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The Effect of Motor Responses Versus Verbal Responses on Sound Localization Accuracy in Young Children with Normal Hearing

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Abstract

Rationale. Sound localization is the ability to pinpoint the origin of a sound source within an auditory space. This ability is essential for safety, orientation, and communication. Poor sound localization abilities, especially in young children, can have a negative impact on academics and safety. This issue is exacerbated when there is a hearing loss. Young children do not localize as well as adults until age 6 or older. Data regarding sound localization accuracy in preschoolers and young children have been sparse. Recently, with the increasing numbers of cochlear implantation (especially in children) there have been more studies investigating sound localization in children. However, these studies mainly focused on children with hearing impairments. Most of them included children with normal hearing only as a reference or for comparison. Similarities and/or differences in sound source localization accuracy between children who are hearing impaired and those with normal hearing were investigated but the mode(s) of response were not regulated or examined. The literature presents localization accuracy ranges for young children with normal hearing but does not offer any knowledge regarding the effect of various response modes on sound localization accuracy. Younger children with normal hearing show greater localization error than older children with normal hearing. This suggests that the auditory system in younger children is still maturing. There is a need to investigate sound source localization accuracy in young children with normal hearing in order to identify factors that may facilitate this skill. This study explored the effect of a motor (movement) response on sound source localization accuracy compared to the traditional verbal response. The purpose was to identify any actors that could enhance sound source localization accuracy in children who have normal hearing in order to gain insight regarding possible auditory training strategies that could be effective in building sound source localization skills especially in children with hearing impairments and/or less mature auditory systems. It was proposed that embodiment, the incorporation of the body through motor movements within the auditory environment, could facilitate auditory spatial mapping and thus yield better sound localization accuracy." Methods. Sound localization accuracy was examined in young children, aged 3 and 5 years old, with normal hearing. Each participant in both age groups was randomly divided into two groups by response modes (verbal or motor) and asked to localize a sound source using that mode. The sound localization task was then repeated using only the verbal response mode. Testing occurred in a sound booth containing a semi-circular array of 15 loudspeakers placed at 10o intervals along the frontal horizontal plane from - 70o (left) to +70o (right) azimuth. There was a small child-friendly picture attached underneath each loudspeaker for sound source identification purposes. The stimulus was the speech spondee “baseball”. Participants either sat in a chair and verbally stated the location of the origin of the sound by naming the picture underneath the corresponding loudspeaker (verbal response) or by walking over and touching/ pointing to the loudspeaker/picture from which the sound originated (motor response). There were seven (7) sound source (target) locations, with a total of five (5) trials randomly presented from" "each target loudspeaker for a total of 35 trials per task. There were two blocks of trials (tasks)." "Results. Sound localization accuracy was quantified using the root-mean-square error measure. Data was analyzed using the Generalized Estimating Equations – Robust Estimator statistical method. There was a statistically significant main effect for age, with the 5-year-olds showing better performance overall. There was not a significant main effect for mode of response or task order. There was however a significant interaction for age*mode*order. The 3-year-old Verbal 1st Group showed significantly better accuracy for the second sound localization task. The 5-year-old Motor 1st Group showed significantly worse accuracy for the second sound localization task in which they had to provide a verbal response." "Conclusions. Performance improved when the same response mode was used for both sound localization tasks but was degraded when the sound localization task was repeated using a different response mode. The initial motor responses did not facilitate auditory spatial mapping. This could be due to immature auditory pathway development and/or the increased cognitive strain of trying to break the memory pattern formed by the initial motor responses in order to transition to the verbal responses required during the second task. The results showed that children do not perform well when asked to change their mode of response when learning a new skill. Using the same mode of response twice emphasized the benefit of practice and repetition. Practice and repetition may be a more effective training technique than response mode for skill building especially for those who have difficulty with sound localization."

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The Effect of Motor Responses Versus Verbal Responses on Sound Localization Accuracy in Young Children with Normal Hearing

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Of the Requirements for the Degree
Doctor of Philosophy
From The University of Tennessee

By
Karen Ann Martin
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DEDICATION

My decision to go back to school and pursue a doctoral degree came later in my life. I had a young family, and a loving husband who travelled for a living. This combination was not suitable for PhD student, but my family was very supportive, and we made it work. The journey was much longer than I ever thought it would be and I could not have endured to the end without my family. I therefore dedicate this dissertation to them. My husband, James, would not let me quit. He insisted that I continue despite my frequent feelings that I was not being “a good mom”. He was my strength when I was weak. My son, Caleb, also helped me to see the glass as being half full, not half empty. My daughter, Joanna, always sent me pictures, posters, quotes and bible verses to spur me on, and put a screensaver on my phone which says, “keep calm and don’t quit” My mother, Thelma, often said “you must finish”. My middle sister, Andrea told me to “discipline my disappointments”. My youngest sister, Beverley told me to keep “digging for the diamonds” and sent me a picture of a person dressed in lab coat who was digging in a tunnel and turned away in despair not realizing he would have struck diamonds with the next swing of the pickaxe. My nephew, Jaydon told me “you just have to trudge through the mud”. My brother-in-love, Jon reminded me to think about my “why”. My cousin, Cheryl told me “it won’t be as long as it has been”. I also wish to mention Erin Tullis with deep gratitude and appreciation because she often kept my children along with her own while I attended classes. There have been endless prayers and words of encouragement from all my family and many friends throughout my journey, and to all I say, “Thank you very much”.

To James, Caleb and Joanna who put up with, sacrificed and endured the most, this dissertation is dedicated to you. I love you!

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A very special thank you is also warmly expressed to all the parents and guardians who volunteered to bring their children to participate in the dissertation study, and to all the children who participated. This project would not have been completed without your kind assistance.

ABSTRACT

Rationale. Sound localization is the ability to pinpoint the origin of a sound source within an auditory space. This ability is essential for safety, orientation, and communication. Poor sound localization abilities, especially in young children, can have a negative impact on academics and safety. This issue is exacerbated when there is a hearing loss. Young children do not localize as well as adults until age 6 or older. Data regarding sound localization accuracy in preschoolers and young children have been sparse. Recently, with the increasing numbers of cochlear implantation (especially in children) there have been more studies investigating sound localization in children. However, these studies mainly focused on children with hearing impairments. Most of them included children with normal hearing only as a reference or for comparison. Similarities and/or differences in sound source localization accuracy between children who are hearing impaired and those with normal hearing were investigated but the mode(s) of response were not regulated or examined. The literature presents localization accuracy ranges for young children with normal hearing but does not offer any knowledge regarding the effect of various response modes on sound localization accuracy. Younger children with normal hearing show greater localization error than older children with normal hearing. This suggests that the auditory system in younger children is still maturing. There is a need to investigate sound source localization accuracy in young children with normal hearing in order to identify factors that may facilitate this skill. This study explored the effect of a motor (movement) response on sound source localization accuracy compared to the traditional verbal response. The purpose was to identify any actors that could enhance sound source localization accuracy in children who have normal hearing in order to gain insight regarding possible auditory training strategies that could be effective in building sound source localization skills especially in children with hearing impairments and/or less mature auditory systems. It was proposed that embodiment, the incorporation of the body through motor movements within the auditory environment, could facilitate auditory spatial mapping and thus yield better sound localization accuracy.

Methods. Sound localization accuracy was examined in young children, aged 3 and 5 years old, with normal hearing. Each participant in both age groups was randomly divided into two groups by response modes (verbal or motor) and asked to localize a sound source using that mode. The sound localization task was then repeated using only the verbal response mode. Testing occurred in a sound booth containing a semi-circular array of 15 loudspeakers placed at 10^{o} intervals along the frontal horizontal plane from -70^{o} (left) to +70^{o} (right) azimuth. There was a small child-friendly picture attached underneath each loudspeaker for sound source identification purposes. The stimulus was the speech spondee “baseball”. Participants either sat in a chair and verbally stated the location of the origin of the sound by naming the picture underneath the corresponding loudspeaker (verbal response) or by walking over and touching/pointing to the loudspeaker/picture from which the sound originated (motor response). There were seven (7) sound source (target) locations, with a total of five (5) trials randomly presented from each target loudspeaker for a total of 35 trials per task. There were two blocks of trials (tasks).

Results. Sound localization accuracy was quantified using the root-mean-square error measure. Data was analyzed using the Generalized Estimating Equations – Robust Estimator statistical method. There was a statistically significant main effect for age, with the 5-year-olds showing better performance overall. There was not a significant main effect for mode of response or task order. There was however a significant interaction for age*mode*order. The 3-year-old Verbal 1^{st} Group showed significantly better accuracy for the second sound localization task. The 5-year-old Motor 1^{st} Group showed significantly worse accuracy for the second sound localization task in which they had to provide a verbal response.

Conclusions. Performance improved when the same response mode was used for both sound localization tasks but was degraded when the sound localization task was repeated using a different response mode. The initial motor responses did not facilitate auditory spatial mapping. This could be due to immature auditory pathway development and/or the increased cognitive strain of trying to break the memory pattern formed by the initial motor responses in order to transition to the verbal responses required during the second task. The results showed that children do not perform well when asked to change their mode of response when learning a new skill. Using the same mode of response twice emphasized the benefit of practice and repetition. Practice and repetition may be a more effective training technique than response mode for skill building especially for those who have difficulty with sound localization.

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LIST OF ABBREVIATIONS

BiCI	Bilateral Cochlear Implants
CDRG	Child Development Research Group
CF	Characteristic Frequency
EE	Excitatory-Excitatory
EI	Excitatory-Inhibitory
GEE	Generalized Estimating Equations
ILD	Interaural Level Difference
IRB	Institutional Review Board
ITD	Interaural Time Difference
LSO	Lateral Superior Olive
MAA	Minimum Audible Angle
MAE	Mean Absolute Error
MOPS	Mothers of Preschoolers
MSO	Medial Superior Olive
NH	Normal Hearing
RMSE	Root-Mean-Square Error
SOC	Superior Olivary Complex
SPSS	Statistical Package for the Social Sciences
UHL	Unilateral Hearing Loss
UTHSC	University of Tennessee Health Science Center
UTK	University of Tennessee Knoxville

CHAPTER 1. INTRODUCTION

Overview

Sound localization refers to a person's ability to indicate exactly which direction a sound is originating (Clarkson, 2008). The ability to localize sounds in the environment is essential for safety, orientation, communication, and, especially where young children are concerned, academics (Johnstone, Nábělek, & Robertson, 2010; Kühnle, Ludwig, Meuret, Kuttner, Witte, Scholbach, Fuchs, & Rubsamen, 2013; Martin, Johnstone, & Hedrick, 2015; Zheng, Godar, & Litovsky, 2015; Zheng, Koehnke, & Besing, 2017). A rustle in the bushes while out walking or camping, a horn or siren while crossing the street, or a smoke alarm going off in the house, are just a few examples illustrating the reason one needs to be able to detect the location of a sound so that one can move away from danger. Poor sound localization abilities could seriously impact a person's safety (Clarkson, 2008).

Being able to localize a sound source is also instrumental in improving speech intelligibility in complex listening environments (Johnstone et al., 2010; Kidd, Argobast, Mason, & Gallun, 2005; Jones and Litovsky, 2008; Garadat and Litovsky, 2007). Young children whose auditory systems are less mature will have challenges in noisy and reverberant environments, which is where they often spend most of their day (Zheng, Koehnke, Besing, & Spitzer, 2011; Leibold, 2012; Zheng et al., 2017). Such environments degrade the signals provided by binaural cues which are essential for sound localization and cause children in such situations to be at risk of missing information that is crucial both academically and in daily life (Jones et al., 2015). Another benefit of sound localization capability would therefore be the ability to selectively attend to a certain speaker across a crowded room, or for a child to be able to listen to his/her teacher in a noisy classroom, cafeteria setting, or on the playground.

Sound source localization is a fundamental function of the human auditory system (Kerber and Seeber, 2012; Johnstone et al., 2013). Thus, an impairment in hearing will not only have a negative effect on sound localization capabilities (Noble et al., 1994; Noble et al., 1998), but will also impact communication and safety awareness in complex listening environments such as busy streets, classrooms and playgrounds, as previously mentioned. Younger children who have a hearing impairment will have even greater difficulty (Leibold, 2012; Schafer et al., 2012). Studies have shown that children who are hearing impaired have more difficulty in sound source localization than children who have normal hearing (Johnstone et al., 2010; Zheng et al., 2015, Gordon et al., 2015). Younger children with normal hearing show greater localization error than older children with normal hearing (Van Deun, van Wieringen, Van den Bogaert, Scherf, Offeceirs, Van deHeyning, … & Wouters, 2009; Johnstone et al., 2010; Martin et al., 2015). This suggests that the auditory system in younger children is still in the process of maturation (Litovsky, 2012; Martin et al., 2015).

Examining factors that affect sound source localization in children who have normal hearing could provide insight regarding auditory training strategies. Such strategies could be effective intervention strategies for training sound source localization in children who are hearing impaired and therefore have compromised or less developed auditory systems. The knowledge acquired could facilitate the enhancement and/or acceleration of their sound localization skill towards normal or at least near-normal function in the least amount of time possible.

A study by Martin et al. (2015), in which adults and children were asked to identify the exact location of a light source and a sound source, found that young children (ages 3, 4 and 5 years old) can localize a light source with adult-like performance, but their sound source localization skills were significantly different from those of adults. Sound source localization accuracy in young children does not seem to become adult-like until about 6 years of age (Van Deun et al., 2009; Johnstone et al., 2010; Lovett, Kitterick, Huang & Summerfield, 2012), and there is quite a bit of variability with younger children (Martin et al., 2015; Zheng et al., 2015). Such variability could either be developmental and/or a result of other possible contributors such as comprehension, attention or testing conditions (Van Deun et al., 2009) or due to "moments of inattentiveness" (Litovsky, 2012, p. 173). Since children as young as 3 years of age demonstrated capability of localizing a light source with adult-like performance, Martin et al. reasoned that young children were able to comprehend and attend to the localization task. Thus, suggesting that their poorer results in sound localization accuracy were not likely to be due to poor task comprehension or attention. Children's poorer performance in sound source localization accuracy could therefore be attributed to other factors, such as a less mature auditory system.

Another finding in the Martin et al. (2015) study was that adults who completed the light source localization task before the sound source localization task, performed better on the sound source localization task, compared to the adults who completed the light source localization task after the sound source localization task. This light order effect on sound source localization in adults did not occur in any of the young children.

This current study therefore seeks to further investigate sound source localization accuracy in young children in order to identify other factors that may facilitate sound source localization. One such factor that will be investigated is the effect of a motor (movement) response on sound source localization accuracy.

