
consent. Approval has been given under expedited review category 7 as
outlined below:

*(7) Research on individual or group characteristics or behavior
(including, but not limited to, research on perception, cognition,
motivation, identity, language, communication, cultural beliefs or
practices, and social behavior) or research employing survey, interview,
oral history, focus group, program evaluation, human factors evaluation,
or quality assurance methodologies.*

Your application will expire on May 4, 2015. If your research will
continue beyond this date, please complete the relevant portions of the
IRB Renewal Application. If you wish to modify the application, please
complete the Modification of an Approved Protocol Form. Changes in this
study cannot be initiated without IRB approval, except when necessary to
eliminate apparent immediate hazards to participants. When the study
closes, please complete the Request for Study Closure Form.

Should you need to submit any further correspondence regarding this
proposal, please include the above application number.

Good luck with your research.

Sincerely,

Stuart Usdan, Ph.D.
Chair, Non-Medical IRB
The University of Alabama

358 Rose Administration Building
Box 870127
Tuscaloosa, Alabama 35487-0127
(205) 348-8461
FAX (205) 348-7189
TOLL FREE (877) 820-3066