Thelen (1989) stated that "movement is the 'final common pathway' for many subsystems working together to accomplish a task or goal" and that it would be unwise to separate any results obtained through movement from the "information that guided it and the body parts that produced it" (p.946). This viewpoint is shaped by the perspective that the body's motor and perceptual capabilities are "intertwined" (Corbetta, 2009) and "inseparably linked" (Thelen, 2000) with the body and its experiences, and interactions with the environment thereby forming the framework for the concept of embodiment from a cognitive aspect. This *embodied cognition* approach places emphasis on what motor action contributes and the part it plays in connecting the individual to his/her environment (Anderson, 2015). It purports that cognitive development is largely influenced by the body's interactions with the world and that the body plays an integral and active role in cognitive processing, decision making and ultimate action (Wilson, 2002), and that it occurs in real time or in the moment (Smith, 2005).

The rationale supporting the investigation of motor action on sound source localization accuracy is that the responses provided may be influenced by the experiences gained from the continuous combination of motor action and bodily interaction within the test environment, thereby adapting/adjusting behavioral responses accordingly (Chiel and Beer, 1997). The traditional Piagetian view on cognitive development is that action is directed solely by the brain. The embodied cognition view in contrast, holds that the brain works in concert with the body and the environment via continuous, mutual interaction, rather than in a hierarchical/ruler-type fashion in which the brain is in control, to perform a task and thus foster developmental changes (Chiel and Beer, 1997; Corbetta, 2009). Thus, according to this view, the body is not controlled by the brain, but needs the brain to make it function (Wilson, 2002).

To date, to the authors' knowledge, there are no studies that investigated whether such a relationship between embodiment and the auditory system exists for the development of auditory spatial representations and sound source localization. The current study proposes that embodiment may influence the development of auditory spatial mapping and thus facilitate the identification of the exact location of a sound source through interaction of the sensory system (audition) with the whole body via motor responses (walking/touching/pointing) and the environment (15-loudspeaker array set in the horizontal hemifield within the sound booth). This study will seek to determine if motor responses yield better sound source localization accuracy than verbal responses. It is proposed that embodiment may occur inter-relationally between sensory and motor systems such that an auditory stimulus (sensory) coupled with whole body movement (motor) may facilitate better identification of the exact location of a sound source in young children, thus giving evidence of potential links between audition and embodiment.

It has been shown that early intervention enhances sound localization in young children (Van Deun, van Wieringen, Scherf, Deggouj, Desloovere, Offeciers … & Wouters, 2010). It is also thought that experience gained through early sensory-motor activity could foster better cognitive responses (Corbetta, Thurman, Weiner, Guan, & Williams, 2014). The sensory-motor activity causes developmental changes due to the ongoing, repeated interaction of the body within the environment (Smith, 2005). The information obtained in this study could broaden our understanding of the effects of embodiment on young children's sound source localization capabilities. Such knowledge gained could also provide insight regarding the design of aural re/habilitation treatment plans aimed at fostering sound source localization skills in young children who are hearing impaired, thereby either compensating for a compromised auditory system and/or promoting development in an auditory system that is not fully mature. It could also provide insight on enhancing the listening (and learning) strategies for children who do have normal hearing but are often situated in noisy environments.

Studies have shown that skills in sound localization accuracy are refined by experience (Zheng et al., 2015). Experience, from an auditory perspective, refers to the amount of time that an individual has had access to hearing whether through normal means or via amplification or activated implantation. Experience from an embodied perspective refers to the past/historical events to which an individual has been exposed or encountered that continually shape future (re)actions based on the perceptual and motor capabilities of that individual's body. Experience is necessary for sensory learning and plays an integral role in embodiment (Thelen, 2000). Given that children are naturally active, sensory explorers, it seems possible that their bodily interaction with the environment could enhance their localization capabilities.

Purpose of the Study

The current study sought to examine sound localization accuracy in young children who were 3 and 5 years of age. They were asked to use one of two response modes (verbal or motor) to identify the exact location of a sound source. The goal for this study was to determine which of these two modes of response could enhance or contribute to better sound localization accuracy in young children. The study compared localization accuracy by age and response mode. The previous Martin et al. (2015) study found that there were no significant differences between 4- and 5- year-olds in sound localization accuracy performance so children aged 4 years old were not included in this study.

Specific Aim and Research Questions

The specific aim of this study was to investigate potential links between auditory spatial mapping and embodiment. The objective was to determine if embodiment influenced a child's ability to localize a sound source. Measures of sound localization accuracy using either a verbal response or a motor response in one task, followed by a verbal response in a second task were compared for groups of children aged 3 and 5 years of age. The purpose was to determine if the initial motor responses provided by the motor group during the first task (Motor 1st Group) would facilitate spatial mapping within that auditory environment in which the experiment occurred such that the verbal responses provided during the second task showed a difference in performance for sound localization accuracy when compared to the performance of the group who provided verbal responses for both tasks (Verbal 1st Group). The study sought to answer the following research questions by testing the corresponding hypotheses stated below:

- *Research Question 1:* Which response mode (verbal or motor) better influences sound localization accuracy in young children with normal hearing?
- *Hypothesis 1:* There would be a difference between verbal and motor response modes in sound localization accuracy, with motor responses yielding better sound localization accuracy compared to verbal responses.

- *Research Question 2:* Will there be better sound localization accuracy in 3-year-olds who use motor responses compared to those who use verbal responses?
- *Hypothesis 2:* Sound localization accuracy for 3-year-olds who use motor responses would be better than 3-year-olds who use verbal responses and closer to 5-year-olds using verbal responses.

- *Research Question 3:* Will there be a difference in performance between the first and second sound localization tasks?
- *Hypothesis 3:* There would be better sound localization accuracy for the second task.

Conceptual Framework

Auditory (sound) localization is defined as the ability of a listener to identify the exact direction or origin of sound source. In other words, it is the ability of a listener to pinpoint where a sound is coming from (Clarkson, 2008; Litovsky, 2011; Kühnle et al., 2013; Lopez-Proveda, 2014)

Aspects of Localization

Absolute Localization

Greico-Calub and Litovsky, (2010), Lopez-Poveda, (2014) and Freigang, Richter, Rübsamen & Ludwig, (2015) described two aspects of localization. The first aspect of sound localization is referred to as *absolute localization*. This is also termed as 'localization accuracy' and is defined as the ability for a listener to determine the absolute or exact location or position of a sound source. Localization accuracy is quantified by calculating the root-mean-square error (RMSE), using the differences between the angular location of the actual sound source (target) and that of the perceived sound source (response) for each trial.

Relative Localization

The second aspect of sound localization is *relative localization*, also known as 'localization acuity' or 'spatial acuity' or 'spatial discrimination'. Relative localization refers to the ability for the listener to detect a shift in the absolute position of the sound source. Thus, rather than pin-pointing the exact location of a sound source, the listener indicates whether the sound emanated from the right or left (Johnstone et al., 2010). It is a discriminatory task and is quantified by the smallest detectable shift in angular location of the sound source, which is referred to as the minimum audible angle (MAA). (Mills, 1958; Litovsky, 2012; Lopez-Poveda, 2014). While the MAA is instrumental in assessing a child's ability to discriminate between two sound source locations, it does not provide information with regard to his/her ability to identify the specific location of a sound source and therefore may not be the best measure for assessing his/her sound source localization capabilities within his/her environment (Grieco-Calub and Litovsky, 2010); In fact it has been shown that localization acuity and localization accuracy are processed in two different areas along the ascending auditory pathway (Kühnle et al., 2013).

Planes and Cues of Localization

Sound localization occurs in various dimensions or planes. The type of cues which contribute to localization vary with each plane.

Horizontal Localization

First, localization can occur in the horizontal or azimuthal plane. This involves the detection of sound occurring to the left or the right of the listener. Localization is possible in this dimension because of the help of the binaural cues known as interaural time differences (ITDs) and interaural level differences (ILDs). They are called binaural cues because they are defined by the time or level at which a sound reaches the two ears. Sounds which occur directly in front (0º azimuth) or behind (180º azimuth) the listener's head, will arrive at both ears at the same time and be perceived at the same level/intensity. However, if a sound is presented from the right side for example, it will reach the right ear *sooner* (ITD) and be perceived as being *more intense* (ILD) at the right ear than the at the left ear and will therefore be judged as being in the right hemifield (Litovsky, 2012; Lopez-Poveda, 2014). The human auditory system is more sensitive to ITDs at lower frequencies of 1500 Hz or less and ILDs at higher frequencies of 3000 Hz or greater (Schnupp, Nelken and King, 2011). This theory of localization via binaural cues is known as the duplex theory of localization (Yost, 2007; Clark and Ohlemiller, 2008).

Another model known as the Jeffress model, describes another perspective of auditory localization. This model focuses on the place of maximal neuronal activation for ITD cues and is often referred to by Jeffress as the "place model of sound localization" (Colburn and Kulkarni, 2005).

Vertical Localization

Localization also occurs in the vertical or elevation plane. This involves the detection of sound occurring up or down in relation to the listener's head. This is made possible by monaural cues. These cues are direction-dependent and are determined by changes in the sound spectrum and are therefore called spectral cues. Spectral cues are shaped by the pinna, head and torso (Batteau, 1967; Lopez-Poveda and Meddis, 1996 cited in Lopez-Poveda, 2014; Litovsky, 2012).

Precedence Effect

Lastly, a phenomenon known as the *precedence effect* can contribute to localization in a reverberant environment in which both the original sound source and the resulting echo of that sound source a short time later, reaches the ears. In such a situation, the human auditory system puts greater emphasis (precedence) on the location of the original sound source over that of the echo or reflected sound source, thus indicating the location of the original or "lead" sound. (Litovsky, 1997; Litovsky, 2012).

Embodiment

Embodiment refers to the role the body plays in shaping cognitive development and/or intelligence. Cognition is viewed by some researchers as being "embodied" because it "arises from bodily interactions with the world and is continually meshed with them" (Thelen, 2000). In other words, cognition is formulated through the ongoing interaction of the body and its brain, with the environment in which they are situated, and it occurs in real time (Smith, 2005). The embodiment hypothesis does not view the brain as being the sole contributor to cognitive growth. It instead purports that bodily movement, guided by the senses (hearing, vision, smell, taste and touch) via environmental interaction, influences cognitive behavior because the brain is connected to the environment through the body.

The concept of embodiment stresses the influence the body has on experience, and the importance of experience for sensory learning, and encompasses the interaction of the nervous system, mind and environment. Previous research has shown that the parietal cortex is involved in processing that transforms spatial information of external objects to coordinates for behaviour (Yamakawa, Kanai, Matsumura, and Naito, 2009; Sakata, Shibutani, and Kawano, 1980; Naito, Scheperjans, Eickhoff, Amunts, Roland, Zilles, and Ehrsson, 2008).

However, there has been no investigation as to whether such a relationship between embodiment and the auditory system exists for the development of auditory spatial representations. There are neural substrates in the superior olivary complex (SOC) that are designed for localization. Within the SOC, there are excitatory-inhibitory (EI) cells with high characteristic frequencies (CFs) in the lateral superior olive (LSO). These cells increase firing rate as ILDs are increased, because they are sensitive to higher frequencies. Excitatory-excitatory (EE) cells which have low CFs are located in the medial superior olive (MSO). These cells increase firing rate when there are ITDs because they are sensitive to lower frequencies – thus fitting nicely with the duplex theory of localization. There is, however, evidence that more central auditory processing mechanisms could be are involved (e.g. Recanzone and Sutter, 2008; Van Deun et al., 2009; Martin, et al. 2015;). It is known that development of the central portions of the auditory system continue into early adulthood (Moore and Linthicum, 2007). It could be that auditory spatial mapping developmentally co-occurs with auditory system development and embodiment. To begin to explore this possible relationship between embodiment and auditory space mapping, the current study tested two groups of children (3- and 5- year-olds) who in previous work had been shown to differ significantly in auditory localization accuracy (Martin et al., 2015).

Definitions of Major Concepts

Localization

Absolute Localization

The specific or exact identification of the origination of the sound source, the pin-pointed location.

Acuity

Described as a relative measure of localization which involves discriminating whether the sound source occurred to the left or to the right of azimuth in a horizontal plane (Litovsky, 2011; Kühnle et al., 2013).

Accuracy

Described as an absolute measure of localization which involves the specific identification of the sound source (Litovsky, 2011; Kühnle et al., 2013).

Azimuth

Also known as the horizontal plane, defines the angular location (in degrees) with respect to the location directly in front/center of the observer/listener such that this front/center location is 0^o azimuth. Angular locations to the left of the observer's head are represented by negative angular values (-10^o, -20^o etc.) and angular locations to the right of the observer's head are represented by positive angular values ($+10^o$, $+20^o$ etc.).

Binaural Cues

The term *binaural* refers to the use of both ears or "two-ear hearing" (Yost, 2007, p.30). Binaural cues pertain to the information that reaches both ears in the azimuthal or horizontal plane, such that sounds that are nearer to one ear will be arrive sooner (time) and be perceived as louder/more intense (level) than at the other ear. There are two binaural cues: interaural time difference (ITD) and interaural level difference (ILD). (Litovsky, 2012: Lopez-Poveda, 2014; Goldstein and Brockmole, 2014).

Interaural Level Differences (ILDs)

The difference in sound intensity level that reaches each ear. Sounds are more intense at the ear that is nearer to the origination of the sound (Litovsky, 2012: Lopez-Poveda, 2014; Goldstein and Brockmole, 2014).

Interaural Time Differences (ITDs)

The difference in time of arrival of a sound at each ear. Sounds arrive sooner to the ear that is closer to the origination of the sound, so the ITD is larger for that ear (Litovsky, 2012; Lopez-Poveda, 2014; Goldstein and Brockmole, 2014).

Mean Absolute Error (MAE)

This is a quantifier which is obtained by calculating the average of the average of the absolute value of the errors per target location. It is sometimes the quantifier of choice for measuring localization in children because of the possibility that large localization errors seen children is due to inattentiveness rather than poor localization abilities (Van Deun et al., 2009).

Minimum Audible Angle (MAA)

A quantifier used in a left versus right discrimination task. It is the measure of the smallest angle from midline that can be reliably discriminated (Litovsky, 1997; Godar and Litovsky, 2010).

Monaural Cues

The term *monaural* pertains to only one ear. Monaural cues refer to localization information that is obtained from only one ear.

Relative Localization

The discrimination of a sound source as originating from the left or right of center (azimuth).

Root-Mean-Square Error (RMSE)

The root-mean-square error (RMSE) is a measure of localization accuracy in degrees azimuth. It is calculated by first squaring the angular difference between a target (source) location and the response location, then averaging all the squared differences for that target location, and finally determining the square root of that average. The equation for the RMSE can be found in Van Deun et al., 2009 (p. 182) and Litovsky and Godar, 2010 (p. 1982). The RMSE measure has been a primary quantifier for localization in many studies (for eg. Litovsky et al., 2004; Van Deun et al., 2009; Litovsky and Godar, 2010; Grieco-Calub and Litovsky, 2010; Johnstone et al. 2010; Martin et al., 2015; Reeder et al., 2015; Zheng et al., 2015).

Spectral Cues

Spectral cues are monaural cues used for localization in the vertical or elevation plane. The frequency distribution or spectrum of the sound that reaches the ear is shaped by the reflections of that sound from the head, portions of the pinna, and torso. These spectral cues are also known as head-related transfer functions or HRTFs. They represent the differences between the original sound and the sound that actually reaches the ear, as a result of the changes that the head and pinnae have had on the frequencies of the sound. The head and pinnae can decrease the intensity of some of the frequencies of the original sound and enhance others. Thus, these cues are direction-dependent and frequency-dependent (Tollin and Yin, 2009; Lopez-Poveda, 2014; Goldstein and Brockmole, 2014).

Embodiment

The current study considered embodiment from a cognitive perspective, or *embodied cognition*. Embodiment refers to the continuous interaction that the body has within the surrounding environment. The body's perceptual (sensory) and motor capabilities as it interacts within the environment are instrumental in shaping cognitive development. Thelen (2000) described this approach to cognitive development as occurring as a result of "bodily interactions with the world". The author explained that cognition is "dependent on the kinds of experiences that come from having a body with particular perceptual and motor capabilities that are inseparably linked" (p. 5). In other words, the way in which a body perceives an event (sensory), and the motor capabilities and/or limitations that a body has, are all merged, "intertwined" (Corbetta, 2009), "coupled" (Chiel and Beer, 1997), "meshed", "inseparably linked" (Thelen, 2000) together and shapes the kind of experience that a body will encounter. Smith (2005) expounded this concept by stating that embodiment is the idea that cognition (or intelligence) is honed by the interaction of the body (organism) with the environment through sensory-motor activity. Cognitive development is therefore viewed as being influenced by individual body characteristics and environmental experiences.

Experience

The Cambridge English Dictionary defines this term as: "the process of getting knowledge or skill that is obtained from doing, seeing, or feeling things…" (https://dictionary.cambridge.org/us/dictionary/english/experience)

Experience is multi-modal. An individual's performance is influenced by the experiences gained through interaction in the world (Smith, 2005). In terms of audition, experience also refers to the length of time one has had access to hearing be it normal or via amplification (acoustic) and/or cochlear implantation (electrical) (Godar and Litovksy, 2010; Zheng et al., 2015).

Motor

The Collins English Dictionary defines this term as: "designating of a nerve carrying impulses from the central nervous system to a muscle that produces motion"; and "of, manifested by, or involving muscular movements". (https://www.collinsdictionary.com/us/amp/english/motor)

Movement however, should not be confused with action. *Movement* is defined by Leisman, Moustafa and Shafir (2016) as the voluntary or involuntary displacement of body parts in physical space. *Action* on the other hand consists of movements that are necessary to accomplish a specific goal. Actions are planned movements. (Leisman et al, 2016).

Sensory

The Collins English Dictionary defines this term as: "of or relating to those processes and structures within an organism that receive stimuli from the environment and convey them to the brain".
(https://www.collinsdictionary.com/us/dictionary/english/sensory)

Simulation

The reenactment of perceptual, motor and introspective states acquired during world, body, and mind experiences (Brouillet, T., Heurley, Martin, & Brouillet, D., 2010).

Situated Action

Cognitive activity which involves sensory-motor processes (perception and action) and occurs in real-life situations or a real-world environment. (Brouillet et al. (2010); Wilson, M (2002).

Significance of the Study

The study sought to investigate the effect of embodiment on sound localization accuracy in young children. Given that early intervention can enhance sound localization in young children (Van Deun et al., 2010), it was proposed that the knowledge gained from this study would:

1) provide direction and input for designing or amending auditory training, (re)habilitation, and early intervention strategies for promoting sound localization accuracy in young children thereby enhancing their safety, communication and academic performance; and

2) contribute to the literature on auditory development and sound localization accuracy in young children with normal hearing, which would be beneficial to science and society.

CHAPTER 2. LITERATURE REVIEW

Sound Source Localization Accuracy in Children

There have not been many studies which have investigated sound source localization accuracy in young children (Freigang et al., 2015). There has been a paucity of data for this population, but this has been improving over the past decade (Litovsky, 2011). Among the few studies which included children with normal hearing, whose ages ranged from 6 through 18 years, were Johnstone et al. (2010); Murphy et al. (2011); Kühnle et al. (2013); Otte, Agterberg, VanWanrooij, Snik, & Van Opstal, (2013) and Reeder et al. (2015). Van Deun et al. (2009); Greico-Calub and Litovsky, (2010); Litovsky and Godar, (2010); Lovett et al. (2012); Zheng et al. (2015) and Martin et al. (2015) are studies that explored sound source localization accuracy in children with normal hearing who were 5 years of age and younger. (The Lovett et al. 2012 study included young children up to 7.9 years of age).

One reason for this lack of data for young children has been the challenge of being able to attend to and/or perform the task (Van Deun et al., 2009). Researchers had greater success with minimum audible angle (MAA) measures for sound localization *acuity* with younger children, because of the easier/less complex task of left-right discrimination, compared to the more complexed task of fine-tuning/pin-pointing exact sound source locations as is required in a sound source identification or *accuracy* task (Litovsky, 2011; Kühnle et al., 2013). The two terms, acuity and accuracy, have been used interchangeably in the literature (Kühnle et al., 2013). However, in this manuscript, the term accuracy will be used consistently because the goal of this current study was to investigate sound source identification.

Secondly, most localization studies were geared to adults, so their methodology was not child-friendly or child-appropriate. Attempting to adapt methodologies to accommodate young children often invalidated the test or created incompatibility for comparison across studies, because the study designs were no longer the same (Van Deun et al., 2009) or because the set-up, procedures and/or means of measurement were different (Johnstone et al., 2010; Dorman, Loiselle, Cook, Yost & Gifford, 2016).

Sound localization accuracy studies that involved children with normal hearing and utilized similar methodologies were reviewed for this current study. Most of the studies selected for review had included children with normal hearing as a reference or for comparison with hearing-impaired populations but did not focus solely on sound localization accuracy in children with normal hearing. Examples of such studies included Litovsky and Godar, (2010); Johnstone et al. (2010), Reeder, Cadieux and Firszt (2015) and Zheng et al. (2015). A study by Van Deun et al. (2009) and a more recent study by Martin et al. (2015) were exceptions. Since the current study was investigating factors which affect sound source localization abilities in children with normal hearing, only the data relevant to normal hearing children was extracted for review and discussion. A summary of selected studies is displayed in **Table 2-1**.

Table 2-1. Studies that investigated sound localization accuracy and included young children with normal hearing

Study	No Subjects	Age	RMSE Range	Mean RMSE	Stimuli/Set Up	No Trials	Roved
Van Deun et al. (2009)	33 children 5 adults	4yr (N=21) 5yr (N=6) 6yr (N=6) Avg age 24yr	Not reported	10º 6º 4º 0º	Broadband bell ring (1 sec) 9 loudspeakers,15º apart	51 27	±5dB
Litovsky & Godar (2010)	9 children 10 adults	4-5yr (Avg age 5.14) Avg age 22yr	3.8º – 38.3º 1.4º – 6.5º	10.2º 3.6º	Pink-noise-burst 15 loudspeakers (7 active) 10º apart	35	±4dB
Grieco-Calub & Litovsky (2010)	7 children	5yr	8.9º – 29.2º	18.3º	Spondaic word “baseball” 15 loudspeakers, 10º apart	150	±4dB
Johnstone, Nábělek & Robertson (2010)	12 children	6-9yr (N=6) 10-14yr (N=6)	3.02º – 11.06º 1.48º – 3.66º	7.04º 2.57º	Spondaic word “baseball: 15 loudspeakers 10º apart	150	±8dB
Zheng, Godar & Litovsky (2015)	6 children	5yr	6.53º – 20.81º	10.51º	25 Bi-syllabic Spondees 15 loudspeakers 10º apart	150	±4dB
Reeder, Cadieux & Firszt (2015)	10 children 23 adults	7.5 to 15.5 Not reported	2.3º – 9.7º	6.0º 3.4º	100 CNC monosyllabic words 15 loudspeakers 10º apart	100	
Martin, Johnstone, & Hedrick (2015)	30 children 12 adults	3yr (N=10) 4yr (N=10) 5yr (N=10) Avg age 26.6yr (N=12)	12.60º – 39.15º 5.49º – 25.59º 6.48º – 37.89º 0º – 6.13º	24.96º 15.26º 16.81º 2.6º	Spondaic word “baseball: 15 loudspeakers (7 active) 10º apart	35	±8dB
Murphy, Summerfield, O’Donoghue & Moore (2011)	40 children	6–10yr, (N=26), avg age 8.3yr; 11-15yr (N=14), avg age 12.9yr			Horizontal ring (3 m diameter) of 24 loudspeakers, 15º apart	120	
Kühnle et al. (2013)	129 children	6 – 18yr in 3 groups: 6-7yr, 8-12yr and 13-18yr	Used Lambda (Λ), instead of RMSE		47 loudspeakers, 4.28º apart	84 per stimulus	

Note: RMSE = root-mean-square error

Van Deun et al. (2009) Study

The purpose of the Van Deun et al. (2009) study was to develop measurement procedures for assessing binaural hearing via sound localization (as well as sound lateralization and binaural masking level differences) in young children with normal hearing, assess task sensitivity with this population, and investigate potential developmental trends. The sound localization experiment involved a total of 33 children between the ages of 4 and 6 years old. There were 21 four-year-olds, 6 five-year-olds and 6 six-year-olds. In this experiment children were asked to localize a broadband signal (a 1-sec bell-ring) presented from one of nine loudspeakers set at 15^o apart in the frontal horizonal plane from -60^o to +60^o. They indicated the perceived location by pointing to it and naming it. A group of 5 adults (between the ages of 23 and 27; mean age, 24yr) who also had normal hearing were included in this portion of the study to obtain reference values.

Van Deun et al. (2009) aimed to identify test procedures that were suitable for young children (in terms of manner of response, attention required to complete the task, and test length) and provide much needed data on preschoolers and yet be comparable (in terms of test procedures and results) to other studies. They found that overall the test procedures employed were child-friendly in terms of interest, attention and execution and therefore feasible for young children. The 4-, 5- and 6-year-old children had mean RMSE scores of 10^o, 6^o and 4^o respectively. The adults had a mean RMSE score of 0^o. Van Deun et al. reported there were no significant differences in performance among the 5-year-olds, 6-year-olds and adults, and that the 4-year-olds had greater errors on the localization task. The researchers posited that their findings were due to binaural hearing development and/or "nonauditory factors, such as comprehension, attention, and testing conditions" (p. 189).

Litovksy and Godar (2010) Study

Litovksy and Godar (2010) investigated sound localization accuracy by comparing single source stimuli with dual source lead-lag stimuli to examine the development of the precedence effect in children and adults. Their study included 9 children with normal hearing who were between 4.4 and 5.8 years of age (average age 5.14 years), and 10 adults between the ages of 19 and 26 years (average age 22 years).

For the single source localization test portion of the study, participants were asked to identify the location of a pink-noise-burst stimulus presented randomly from one of 15 loudspeakers (only 7 were active) set at 10^o apart in the frontal horizonal plane from -70^o to +70^o. Participants indicated the location of the sound source by either clicking the computer mouse or verbal report. Although the loudspeaker array was similar to that used in the Van Deun et al. (2009), the set-up in this study had 6 more speakers (15 instead of 9) set more closely together (10^o apart instead of 15^o) and spanned a slightly wider horizontal arc of 140^o instead of 120^o (-70^o to +70^o instead of -60^o to +60^o).

Sound localization accuracy results for the Litovsky and Godar (2010) study revealed a mean RMSE of 10.2º ± 10.72º, with a range of 3.8º to 38.3º for the 4-5yr children. Removal of an outlier value of 38.3º (which left all remaining 8 values for the children being less than 10º), reduced the mean RMS error for children to 6.64º. Mean RMSE for the five adults was 3.6º ± 1.63º, with a range of 1.4º to 6.5º. These mean RMSE values were similar to the values obtained in the Van Deun et al. (2009) study for the 4-year-old children (10º) and for the 5-year-olds (6º). The RMSE values of 3.6º ± 1.63º for the adults in the Litovsky and Godar (2010) study were slightly higher than that of 0º for the adults in the Van Deun et al. (2009) study.

Grieco-Calub and Litovsky (2010) Study

Another study by Grieco-Calub and Litovsky (2010) examined sound source localization accuracy in children who had sequential bilateral cochlear implants (BiCIs). One of the goals of this study was to determine if performance in this task correlated to performance in a right-left discrimination task which was quantified using the minimum audible angle (MAA) measure. The study included 21 children between the ages of 5 and 14 years of age who had sequential BiCIs. Seven typically developing 5-year-old (average age 5.5 ± 0.1years) children who had normal hearing were also included in the study because their performance would be representative of children who were normal hearing and of the equivalent age to the youngest child in the BiCI group.

The set-up in this study was very similar to the Litovsky and Godar (2010) study in terms of speaker array (15 loudspeakers in a horizontal arc arranged at 10º intervals from -70º to + 70º). However, in this study the stimulus was the spondee word “baseball” instead of the pink-noise-burst. This stimulus was selected because the researchers determined that a speech stimulus would be more effective. Another difference with this study was that the stimulus was presented 10 times from each of the 15 loudspeaker locations for a total of 150 trials, whereas there were only 5 presentations from each of the 7 active loudspeakers, for a total of 35 trials in the Litovsky and Godar (2010) study previously discussed.

The 5-year-old children in this Grieco-Calub and Litovsky (2010) study indicated the location of a sound source by clicking a computer mouse or verbal report. They performed the sound localization task with a mean RMSE of 18.3º ± 6.9º and a range of 8.9º to 29.2º. These results were not only poorer than those seen in adults but also were not consistent with the 5-year-olds’ performance of 6º (mean RMSE) in the Van Deun et al. (2009) study. It was suggested this may indicate that the sound localization skill in young children with normal hearing is still emerging at age 5 rather than being adult-like as indicated in the Van Deun et al. (2009) study in which it was reported that there was no significant difference in performance between 5-year-olds and adults.

The difference in experiment set-up and procedure was also considered. Given the increased number of loudspeakers (15 compared to 9 in the Van Deun et al. (2009) study) and the smaller loudspeaker intervals (10º instead of 15º in the Van Deun et al. (2009)

study), it was proposed that the task in the Grieco-Calub and Litovsky (2010) study was probably more challenging and the stimuli (spondee "baseball" compared to a 1-sec bell-ring) may have been more difficult to localize. The poorer performance of these 5-year-old normal hearing children in this study was not attributed to a lack of their understanding of the task because they had received ample training and feedback.

Johnstone, Nábělek and Robertson (2010) Study

A study investigating sound localization in children who had a unilateral hearing loss (UHL) was conducted by Johnstone, Nábělek and Robertson (2010) to investigate the effect that such factors as amplification, age of early intervention, and degree of hearing loss, may have on sound localization ability. In this study, 12 children who had UHL were age-matched with 12 children who had normal hearing as controls and for comparison. These children with normal hearing were divided into two age groups: younger children between 6 and 9 years of age (mean age 7 years), and older children between 10 and 14 years of age (mean age 12 years). There were 6 children in each group.

Testing set-up and procedures were the same as in the Grieco-Calub and Litovsky (2010) study. Each child sat in the center of a horizontal arc of 15 loudspeakers arranged from -70º to + 70º and set apart at 10º intervals. S/he was asked to identify the source of the speech sound stimulus – the spondee word "baseball" – presented randomly for a total of 10 times per loudspeaker, resulting in 150 trials per participant. The perceived location of the sound source was indicated by clicking the computer mouse or verbal report. Results for the children with normal hearing showed a mean RMSE of 7.04º for the younger (age 6-9yr) group and 2.57º for the older (age 10-14yr group).

The children with normal hearing in this study were older than those in the studies previously mentioned. The ages ranged from 4 to 6 years of age in those studies (Van Deun et al., 2009; Litovksy and Godar, 2010; and Grieco-Calub and Litovsky, 2010), whereas the younger group in the Johnstone et al. (2010) study was between 6 and 9 years old. Yet the mean RMSE for this age group (7.04º) was slightly higher than that reported in the Van Deun et al. (2009) study for 6-year-olds (4º). Given that the participants in the younger group in the Johnstone et al. study, were equal to or older than the 6-year-olds in the Van Deun et al. study, it would be expected that the RMSE for the Johnstone et al. group would be lower/better than that in the Van Deun et al. group. Here again this result could be attributed to possible sound source localization skill emergence in the younger children and/or the experimental protocol being somewhat more challenging for the younger children in the Johnstone et al. (2010) study than that used in the Van Deun et al. (2009) study, as previously suggested by Grieco-Calub and Litovsky, 2010). The older age group (10 to 14 years) in the Johnstone et al. (2010) study showed results that were comparable to the adults in both the Van Deun et al. (2009) study and the Litovsky and Godar (2010) study.

Zheng, Godar and Litovsky (2015) Study

A group of six typically developing 5-year-old children (4.9 to 5.5 years) with normal hearing were included for comparison in a study by Zheng, Godar and Litovsky, (2015). This study aimed to assess localization development by investigating the emergence of spatial hearing sensitivity in children who use BiCIs. Nineteen children between the ages of 4 and 9 who had BiCIs participated in this study.

As with the Grieco-Calub and Litovsky (2010) study the performance of the group of 5-year-old children with normal hearing was treated as a representation of the performance of the general population of children with normal hearing, with ages that were equivalent to those of the youngest participants in the group with BiCIs. The experiment set-up was the same as the Litovsky and Godar (2010), Grieco-Calub and Litovsky (2010), and Johnstone et al. (2010) studies (15 loudspeakers set at 10^o intervals apart, on a horizontal arc from -70^o to +70^o). Instead of the single spondee word "baseball", however, the stimuli in this study by Zheng et al. consisted of 25 bi-syllabic Children's Spondees. Stimuli were presented randomly from all 15 loudspeakers for a total of 150 trials. Participants indicated the location of the sound source by clicking a computer mouse or verbal report. Results for the children with normal hearing in this study yielded a mean RMSE of 10.51^o with a range of 6.53^o to 20.81^o. These results were similar to that obtained in the Litovsky and Godar (2010) study (10.2^o) which used the pink-noise-burst stimulus, but lower than those obtained in the Grieco-Calub and Litovsky (2010) study (18.3^o) which used the single spondaic word "baseball" as stimulus. The normal hearing children in these studies were all the same ages of 4 to 5 years old. This suggests that localization accuracy could be influenced by the type of stimulus used.

Reeder, Cadieux and Firszt (2015) Study

Another study also included children who had normal hearing as a comparison when investigating speech-in-noise and sound localization abilities in children with unilateral hearing loss. Since sound localization measures are one means of quantifying the abilities of children with UHL, this test was included as one of the areas of investigation in this study by Reeder et al. (2015).

The study compared 20 normal hearing (NH) children with 20 children with UHL by gender and age matching the two groups (NH and UHL). The NH group had an age range of 7.5 to 17.8 years (mean age 12.0 years) and the UHL group had an age range of 6.9 to 16.3 years (mean age also 12.0 years). However, only 10 of the NH children (age range 7.5 to 15.5 years; mean age 10.4 years) were involved in the sound localization portion of the study along with 11 of the UHL children (age range 6.9 to 13.4 years; mean age 13.5 years).

The experiment set-up for the sound localization was similar to the Litovsky and Godar (2010), Grieco-Calub and Litovsky (2010), and Johnstone et al. (2010) studies (15 loudspeakers set at 10º intervals apart, on a horizontal arc from -70º to +70º). The stimuli in this study were 100 monosyllabic words presented randomly and in equal number from only 10 of the 15 loudspeakers, for a total of 100 trials per participant. Sound source location was indicated by verbal report.

Mean RMSE for the 10 NH children was 6º (SD 3.7º). This result suggested that even the 7-year-olds in this NH subgroup were performing similarly to a group of 23 NH adults who had a mean RMSE of 3.4º (SD 2.5º) (collected in the Firszt lab, but not yet published). Thus, this NH group of children in this study showed near adult-level performance when compared to the adult data. It should be mentioned however that the mean age of this group was 10 years, so although the group included 7-year-old(s), the number of children in the group who were younger than 10 years of age is not reported. These results were also consistent with adult results obtained in the Litovsky and Godar (2010) for 10 NH adults (3.6º ± 1.63º), and to the older children (age 10 to 14 years) in the Johnstone et al. (2010) study in which the mean RMSE was 2.57º ± 1.09º. Each of these studies used a similar set-up for loudspeaker array (15 loudspeakers set at 10º intervals apart, on a horizontal arc from -70º to +70º), but different sound stimuli (Litovsky and Godar (2010) study – pink-noise-burst; Johnstone et al. (2010) study – single spondee “baseball” and Reeder et al. (2015) study – 100 CNC monosyllabic words.

Martin et al. (2015) Study

Martin et al. (2015) also conducted a study focusing on sound source localization in children and adults with normal hearing only. Unlike the Van Deun et al. (2009) study, the Martin et al. study solely explored sound source localization accuracy. The primary goals were to 1) attempt to separate non-auditory factors such as attention, task comprehension and testing conditions from the developmental central auditory processing factors that may affect sound localization accuracy in young children and adults, and 2) to determine what factors may enhance the development sound source localization skills in young children. Sound source localization *accuracy* abilities in young children (quantified by RMSE measure) are not as clearly understood as sound localization *acuity* (quantified by the MAA measure) and although there is data on young children with regard to sound localization acuity, data from young children with normal hearing with regard to sound source localization accuracy – whereby the exact location of a sound source is pin-pointed – is lacking (Van Deun et al., 2009; Johnstone et al., 2010; Litovsky, 2011; Kühnle et al., 2013). As previously mentioned, the MAA is a relative measure which provides information regarding left-right/spatial discrimination but does not give information regarding the ability to identify the exact location of a sound source.

Thus, Martin et al. (2015) aimed to gain knowledge and acquire much needed data on sound localization accuracy in young children using test procedures that were proven to be suitable for testing young children (Van Deun et al., 2009) and could be compared to other sound localization studies that employed similar procedures. Three-year-old children with normal hearing were included in the Martin et al. (2015) study to explore the developmental patterns in younger preschool children and attempt to close the gap where data regarding skills in sound source localization accuracy is lacking for preschool children. Adults served as a reference group.

In the quest to further examine the development of sound source localization, an unroved/fixed intensity stimulus was included to investigate the extent to which overall level cues affect sound localization accuracy. All the sound localization accuracy studies mentioned thus far had used a roved stimulus. A light stimulus was also included to further examine and tease apart attention and task comprehension factors. The experiment set-up was similar to that used in the Litovsky and Godar, (2010), Grieco-Calub and Litovsky (2010), and Johnstone et al. (2010) studies (15 loudspeakers set at 10° intervals apart, on a horizontal arc from -70° to +70°). The stimulus was the speech spondee "baseball" similar to the Grieco-Calub and Litovsky (2010) and Johnstone et al. (2010) studies. Stimuli were randomly presented from only 7 active loudspeakers at 5 repetitions per location for a total of 35 trials as in the Litovsky and Godar, (2010) study. Participants were asked to indicate the location of a sound for light source by clicking a computer mouse, pointing or verbal report. The light stimulus was presented in a separate block of trials, either before or after the sound source localization task test was administered. The purpose was to investigate light order effect on sound source localization accuracy.

Results of this study for the roved sound localization task revealed a mean RMSE of 24.96° (range = 12.60° – 42.02°) for 3-year-olds (N = 10); 15.26° (range = (5.49° – 25.59°) for 4-year-olds (N = 10); 16.81° (range = 6.49° – 37.89°) for 5-year-olds (N=10) and 2.60° (range = 0° – 6.14°) for adults (N = 12). The mean RMSE for the unroved sound localization task was 29.02° (range = 8.60° – 50.37°) for 3-year-olds; 13.62° (range = 4.63° – 38.26°) for 4-year-olds; 15.39° (range = 5.03° – 43.81°) for 5-year-olds; and 2.49° (range = 0° – 4.83°) for adults. There were no significant differences between the roved and the unroved values. Mean RMSE results for the light source localization task were 1.16° (range = 0° – 2.18°) for 3-year-olds; 2.89° (range = 0° – 8.31°) for 4-year-olds; 1.97° (range = 0° – 7.67°) for 5-year-olds and 0.21° (range = 0° – 1.28°) for adults.

The results of the light localization task revealed two interesting findings. First, all the children performed at adult level performance in this task. This suggested that even the youngest (3-year-old) children in this study understood the task and could provide reliable source localization responses in a setting with a multi-loudspeaker array. Prior to this study, Litovksy and Godar (2010) had reported that age 4-5 years was the youngest age at which this could be done. This new finding not only provided much needed preschool data, but also extended knowledge that 3-year-olds are able to perform a localization accuracy task. Second, there was a significant effect of light order for adults such that the adults who performed the light localization task before the sound localization task, had better sound source localization accuracy results than those adults who performed the sound source localization task before the light localization task: rove ($t[10] = -3.09$, $p = 0.011$); unrove: ($t[10] = -2.90$, $p = 0.016$). There was no light order effect observed in any of the children groups. This suggested that the light stimulus, a visual and more salient cue, influenced sound localization accuracy at least for adults, but did not influence or enhance the children's ability to map auditory space.

The Martin et al. (2015) study yielded results like those found in the Litovsky and Godar (2010), Grieco-Calub and Litovsky (2010) and Zheng et al. (2015) studies which included similar (4-5yr) age groups. Mean RMSE was 10.2^o for ages 4-5yr in the Litovsky and Godar (2010) study compared to 15.26^o for the 4yr and 16.81^o for the 5yr in Martin et al. (2015) study; mean RMSE was 18.3^o for 5yr in Grieco-Calub and Litovsky (2010), and 10.51^o for 5yr in the Zheng et al. (2015) study compared to 16.81^o in Martin et al. (2015). Although the set-up was the same in four of these studies, the stimuli were not all the same. Interestingly, the closest RMSE results were in the studies that used the same stimulus, the speech spondee "baseball" (18.3^o for 5yr in Grieco-Calub and Litovsky (2010) and 16.81^o for the 5yr in Martin et al. (2015)). The RMSE values in the Martin et al. (2015) study were higher (worse performance) than those in reported by Van Deun et al. (2009). They reported 4- and 5-year-olds had RMSE averages of 10^o and 6^o respectively, compared to 15.26^o and 16.8^o respectively for the Martin et al. (2015) study.

This outcome could be attributed to the differences in stimuli (1s bell-ring vs spondaic word) and/or loudspeaker set-up (9 vs 15) thus possibly creating a more challenging test experience in the Martin et al. (2015) study as suggested by Grieco-Calub and Litovsky (2010). It could also indicate that although some young children perform at or near adult level, the sound localization skills in others are still emerging (Litovksy and Godar, 2010). Completing the light localization task at an adult level showed that all these young children in Martin et al. were able to comprehend and attend to the task, yet they were not able to perform at adult levels with the sound localization tasks. It is therefore possible that the reason could be related to auditory development. Except for the 4-year-old group in the Van Deun et al. (2009) study which had 21 participants, the Martin et al. (2015) study had the largest, most homogenous age groups, which would allow the mean RMSE measures obtained to be more age specific. The children groups in the other studies were more heterogenous and had wider age ranges, making the average RMSE measures less age specific.

Common threads throughout all these studies include a multi-loudspeaker array arranged on a semicircular arc in the frontal horizontal plane. In addition, they all included the RMSE measures as a means of quantifying responses. Thirdly, the tasks were suitable for children as well as adults. This facilitated comparison of results across studies.

Murphy, Summerfield, O'Donoghue and Moore (2011) Study

Two other studies which included sound localization testing in children with normal hearing but used different measures of quantification were also reviewed. The first, a study by Murphy, Summerfield, O'Donoghue and Moore (2011), examined spatial hearing in children with normal hearing for comparison with children who had either unilateral or bilateral cochlear implants. The study aimed to investigate this comparison under conditions that were ecologically valid in order to obtain norms for children with NH and UCI and preliminary data for children with BiCIs. Participants included 40 children between the ages of 6 and 15 years old with normal hearing. These were divided into two age groups: 6 – 10yr, (N = 26), mean age = 8.3yr; and 11 – 15yr, (N=14), mean age = 12.9yr. There were also 12 children (mean age 10.3 years) who had a unilateral cochlear implant, and 6 children (mean age 8.8 years) who had bilateral cochlear implants. The experiment set-up included a ring of loudspeakers set at 15^o intervals. The sound localization task involved the identification of a specific toy seen on monitors underneath one of 5 target loudspeakers, following the audible carrier phrase: "Hello, what toy is this?" Measures of localization accuracy were quantified using the likelihood ratio test statistic 'lambda' (Λ), reported as -2 log (Λ) (Murphy et al., 2011, p. 491). In this study all the children with NH performed at or near ceiling levels on all the localization tasks.

Kühnle et al. (2013) Study

A second study by Kühnle et al. (2013) investigated the development of auditory localization accuracy and auditory spatial discrimination in children and adolescents who all had normal hearing, with the purpose being to directly compare the two skills (localization accuracy and localization acuity) and provide comprehensive data on both. A total of 136 children between the ages of 6 and 18 years (mean 9.2 years) participated in this study. There were 3 age groups: 6-7yr (N=43); 8-12yr (N=78) and 13-18yr (N=15). Only 129 participants completed the localization task. The experiment set-up included a loudspeaker array consisting of 47 loudspeakers set at 4.28^o intervals on a semicircular arc of -98.6^o to +98.6^o. Sound stimuli included low frequency and high frequency noise bursts. Stimuli were randomly presented 6 times from each of 14 loudspeakers for a total of 84 trials per stimulus. Localization accuracy was quantified in two ways: 1) The deviation from the actual stimulus location or the "hit accuracy" defined as the distance between the identified/response location and the actual sound source location. 2) Intraindividual variability or "dispersion" defined as the median of the 6 distances for each signal location (p. 51-52). Localization accuracy test results revealed that hit accuracy means increased from frontal to lateral azimuthal hemifields and were better for low frequency than for high frequency noise bursts. Dispersion means increased slightly from frontal to lateral azimuthal hemifields but decreased as age increased. There was no frequency dependence.

The results of these studies (**Table 2-1**) provided valuable information regarding the development and performance of normal hearing listeners in terms of spatial hearing (localization accuracy and lateral release skills) compared to children who wore one or two cochlear implants (Murphy et al. 2011) and data regarding the relationship between sound localization accuracy (absolute localization) and sound localization acuity (spatial discrimination) (Kühnle et al. 2013). However, the results from Murphy et al. (2011) and Kühnle et al. (2013) cannot be compared with those of the other studies (Van Deun et al. 2009; Litovksy and Godar, 2010; Grieco-Calub and Litovsky, 2010; Johnstone et al. 2010; Zheng et al. 2015; Reeder et al. 2015 and Martin et al. 2015) because of the different experiment set-up/procedures and quantification measures employed for sound localization accuracy.

Summary

A primary purpose for the human auditory system is sound source localization. This ability is essential for orientation and safety in the environment and facilitates spatial hearing in communication. Children with normal hearing, who are often in noisy environments for most of their day, will find it more challenging than adults to localize a sound source and/or understand speech in noisy settings because of their less mature auditory systems. Children who have a hearing loss will be at an even greater disadvantage. Sound localization acuity (relative localization) which is quantified by the MAA, has been a frequent and reliable means of assessing spatial discrimination especially in children, but this measure cannot give the fine-tuned exact sound source identification measure that sound localization accuracy (absolute localization) provides.

In the past, sound source localization accuracy testing was done primarily with adults because of the challenge of designing a test protocol that was both manageable (for children) and capable of sustaining a child's attention. A second challenge was the difficulty in comparing results across studies because of the variety of test protocols and measures that were employed. Over the past decade, researchers have worked to address these challenges, resulting in a few sound localization studies which included young children and utilized the RMSE measure for quantification. Most of these studies also used very similar protocols for set-up and procedures, such as a multi-speaker array. in the horizontal hemifield. Although these studies included children with normal hearing, they were included mainly for comparison with populations of children who were hearing impaired (such as those with a unilateral hearing loss or one or two cochlear implants).

There has not been much emphasis on tracking the developmental process of sound localization accuracy in young children beyond investigating the ages at which their performance becomes adult-like. It is critical to understand the developmental process of sound localization accuracy in young children so that factors that could contribute to the enhancement of that skill can be identified. In so doing, the knowledge gained could also be used to develop auditory training protocols for young children who are hearing impaired with the goal of stimulating and/or enhancing development in sound source localization skills towards normal or near-normal function.

Embodiment

Much of an individual's exploration and interaction within the environment occurs through movement or motor actions. During such movement, there is an ongoing cycle of information that is picked up from the environment through sensory receptors (such as sight, hearing, touch, smell), the central nervous system and the musculoskeletal system (Buckley and Toyoizumi, 2018). Within this cycle, sensory input guides motor behaviors which in turn are influenced by sensory feedback signals that are encountered within the environment. Both sensory and motor interaction with the world are crucial for a child's development. This traditional view for cognitive development however has placed heavy focus on the role of the brain. There is now a growing shift in perspective on cognitive development which places the emphasis on the role of the body and the way in which it interacts with the environment. This shift is being referred to as embodiment.

Perspectives of Embodiment

Em*bodi*ment, as the term implies, incorporates the role *the body* plays in shaping the mind within the context of the environment (Dove, 2015). It has become a popular term in fields such as psychology, linguistics, artificial intelligence/robotics and philosophy, and is used to define and describe how the body interacts with the environment to perform a task and/or how the environment is perceived based on the body's physical or psychosocial state (Schnall et al. 2008). This perspective views the brain as being embedded in the body which itself is embedded in the environment. Thus, brain output is influenced by the body's experiences within the environment.

Embodiment purports that thoughts, feelings and actions are not based on solely on cognitive processing, but on the body's sensorimotor experiences (Corbetta, Weiner, Thurman and McMahon, 2018). Chwilla et al. (2007) explained that embodiment is founded on the assumption that cognition is based on the kinds of physical interactions that individuals have with their environment. In other words, embodiment focuses on what *the body* does within the context of the environment that contributes to cognitive development. The body, specifically, physical movement of the body can affect cognition by way of memory. The embodied approach to cognitive development diverts from the traditional view that the mind/brain is in direct control of the body and lends support to the notion that not only does the mind influence the body, but the body also influences the mind (Madan and Singhal, 2012). The traditional view on cognitive processes purports that sensorimotor experiences are not involved in cognitive development and/or processing (Wellsby and Paxman, 2014). However, embodiment purports that meaning or representation is not generated from a combination of abstract symbols but is derived from the combination of our current physical actions, interactions and our past physical interactions/experiences within our environment. The interaction of our bodies within our environment influences how we think about or carry out the perceptual and action details commanded by a situation (Chwilla et al. 2007).

Similarly, Brouillet et al. (2010) expounded on embodiment from a cognitive standpoint, by stating that cognitive processes are firmly planted in the body's interactions with the world thus enabling understanding of cognition and behavioral responses within the environment. They added that embodied cognition has various viewpoints. Some focus on the effect that bodily states can have on cognitive states, others focus on the effect of simulation on cognition, and others focus on situated action, social interaction and the environment. In general, however, much like different people can utilize different methods to solve a Math problem and still get the same result, Brouillet et al. (2010) purport that embodiment is the incorporation of "interactions between perception, action, the body, the environment and other agents" in order to achieve a goal, regardless of viewpoint.

Construct of Embodiment

Within the construct of embodiment, the body is viewed as being the medium that connects the brain (mind) and the environment (world). It acts as a "liaison between the mind and the outer world." (Corbetta, 2009). This interaction of body, brain and environment dethrones the brain from being in control or "director" as Chiel and Beer (1997) describe it, to being simply another musician in the "orchestra" instead.

The traditional viewpoint puts the brain in control, where information is processed via a unidirectional, serial and hierarchical manner in which the nervous system (brain) receives the information from the environment (world) and then sends directions to the body which then interacts with the environment: environment → nervous system (brain) → body → environment. The embodied viewpoint is cyclic (Buckley and Toyoizumi, 2008) multimodal (Anderson, 2015) and bidirectional (Chiel and Beer, 1997), where the brain is embedded in the body, and the body embedded in the environment (Corbetta, 2009), and all are therefore "nested" and "coupled" (Thelen, 2000), thus making cognitive activities inseparable from, intertwined with, and influenced by the body and the environment in which these cognitive activities occur: environment ↔ body ↔ nervous system (brain) ↔ body ↔ environment. (Please refer to Beer, 2014, p. 137 for an illustration of the nested and bidirectional properties of the nervous system, body and environment). In this approach, the nervous system is not directly connected to the environment, but instead is linked by way of the body.

There is no other means by which information is transmitted to the brain but through the body. So, contrary to the traditional approach, the embodied approach views knowledge acquisition as resulting from sensorimotor experiences gained through bodily interactions in the environment (Wellsby & Paxman, 2014).

Examples of Embodiment

An example of embodiment from a linguistic perspective is demonstrated in a study by Hauk, Johnsrude and Pulvermuller, (2004) in which fMRI was used to observe brain activity in response to listening to the action words "kick", "pick" and "lick". These action words (verbs) are associated with the leg, arm and face respectively. fMRI results indicated that areas in the motor cortex that would produce the actions were activated (along with the areas in the primary somatosensory cortex that represented the body parts) even though there was no activity involved (Hauk et al., 2004; also cited by Beilock, 2009 and Anderson, 2015).

Another study by Van den Bergh, Vrana and Eelen (1990) explored typists' vs nontypists' preferences for typing a given pair of 2-letter combinations either with the same finger or with different fingers. Results showed that typists preferred letter combinations that were typed with different fingers to those typed with the same finger, whereas nontypists' showed no preference. Although the typists could not articulate the rationale for their preference, it was determined that their skill/experience at typing formed a motor program for typing movements which made using different fingers preferable (Van den Bergh et al., 1990; and cited by Beilock, 2009).

In a study by Williams and Bargh (2008), they described how a holding a warm cup of coffee or a hotpack versus a cup of iced coffee or an icepack influenced how an individual judged the personality of others or was willing to choose a gift for others instead of him/herself. Those who held a warm cup of coffee, when asked to complete a personality impression questionnaire and rate a person, were more likely to rate that target person as warmer and more trustworthy, compared to those who rated the target person after holding a cup of iced coffee. Similarly, participants who held a hotpack, when presented with a choice of selecting a reward for themselves or gift for a friend, more often chose a gift for a friend; whereas those who held a coldpack, more often chose a reward for themselves. Here, Williams and Bargh suggest that the warm or cold physical experience influenced the participants' interpersonal judgements and prosocial behavior towards other people.

Mattingly (2012) used William and Bargh's study, along with other examples including an analogy of sitting on a wobbly chair (Kille, Forest and Wood, 2013), to illustrate embodiment and discuss the effect physical experiences can have on relationships. He pointed out that people who sat on wobbly chairs expressed a desire for more stable, trustworthy partners when asked to choose the traits they would want to see in a romantic partner. They also more often said they thought celebrity couples would break up. Those who sat on stable chairs did not make that prediction. Mattingly commented that the "physical experience of instability" influenced participants who sat on wobbly chairs such that they perceived other people's relationships as being unstable and preferred a partner who could be trustworthy and reliable. These results support the embodied view that a person's physical experiences influence his/her psychological state without his/her awareness (Mattingly, 2012). Still another example of embodiment from a psychosocial state perspective is seen in the study by Schnall et al. (2008) where participants who were given heavy backpacks perceived a geographical slant to be much steeper than those who had lighter backpacks. Again, the participants' perception of the environment was influenced by their psychosocial state.

Summary

The body, brain and environment are all embedded systems that work together toward a specific goal-directed activity. Each of these systems have their own dynamic architecture but they, working in concert, all contribute to further growth and development. The embodied approach to cognition is therefore dynamic because an individual's (body's) continuous interaction within his/her environment influences his/her judgements and/or behavioral responses within that environment from moment to moment, in real time (Brouillet, et al., 2010; Smith, 2005). While it is absolutely fundamental, the brain cannot do anything without the body. The body is instrumental for action to occur. Action occurs through the body, and that action is not "pre-script-ed" but is always being modified or transformed based on the body's sensory and motor capacities, past experiences and current environmental conditions.

Embodiment and Sound Source Localization Accuracy

When a sound is presented, the ear detects it but the whole body reacts in its quest to locate it. The head may turn, the eyes may search the surrounding environment, and the body may move closer to or away from the sound source depending on the memory or specific goal associated with that sound. The listener surveys the environment to determine where the sound originated and how to respond. The environment influences the listener's response by providing cues such as interaural timing and level differences. Sensory input such as vision (looking for the sound source), motor input such as walking or turning the head (toward or away from the sound source) reasoning (what to do about the sound source) and memory (previous experiences) all "mesh" together during the act of localizing the sound source. Since children 5 years of age and under do not all localize a sound source as accurately as adults (Grieco-Calub and Litovsky, 2010; Martin et al., 2015; Litovsky and Godar, 2010; Zheng et al., 2015), it is possible that this skill of identifying the exact location of a sound source could be enhanced by embodiment. Since the mind and body work together in concert, it is suggested that the repeated sensory-motor experience during the act of identifying the exact location of the sound source, which is a goal-directed activity, will create a mapping between the intentions and the motor movement thus producing an action or behavior that becomes more accurate in its plan to achieve the goal being pursued (Corbetta et al. 2014). The practiced, repeated action of localizing the sound source by walking and pointing to it would build the memory of its origin and thus improve accuracy (Diedrich, Thelen, Smith, & Corbetta, 2000; Madan and Singhal, 2012).

Incorporating embodiment in this study would require bodily interaction with the environment – in this case, walking and pointing. The rationale was that the biomechanics of the body (including legs, arm, hand, fingers), interacting with the nervous system/brain and the test environment, resulted in continuous feedback between the nervous system/brain, body (musculo-mechanical system of walking and pointing movements) and the test environment, which consisted of auditory stimuli emanating from a variety of sources (Chiel and Beer, 1997). Although verbal responses are a type of motor response, walking and pointing are more salient motor responses, which form a coupling between what is heard and the response. Stated more simply: "because your mind and body act together you can recall more of what you hear…" (Rohde, 2013, p.11). Additionally, the more salient, deliberate, conscious, and intended motor response of walking/pointing would provide another modality through which the mapping of the responses to the sound stimuli would occur (Anderson, 2015; Corbetta et al., 2014;

Diedrich et al., 2000). Representation is multimodal in this scenario and thus characteristic of the theory of embodiment. The mind and body are working together, “in concert”, creating a memory/map between intentions and movement through the repetition of sensory and motor experiences gained through source identification efforts, thus yielding an increasingly accurate behavioral response (Chiel and Beer, 1997; Corbetta, 2009; Corbetta, et al. 2014).

The current study therefore sought to investigate the effect of embodiment on sound localization accuracy. This study involved at minimum, a sensory modality – audition; a motor modality – walking and pointing; and a cognitive response – the identification of the exact location of the sound within the test environment, which consisted of a semicircular array of 15 loudspeakers, child-friendly pictures attached underneath each loudspeaker and a computer monitor displaying images of those pictures on the screen in the same order. This study aimed to determine whether there was a difference in sound source identification accuracy when a participant walked up to and pointed (motor response) to the perceived location of the sound source compared to when a participant verbally reported (verbal response) where the sound source originated.

CHAPTER 3. METHODOLOGY

Purpose of the Study

The purpose of the study was to examine and compare sound localization accuracy in young children aged 3 and 5 years old when asked to use certain specific response modes (verbal or motor) to localize a sound source. The goal was to determine which modal response (verbal or motor) would better facilitate spatial hearing and sound localization development. Participants were asked to either sit in a chair and name the location of the origin of the sound (verbal response) or to walk over and point to or touch the loudspeaker or picture from which the sound originated (motor response).

Overview of the Study

Participants were recruited through the distribution of Institutional Review Board (IRB)-approved flyers seeking volunteers, throughout the University of Tennessee Knoxville (UTK) campus and within the Knoxville community. Volunteers who were willing to participate were invited to the Spatial and Binaural Hearing Laboratory located on the UTK campus for testing.

On arrival, the principal investigator described the study procedure to the parent(s)/legal guardian(s) and the participant(s), and then obtained signed consent forms. Following signature of the consent form, screenings for hearing, vision and vocabulary were then conducted. If the participant met eligibility by passing all screenings, sound localization testing was then conducted in the sound booth. Each response was recorded in terms of angular location (in degrees azimuth) of the loudspeaker presenting the stimulus (source) and angular location of the loudspeaker from which the participant perceived/reported the stimulus originated (response). The principal investigator then input the participant's response after each trial. There were seven (7) sound (target) locations, with a total of five (5) trials randomly presented from each target loudspeaker for a total of 35 trials per block of trials. At the end of each block of trials, participants were presented with stickers and/or prizes as a reward for participating.

The absolute difference between each target and response location was calculated (in degrees azimuth), and then squared. The squares of all five responses were summed for each of the seven target locations, and then the square root was calculated for each sum per target location. Finally, the mean average for all seven square roots were calculated to give the average root mean square error (RMSE). The formulae for these calculations were all preprogrammed in an Excel file. There was an Excel file for each participant's results. The RMSE for each participant was the data used for analysis.

Study Design

The study was a mixed design. There were two independent variables: age and response mode. Each independent variable had two levels: ages – 3 and 5; response modes – verbal (V) and motor (M). The dependent variable was the RMSE measure of localization accuracy for sound source identification. Data regarding response mode would be analyzed within each age group and between age groups.

Participants

Age

A total of 79 children were recruited for this study. Of these, 41 children were three years old and 38 children were five years old.

Inclusion Criteria

Inclusion criteria for each participant included:

1) normal hearing and
2) normal or corrected vision.

Exclusion Criteria

A participant was excluded from the study if s/he:

1) failed the otoscopic screening or
2) failed the hearing screening or
3) failed the vision screening or
4) had an abnormal middle ear immittance or
5) had normal hearing but showed a difference in hearing sensitivity between ears greater than 10 dB HL for any frequency tested or
6) showed a hearing sensitivity greater than 20 dB HL at any frequency tested or
7) failed a vocabulary screening using the picture cues located under each of the loudspeakers in the sound booth.

Informed Consent

The participants' parents or legal guardians were asked to sign a written consent form allowing them to participate in the study.

Recruitment

Participants were recruited through the IRB-approved Child Development Research Group (CDRG) at the University of Tennessee, Knoxville (UTK). IRB approved recruitment flyers were also posted on the UTK campus and in the community.

Experimental Set-Up and Procedure

Set-up

The experimental set-up was the same as that used in the Martin et al. (2015) study and similar to the Greico-Calub and Litovsky (2010) and Johnstone et al. (2010) studies. There was a semicircular array of 15 loudspeakers set apart at 10^{o} intervals on a horizontal arc from -70^{o} to +70^{o} azimuth. A small child-friendly picture was attached underneath each loudspeaker to the shelf on which the loudspeakers were sitting, for the sound source identification purposes.

Instrumentation

Localization testing was conducted in a double-walled sound-attenuating booth (IAC, 2.2 x1.8 m). This booth contained the horizontal semicircular array of fifteen (15) loudspeakers (Cambridge Sound Works Center/Surround IV; matched within 1 dB at 100 to 8000 Hz). The loudspeakers were positioned at ear-level, at 10^{o} intervals, from -70^{o} to 70^{o} azimuth, along an arc with a radius of approximately1m, thus ensuring that the distance aspect of localization remained constant.

Each loudspeaker had a child-friendly laminated picture of a colored drawing that was fastened underneath by Velcro on to the shelf on which the loudspeakers were sitting. Each drawing represented items that were typically recognized by a child, such as a bear, dog, cat, hotdog, ice-cream, bathtub etc. A 17" multimedia LCD monitor (View Sonic VG730m) was located under the shelf holding the loudspeakers at 0^{o} azimuth. There was a keyboard and mouse (Manhattan 176392) attached to the monitor for experimental set-up and data entry purposes. The monitor showed a display of the colored drawings on the screen, arranged in the exact semicircular format as those fastened under the loudspeakers. There was a chair-desk located in front the monitor at 1m from the center loudspeaker (which was sitting at 0^{o} azimuth on the shelf above the monitor). An additional monitor (NEC Multisync LCD 1770VX), keyboard and mouse (Dell Keyboard KB212-B) were set-up on a desk outside the booth so that the software could also be controlled from outside the booth. Both monitor systems were controlled by a computer (Dell Optiplex 9020) that was located under the desk.

Stimuli

The sound stimulus was the spondee word "baseball". This stimulus was digitally recorded with a male voice at a sampling rate of 44.1 kHz and stored as a .wav file.

Stimulus duration was 0.719ms and calibrated to 60 dB SPL. The stimulus was randomly presented a total of five (5) times from each of seven target loudspeakers for a total of 35 trials.

There was also a light stimulus which was presented via the flashing of a small 3x8mm light incandescent light bulb (8V, 35mA). Each bulb was attached centrally under each loudspeaker.

Stimulus presentation was controlled by Tucker Davis Technologies (TDT) System III (RP2, PM2, AP2) hardware in conjunction with an IBM PC host. The system also controlled the multiplexer used for switching loudspeakers and light presentation. Software for the stimulus presentation and data collection was operated on a custom-written MATLAB platform.

Procedure

There were two age groups of participants: 3-year-olds and 5-year-olds. Each age group was randomly divided into two groups by response mode: Verbal (V) or Motor (M). Each task consisted of 35 trials as previously described.

Following the signature of the informed consent paperwork, each participant underwent:

1) an otoscopic examination
2) a tympanometric screening
3) a hearing screening at 20 dB HL across all frequencies from 250 to 8000 Hz
4) a vision screening using a Snellen chart (obtained from http://www.disabled-world.com/artman/publish/eye-chart.shtml) and
5) a vocabulary screening using the pictures placed under each loudspeaker.

Upon passing all the screenings, each participant was then verbally instructed to sit in the chair-desk, facing 0^{o} azimuth, and listen for the word "baseball" for the sound localization task. The participant was then asked to indicate the loudspeaker from which the word "baseball" originated by either saying the name of the picture underneath the corresponding speaker (verbal response) or by walking over to that loudspeaker and pointing to the picture (motor response). The mode of response for each participant was previously determined by a random generator.

Once the participant responded, the investigator recorded the participant's selection by using the computer mouse to click on the picture on the computer screen that matched the picture under the loudspeaker that the participant indicated the sound (the spondee "baseball") emanated. Feedback was not be provided but following each entry/response, a piece to a computerized puzzle picture appeared on the screen to provide reinforcement. This continued with each response entry. The completed puzzle picture indicated the end of that block of trials (35 pieces representing 35 trials).

After a brief break during which the experimenter changed over the cables from sound to light, and issued a few stickers and prizes, the participant returned for a second block of trials using the light stimulus and the same mode of response as was previously used.

After testing a few children using this methodology it was determined that adding a second sound source localization task in which the participants responded by verbal report only, would allow for better assessment of the effect of motor responses on auditory spatial mapping by comparing the second (verbal) responses of those who initially used a motor response with that of those who used an initial verbal response. Each participant then completed two sound source localization tasks. The first sound source localization task was completed using either a verbal or motor response (previously determined by random generator), and the second sound source localization task was completed using a verbal response.

There were a few instances where a young child could not or would not complete a second sound source localization task, and in those cases, the child was asked to complete a light source localization task instead for the second block of trials.

CHAPTER 4. RESULTS

Participants

Participants were recruited from the community via several means: Parents were contacted via phone calls and emails inviting their child(ren) to participate. Flyers were posted in several locations within the community such as public libraries, kindergarten school groups, and mothers-of-preschoolers (MOPS) groups. They were also posted on appropriate social media groups.

A total of 79 children participated in this study. There were 38 five-year old children (17 boys and 21 girls) between the ages of 5.0 and 5.9 years (mean 5.4 years). and 41 three-year-old children (20 boys and 21 girls) between the ages of 3.0 and 3.9 years (mean 3.4 years). Three children (one 5-year-old girl, and two 3-year-old girls) were excluded from the study because they could/did not complete the experiment. A fourth participant, a 5-year-old boy, was excluded because of an error during the first task in which the speech monosyllabic "ball" was presented as the stimulus instead of the speech spondee "baseball". Thus, data from a total of 75 participants (36 five-year-olds and 39 three-year-olds) were used for analysis in this study.

Five-Year-Olds

Thirty-six 5-year-olds completed the first sound localization task as requested. They were randomly divided into two groups by mode of response: motor (walking and pointing to the location of the sound source) or verbal (naming the location of the sound source). Eighteen of the 5-year-old children (12 boys and 6 girls) responded motorically during the first sound localization task. The other eighteen children (4 boys and 14 girls) completed the first sound localization task using only verbal responses. Prior to the addition of a second sound localization task, five of the children (2 boys and 3 girls) had completed a light localization task as a second task, therefore 31 children (14 boys and 17 girls) completed the second sound localization task using verbal responses.

Three-Year-Olds

All 39 three-year-olds who participated in the study completed the first sound localization task. As with the 5-year-olds, the 3-year-old group was randomly divided into two groups by mode of response (motor or verbal). The motor group consisted of 7 boys and 13 girls, and the verbal group consisted of 13 boys and 6 girls. Prior to the addition of a second sound localization task, nine of the 3-year-old children (4 boys and 5 girls) had completed a light localization task as a second task. Another nine (5 boys and 4 girls) were either unable or unwilling to complete the second sound localization task as requested and were subsequently asked to complete a light localization task instead.

Thus, there were 21 three-year-old children (12 boys and 9 girls) who completed the second localization task using verbal responses.

Data Analysis

The difference between each target and response location was calculated (in degrees azimuth), and then squared. The squares of all five responses were summed for each of the seven target locations (-60°, -40°, -20°, 0°, 20°, 40°, and 60°) and then the square root was calculated for each sum per target location. Finally, the mean average of all seven square roots were calculated to give the average root mean square error (RMSE). The RMSE is a negatively-oriented score which means the lower the score the better (or more accurate) the response. The RMSE for each participant was the dependent variable used for data analysis. Data were analyzed via the Generalized Estimating Equations (GEE) – Robust Estimator statistical approach using the Statistical Package for the Social Sciences (SPSS) software, version 25. The GEE statistical approach was selected because it can be used for continuous measurements (RMSEs) and repeated categorical responses (motor and verbal), and handles missing data using quasi-likelihood estimation.

Descriptive Statistics

First Sound Localization Task

Participants were randomly selected to identify the locations of a sound source using either a motor response (walking and pointing to the source) or a verbal response (sit in a chair and verbally name the location). The sound stimulus, the speech spondee "baseball" was randomly presented from each of seven loudspeakers for a total of five times per target speaker, so there were 35 trials in this block. This task was completed by 36 five-year-olds (5yr) and 39 three-year-olds (3yr).

Descriptive statistics revealed RMSEs (in degrees azimuth) were larger both in mean and range for 3yr compared to 5yr. The mean for the 3-year-old children who responded motorically (3M) was 28.97° with a range of 2.97° to 55.97°. The 3-year-old children who responded verbally (3V) had a mean of 27.79° with a range of 3.39° to 63.60°. The 5-year-old children who responded motorically (5M) had a mean of 6.27° and a range of 1.91° to 21.85°, and the 5-year-old children who responded verbally (3V) had a mean of 6.13° with a range of 1.91° to 11.62°.

Second Sound Localization Task

Participants were asked to identify the locations of the sound source a second time by using only a verbal response. As with the first task, the sound stimulus, the speech spondee "baseball" was randomly presented from each of seven loudspeakers for a total of five times per target speaker, so there were 35 trials in this block. This task was completed by 31 five-year-olds and 21 three-year-olds.

Descriptive statistics revealed RMS errors were also greater both in mean and range for 3yr compared to 5yr in the second sound localization task. The mean for the 3M group (who initially responded motorically) was 33.49º (range 5.38º to 49.89º) for this second task in which they provided a verbal response. The 3V group (who responded verbally initially) had a mean of 22.47º (with a similar range of 5.36º to 45.67º) the second time. The 5M group (who initially responded motorically) had a mean of 8.68º (range 3.19º to 24.64º) for this second task in which they provided a verbal response. The 5V group (who responded verbally initially) had a mean of 6.60º with an approximate range of 2.71º to 12.06º. Mean and range details for all the groups by age and mode of response for both tasks are summarized in **Table 4.1**.

Light Localization Task

Eighteen 3-year-old children and five 5-year-old children performed the light localization task. Nine 3-year-olds and five 5-year-olds had performed this task prior to it being replaced with a second sound localization task. Another nine 3-year-olds performed this task in lieu of the second sound source localization task. Mean RMS error was 3.2º. When an outlier of 32.01º was removed all other 22 RMS errors were at or less than 10º and the mean RMS error was 1.9º.

Generalized Estimating Equations (GEE) – Robust Estimator

Data for sound localization accuracy was analyzed using the Generalized Estimating Equations (GEE) robust estimator statistical approach and Least Significant Differences as the post hoc test. Results revealed statistical significance for age, mode*order and age*mode*order. Details are shown in **Table 4-2**. Summaries of means and standard errors for each model are provided in the **Appendix**.

Age

The mean RMSE for 3-year-olds was 28.18º. Five-year-olds had a mean RMSE of 6.92º There was a significant main effect for age ($p < .001$). Results are illustrated in **Figure 4-1**.

Mode of Response

The mean RMSE for motor responses was 19.35º. The mean RMSE for verbal responses was 15.75º There was no significant main effect for mode ($p = .146$). Results are illustrated in **Figure 4-2.**

Table 4-1. Mean and range RMSEs for each subject group by sound task order

Task Order	Subject Group	Mean RMSE	RMSE Range
First Sound Localization Task	3M	28.97°	2.97° to 55.57°
	3V	27.79°	3.39° to 63.60°
	5M	6.27°	1.91° to 21.85°
	5V	6.13°	1.91° to 11.62°
Second Sound Localization Task	3M	33.49°	5.38° to 49.89°
	3V	22.47°	5.36° to 45.67°
	5M	8.68°	3.19° to 24.64°
	5V	6.60°	2.71° to 12.06°

Notes: 3M = 3-year-old children who responded motorically during the first sound localization task; 3V = 3-year-old children who responded verbally during the first sound localization task; 5M = 5-year-old children who responded motorically during the first sound localization task; and 5V = 5-year-old children who responded verbally during the first sound localization task.

Table 4-2. Test of model effects

	Type III		
Source	Wald Chi Square	df	Sig.
(Intercept)	200.090	1	.000
Age	73.375	1	.000
Mode	2.112	1	.146
Order	.301	1	.583
Age*Mode	1.011	1	.315
Age*Order	.938	1	.333
Mode*Order	9.539	1	.002
Age*Mode*Order	4.313	1	.038

Notes: Dependent variable is the RMSE. Models (Intercept) are age, mode, order, age*mode, age*order, mode*order and age*mode*order. Significant values are highlighted in yellow.

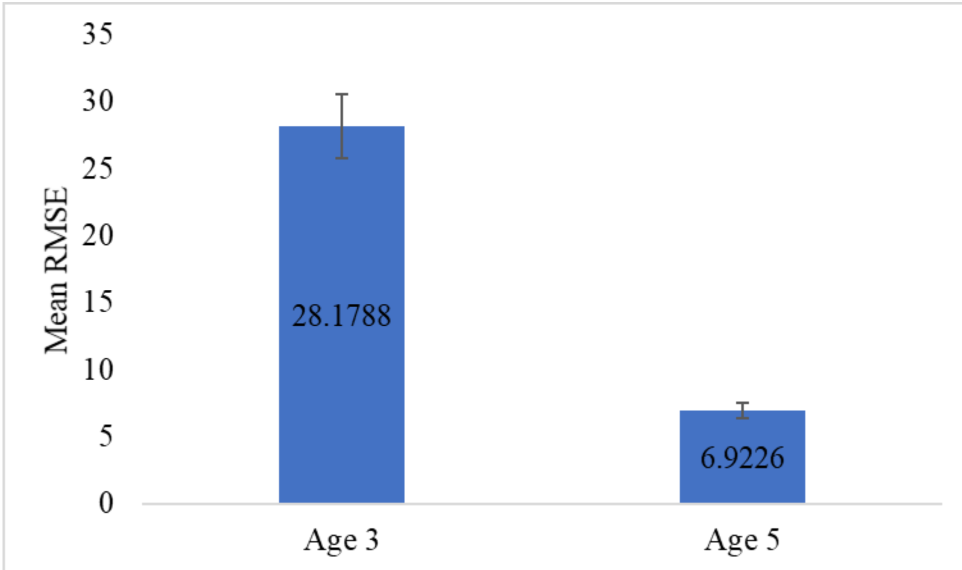

Figure 4-1. Sound localization accuracy results were significant for age group
Note: Lower RMSEs = better accuracy.

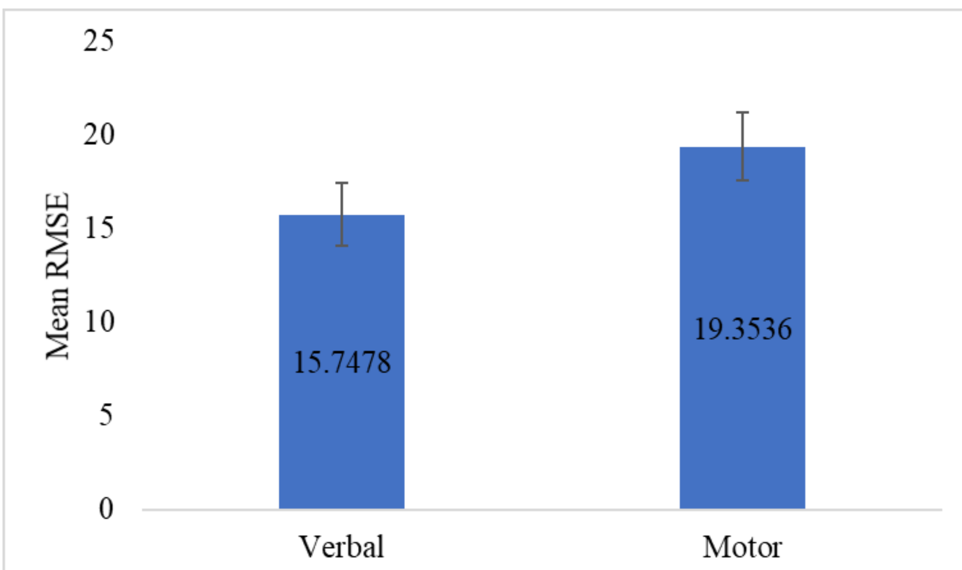

Figure 4-2. Sound localization accuracy results were not significant for mode of response
Note: Lower RMSEs = better accuracy.

Order

There was also no significant main effect for the order in which the sound localization tasks occurred (p = .583). The mean RMSE was 17.29^{o} for the first sound localization task and 17.81^{o} for the second sound localization task. See **Figure 4-3** for illustrated results.

Interactions

Mode*Order. There was a significant interaction for mode*order (p = .002). The Verbal 1st Group who started with a verbal response during the first sound localization task showed similar results in the second task. The Motor 1st Group who responded motorically in the first sound localization task were less accurate in the second task which required a verbal response. Pairwise comparisons with Least Significant Differences corrections revealed significant differences between the means of the Verbal 1st Group and the Motor 1st Group in the second localization tasks (p = .009); and between the means of first sound localization task and the second sound localization task for the Motor 1st Group **(Figure 4-4)**.

Age*Mode*Order. There was also a significant interaction for age*mode*order (p = .038). which is illustrated in **Figure 4-5**. Pairwise comparisons with Least Significant Differences corrections revealed significant differences within both age groups. There was a significant difference between the first and second sound localization tasks for the 3yr Verbal 1st Group showing that there was better accuracy in the second task (p = .030). There was also a significant difference between the performance of the 3yr Verbal 1st Group and the 3yr Motor 1st Group in the second sound localization tasks (p = .023) such that the verbal group had better accuracy than the motor group in the second task. The 5yr Motor 1st Group showed a significant difference in accuracy between the first sound localization task and the second sound localization task (p = .001). Their accuracy was significantly worse on the second task which required a verbal response (following an initial motor response in the first task). There was also a significant difference (p = .043) in performance between the 5yr Verbal 1st Group in the first sound localization task and the 5yr Motor 1st Group in the second sound localization task (which required a verbal response).

There were no significant interactions for age*mode (p = .315)**.** There were also no significant interactions for age*order (p = .333).

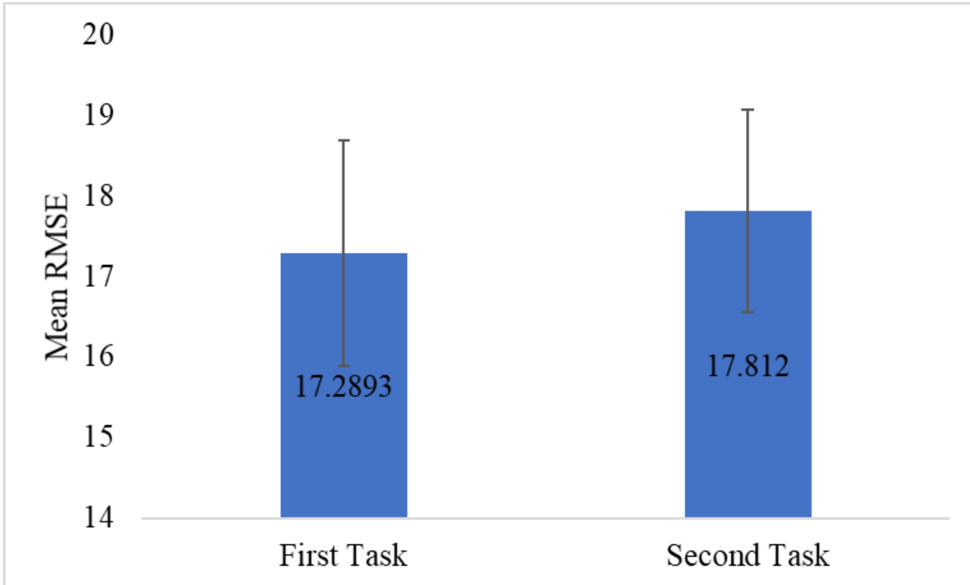

Figure 4-3. Sound localization accuracy results were not significant for order of sound localization tasks
Note: Lower RMSEs = better accuracy.

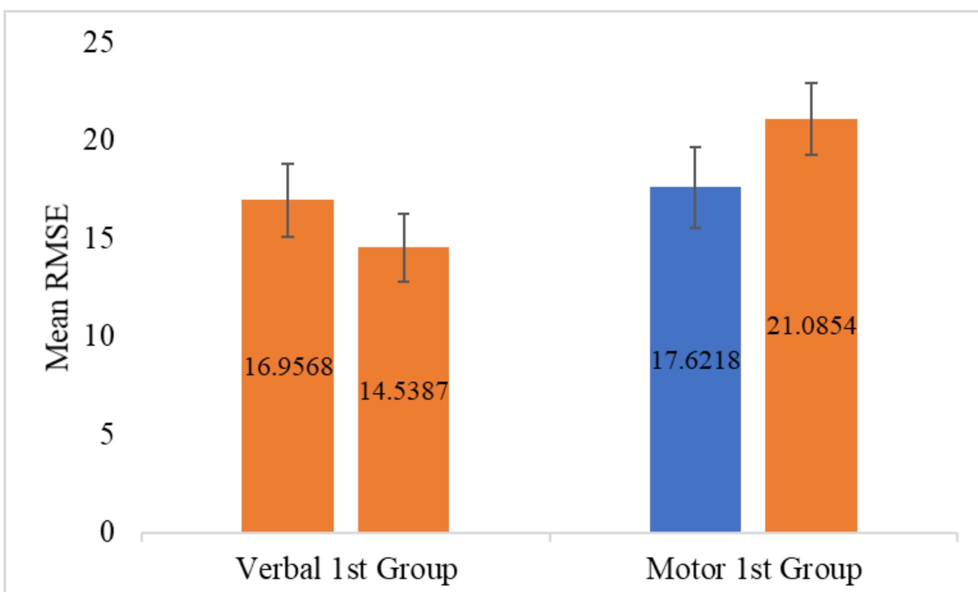

Figure 4-4. Sound localization accuracy results showing mode*order
Notes: The left bar in each mode group represents the mean for the first sound localization task. The right bar in each mode group represents the mean for the second sound localization task. Lower RMSEs = better accuracy.

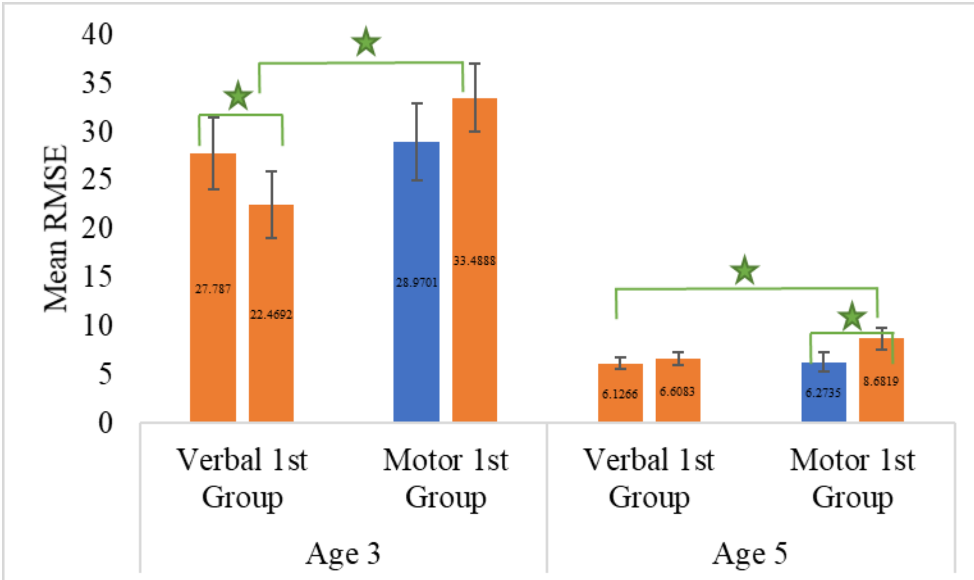

Figure 4-5. Sound localization accuracy results showing interaction for age*mode*order

Notes: The numbers in the bars represent the means. Orange bars represent verbal responses. Blue bars represent motor responses. Lower RMSEs = better accuracy.

CHAPTER 5. DISCUSSION

Recapitulation

Previous studies which also examined sound localization accuracy in children using the same experimental set-up – of 15 loudspeakers arranged at 10° intervals in a semicircular array in the frontal azimuthal plane – (Grieco-Calub and Litovsky, 2010; Johnstone et al., 2010; Litovsky and Godar, 2010; Martin et al., 2015; Reeder et al., 2015; Zheng et al., 2015) and the same stimulus – the speech spondee “baseball” (Grieco-Calub and Litovsky, 2010; Johnstone et al., 2010; Martin et al., 2015) allowed for comparison of data across studies. However, the methodology used in these studies did not regulate the manner in which the participants indicated their exact perception of the location of the sound source.

The Martin et al. (2015) study added a light localization task as well as an unroved sound localization task. By doing so, Martin et al found that there were no significant differences in sound localization accuracy between roved and unroved sound stimuli, indicating that young children did not rely on overall level cues to localize a sound source. Martin et al. also found that all the young children were able to localize the light source with the same accuracy as adults, but that the light localization task did not facilitate better sound localization accuracy in young children (regardless of order) as it did for adults who received the light localization task first. The young children’s adultlike performance in the light localization task did, however, indicate that they were able to understand and complete the task at hand, thus pointing to the suggestion that their poorer sound localization performance could be developmental rather than due to task comprehension difficulties. With Martin et al. having shown that young children were able to comprehend and complete the task, the current study then sought to further tease out other factors that could enhance sound localization accuracy by regulating the way each participant indicated his/her perception of the exact location of the sound source. Specifically, this study aimed to separate motor (walking and/or pointing) responses from verbal (naming) responses to determine if there was a difference in the effect of one mode of response versus another on sound localization accuracy by using similar testing conditions as in previous studies on sound localization accuracy in children (Grieco-Calub and Litovsky, 2010; Johnstone et al., 2010; Martin et al., 2015).

Age Group Differences

There was a significant age group effect seen in this current study. The 5-year-old children had better sound localization accuracy and less variation (smaller ranges of RMS errors) than the 3-year-old age group. This significant age group difference in sound localization accuracy in young children with normal hearing was consistent with the results in previous studies (Van Deun et al., 2009; Martin et al., 2015). Considering that the testing environment, set-up, equipment and procedures were like those reported in other studies which also explored sound localization accuracy in children (Grieco-Calub and Litovsky, 2010; Johnstone et al., 2010; Martin et al., 2015), it is not likely that the age differences observed would be attributed to testing conditions. A more likely reason the 3-year-olds had greater error in sound localization accuracy could be developmental, in that their central auditory processing systems are less mature (Van Deun et al. 2009; Martin et al., 2015). Also, despite experimenter efforts to keep these 3-year-olds engaged in the sound localization task(s), instants of inattentiveness, reduced motivation and/or boredom or fatigue cannot be entirely ruled out.

Mode of Response

The current study sought to control the way in which children identified the exact location of the sound source by limiting the mode of response to EITHER a motor response OR a verbal response. Participants were not allowed to combine the two modes of responses during a block of trials. In previous studies where children were asked to identify the exact location of a sound, they responded by pointing to or naming the location (Van Deun et al. 2009) and by clicking a computer mouse to indicate the location or verbally reporting the location to the experimenter (Grieco-Calub and Litovsky, 2010; Johnstone et al., 2010; Zheng et al., 2015). In essence, these responses in these studies were both motoric and verbal simultaneously.

Although this study attempted to isolate or tease apart the motor responses versus the verbal responses to investigate the individual effects of each modal response on sound localization accuracy, the results obtained indicated that there was no significant difference between motor responses and verbal responses on sound localization accuracy for either 3-year-old children or 5-year-old children. Experimenter observation indicated that in general, children showed a tendency to spontaneously point to the perceived location even when asked to respond verbally and vice versa, so it is suggested that cognitive effort was required to suppress the tendency towards a simultaneous motor and verbal response. Visually, it seemed that verbal responses yielded slightly better accuracy, but statistically, there was no significant difference between verbal responses and motor responses.

Order

The mean for the first sound localization task was very similar to that of the second sound localization task. There was no significant difference for order suggesting that sound localization accuracy for one task was not influenced by whether it occurred before or after another task.

In the previous Martin et al. (2015) study, the adults who performed a light localization task before the sound localization task did better on the sound localization task that followed compared to those adults who had the sound localization task first. This light order effect was not observed in any of the children. In this study one sound task was followed by another sound task. The stimulus was the same which could explain the non-significant order effect. The parameter that did change from one sound localization task to the next was the mode of response. Half of the participants were asked to respond motorically during the first sound localization task and then respond verbally during the second sound localization task; the other half were asked to respond verbally in both sound localization tasks.

Mode*Order Interaction

While there were not significant main effects for mode of response or order of sound localization tasks, there was significant interaction of mode and order. The children who responded with a motor response in the first sound localization task showed better accuracy in that task (mean RMSE = 17.62º) than in the second sound localization task in which they were asked to change their response to a verbal response (mean RMSE = 21.09º). The children who responded via verbal report during the first sound localization task (mean RMSE = 16.96º) showed similar accuracy on the second sound localization task in which they did not have to change their mode of response (mean RMSE = 14.54º).

The better performance using motor responses during the first sound localization task does indicate that the use of motoric actions could be an effective means of enhancing the skill of sound source localization. It is suggested that the significant mode*order effect observed was likely influenced by the challenge of having to make the transition in mode of response from motor to verbal. In other words, it is proposed that the embodiment of mind and body established during the initial motor responses, had an effect on the accuracy of sound localization during the second task not because of an inability to localize the sound (as evidenced by the similar results for sound localization order) but because of difficulty or immaturity in the dynamics necessary to make the transition from a motor response to a verbal response. Corbetta (2009) explained (in reference to the Piagetian A not B task), that such factors as body mechanics, flexibility in breaking a "forming" habit and frequency of previous trials can all contribute to erroneous responses because of the intertwining characteristics of the mind, body and environment known as embodiment (p. 56). In light of this thought, it is suggested that the repeated motor responses for 35 trials during the first block of trials in this study likely started the formation of a habit that was then difficult to break when asked to respond verbally during the second block of trials. Nevertheless, the use of motor responses did yield better sound source localization results during the task in which they were employed and could therefore be an effective technique that could be included in a training protocol for sound source localization.

Other Interactions: Age*Mode*Order

There was a significant interaction for age*mode*order (p = .038) but no significant interaction was found for age*mode or age*order. Specifically, in addition to the overall differences between the 3-year-olds and the 5-year-olds, paired comparisons revealed there was also a significant interaction of age*mode*order for the 5-year-old children who had an initial motor response on both the first sound localization task (p = .020) and the second localization task (p = .020). These children showed better accuracy when using a motor response during the first sound localization task and less accuracy when using a verbal response during the second sound localization task. It is interesting that this was not a significant finding for 3-year-olds.

It seems that age is the primary driving force for significant interactions; but it is also likely that the less accuracy observed in the second sound localization task could again be due to difficulty breaking the habit generated when executing the first sound localization task and transitioning to the verbal response mode required when performing the second sound localization task.

Light Source Localization Task

Although the light source localization task was replaced with a second sound localization task using verbal only responses, there were nine 3-year-old children who were judged by the experimenter as being unwilling or unable to complete a second sound localization task. These children were asked to perform the light localization task instead for their second block of trials. In doing so, each of the children were observed to willingly and enthusiastically complete the light task. This also gave the visibly concerned parent who was present throughout the testing, reassurance that the child was able to comprehend the task that was required of him/her. All but one child completed the light source localization task with adult-like performance.

Comparison with Previous Studies

One benefit of this present study is that the number of participants was larger and more homogenous per age group than those in the studies previously mentioned. This study had 39 participants in the 3-year-old age group and 36 participants in the 5-year-old age group. Each age group in this study was therefore approximately 4 times larger than similar age groups in previous studies, which contributed to the strength of the present study and better generalizability for the ages represented.

The mean and range of RMSEs for the 3-year-old group in this study were consistent with those in the previous Martin et al. (2015) study despite the larger group number in this present study. The mean for the three-year-old group (N = 10) in 2015 was 29.03º. The mean for the three-year-old age group (N = 39) in the current study was 28.36º. The mean and range for the 5-year-old group was smaller (better accuracy) for the current (larger) group (N = 36) in this study compared to the smaller 2015 group (N = 10). The mean for the 5-year-old group in 2015 was 15.4º, but when an outlier of 43.81º was removed (which changed the range from 5º – 43º to 5º – 19º), the mean was reduced to 12.23º. The mean for the 5-year-old group (N = 36) in the current study was 6.2º. However, there was no significant difference between the means of these two groups after the removal of the outlier. RMSE means and ranges for both age groups for the Martin et al. (2015) study and the current (2019) study are shown in **Table 5-1**.

Conclusions

This study aimed to investigate potential links between auditory spatial mapping and embodiment. Specifically, the study compared the effect of motor responses versus verbal responses on sound source localization accuracy in young children aged 3 and 5 years old, who had normal hearing. Answers to the proposed research questions were determined to be as follows:

Answer for Research Question 1

Q. Which response mode (verbal or motor) better influences sound localization accuracy in young children?

A. Neither. There was no significant difference observed between verbal and motor responses modes. However, results showed that performance improved when the same mode of response (verbal) was used. Performance worsened when the task was repeated using a different response mode the second time (motor to verbal).

Answer for Research Question 2

Q. Will there be better sound localization accuracy in 3-year-olds who use motor responses compared to those who use verbal responses?

A. No. There were no significant differences between verbal and motor response modes for 3-year-old children. Three-year-old children who used motor responses did not perform better than those who used verbal responses. The 3-year-olds who used an initial verbal response showed a significantly better performance when they repeated the task using a verbal response again; but the 3-year-olds who used an initial motor response did worse when they repeated the task using a verbal response, and worse than the 5-year-olds who used a verbal response. Overall, the 3-year-old children showed significantly poorer performance than 5-year-old children for both response modes.

Answer for Research Question 3

Q. Will there be a difference in performance between the first and second sound localization tasks (order)?

Table 5-1. RMSE means and ranges for Martin et al. (2015) study and this present (2019) study

Age	RMSE	2015 Study	2019 Study
3yr	Mean	29.03º (N = 10)	28.36º (N = 39)
	Range	8.6º – 50.37º	2.97º – 63.59º
5yr	Mean	15.39º* (N = 10)	6.20º (N = 36)
	Range	5.03º – 43.81º*	1.92º – 21.85º

Note: When an outlier of 43.81º was removed, the revised mean was 12.24ºand range was 5.03º to 19.55º.

A. No. There was no significant difference for order. However, the 3-year-old children who were in the Verbal 1st Group showed significantly better performance on the second sound localization task; and the 5-year-old children who were in the Motor 1st Group showed significantly worse performance on the second sound localization task (so their performance was better with the initial motor response).

Summary

5-year-olds showed better performance overall, which is consistent with previous studies. There was not a significant difference between response modes. However, localizing sound using an initial motor response degraded performance in the second task in which a verbal response was required.

A novel finding in this study is that children do not perform well when asked to change their mode of response when learning a new skill. In this study there was a significant difference between initial motor response and second verbal response in the 5-year-old Motor 1st Group. Adults learning a new skill perform worse when first asked to change the mode they initially used, but this has not been previously tested in young children.

Implications

The poorer performance with the verbal responses following a motor response suggests that the previous motoric actions did not create a spatial map for that auditory space that would facilitate better sound localization accuracy on the second task. It is also proposed that the poorer results on the second task by those who initially responded motorically could be due to the body's difficulty in breaking that memory (created by the repeated motor actions) and making the transition from a motor response to a verbal response.

Since the stimulus and experimental set-up for this study was the same as other studies (Grieco-Calub and Litovsky, 2010; Johnstone et al., 2010; Martin et al., 2015) thus making it possible to compare results across these studies, it is inferred that testing conditions were not the cause for the poorer performances. It is also proposed that the adult-like performance on the light localization task (specifically for the 3-year-olds) indicated that poorer performance on sound localization was not due to inadequate task comprehension (consistent with Martin et al., 2015). The wide variation in performance on sound localization tasks however indicates that attention issues cannot be completely ruled out (Litovsky, 1997, 2012; Van Deun et al., 2009; Lovett et al., 2012).

The overall age differences strongly suggest that there is also a developmental component that explains the poorer performance in sound source localization seen in 3-year-olds compared to 5-year-olds. In many instances a participant was observed to show an immediate head turn response in the correct direction of the sound stimulus but yet would verbalize or point to a different location, suggesting difficulty in the ability to process the auditory input and provide an appropriate verbal or motor response. Central auditory processing development is still underway in young children (Freigang et al. 2015) and progresses through the 6th to 12th year (Moore and Linthicum, 2007). A less mature auditory system would therefore be a contributing factor to the greater errors seen in the 3-year-olds in their sound source localization tasks. This skill of identifying the exact location of a sound source is however emerging in children as young as 3 years of age as evidenced by the lower ends of the RMSE ranges (**Table 5-1**).

Localization is a skill that is affected in children who have an auditory processing disorder, a unilateral or bilateral hearing loss, or wear cochlear implant(s). It is a skill that needs to be enhanced for all the safety and communication reasons mentioned in the introduction of this study. Building this skill would also be beneficial in children with normal hearing who spend a great portion of their day in noisy environments.

Using the same mode of response twice (verbal) seemed more effective and yielded better results the second time for the 3-year-olds. This substantiates the benefit of practice and repetition. Practice and repetition may be more pertinent contributing factors than response mode in skill building especially for those who are having difficulty with sound localization.

Recommendations

It is recommended that only one response mode be used during sound localization accuracy skill training. It is also recommended that a young child not be asked to switch from one mode to another within the same session/training period.

Limitations

Instances of reduced attention and motivation may have contributed to the wide variation seen in 3-year-olds. Some 3-year-olds had a preference and determination for certain pictures to “say it” when listening for the sound stimulus.

Recruiting children in these age groups was challenging due to many no-shows and cancellations for sickness, possibly because of the time of year that recruiting occurred (Fall and Winter season). A second reason was a lack of funding. Many parents inquired about compensation when asked if they would be willing to allow their child to participate.

Future Directions

In the future it would be interesting to compare motor responses to motor responses using the same experimental set-up and stimulus. The objective would be to investigate if sound localization accuracy improved when a sound localization task was executed twice using the same mode of response (motor) in both tasks. Including an eye-tracking measure for response time may also be beneficial.

It would also be interesting to investigate if there is a difference in performance between younger 3-year-olds and older 3-year-olds, as in this study, some children who were closer to 4 years of age seemed to do better than the ones who had just turned 3 years old.

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APPENDIX. TABLES SHOWING MEAN RMSES AND STANDARD ERRORS

Table A-1. Mean RMSEs and standard errors for age

Age	Mean RMSE	Std. Error
3yr	28.1788	2.41768
5yr	6.9226	0.5509

Note: Significant main effect for age (p <.001). Std. Error = Standard error.

Table A-2. Mean RMSEs and standard errors for mode

Mode	Mean RMSE	Std. Error
Verbal	15.7478	1.69102
Motor	19.3536	1.81609

Note: There was not a main effect for mode (p = .146). Std. Error = Standard error.

Table A-3. Mean RMSEs and standard errors for order

Order	Mean RMSE	Std. Error
First Sound Localization Task	17.2893	1.39444
Second Sound Localization Task	17.8120	1.26004

Note: There was not a main effect for order (p = .583). Std. Error = Standard error.

Table A-4. Mean RMSEs and standard errors for age*mode

Age	Mode	Mean RMSE	Std. Error
3yr	Verbal	25.1281	3.34750
3yr	Motor	31.2294	3.48928
5yr	Verbal	6.3674	0.48213
5yr	Motor	7.4777	1.00880

Note: Age*mode was not significant (p = .315). Std. Error = Standard error.

Table A-5. Mean RMSEs and standard errors for age*order

Age	Order	Mean RMSE	Std. Error
3yr	First Sound Localization Task	28.3785	2.72570
3yr	Second Sound Localization Task	27.9790	2.43234
5yr	First Sound Localization Task	6.2001	0.59028
5yr	Second Sound Localization Task	7.6451	0.65916

Note: Age*order was not significant (p = .333). Std. Error = Standard error.

Table A-6. Mean RMSEs and standard errors for mode*order

Mode	Order	Mean RMSE	Std. Error
Verbal	First Sound Localization Task	16.9568	1.87685
Verbal	Second Sound Localization Task	14.5387	1.74314
Motor	First Sound Localization Task	17.6218	2.06284
Motor	Second Sound Localization Task	21.0854	1.81995

Note: There was a significant interaction for mode*order (p = .002). Std. Error = Standard error.

Table A-7. Mean RMSEs and standard errors for age*mode*order

Age	Mode	Order	Mean RMSE	Std. Error
3yr	Verbal	First Sound Localization Task	27.7870	3.70659
3yr	Verbal	Second Sound Localization Task	22.4692	3.41495
3yr	Motor	First Sound Localization Task	28.9701	3.99738
3yr	Motor	Second Sound Localization Task	33.4888	3.46456
5yr	Verbal	First Sound Localization Task	6.1266	0.59289
5yr	Verbal	Second Sound Localization Task	6.6083	0.70164
5yr	Motor	First Sound Localization Task	6.2735	1.02088
5yr	Motor	Second Sound Localization Task	8.6819	1.11609

Note: There was a significant interaction for age*mode*order (p = .038). Std. Error = Standard error.

VITA

Karen Ann Patricia Wright Martin was born in England in 1963. She moved with her family to Jamaica at the age of 5 where she completed her elementary and high school education. She then obtained a teaching diploma from Shortwood Teachers' College and taught high school for 3 years before moving to the United States to further her education. Karen received both her Bachelor and Master of Science degrees from Western Carolina University in December 1988 and June 1990 respectively; and then went on to work as a Speech Language Pathologist in the skilled nursing facility setting for several years.

Karen was accepted into the Ph.D. program for Speech and Hearing Science at the University of Tennessee Health Science Center (UTHSC) in 2008. As a doctoral student at UTHSC her research focused on investigating how young children with normal hearing learn to localize sound accurately; and on the use (and need for the use) of cognitive screening tools in hearing (aid) evaluations with older adults. She presented posters on those topics at various conventions such as the American Academy of Audiology, American Auditory Society, Association for Research in Otolaryngology and the American Speech-Language Hearing Association. Karen is first author on an article entitled "Auditory and Visual Localization Accuracy in Young Children and Adults" which was published in the *International Journal of Pediatric Otorhinolaryngology* in 2015. Karen will be receiving her PhD in Speech and Hearing Science with a concentration in Hearing Science from UTHSC in May 2019.