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Investigating Auditory-Based Spatial Reorientation Abilities in Individuals with Dyslexia

Leanna Pantier
Eastern Illinois University

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Investigating Auditory-Based Spatial Reorientation Abilities in Individuals with Dyslexia

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Arts

Clinical Psychology

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Abstract

Dyslexia, a common learning disorder, is currently understood to affect the processing of visual and auditory information. The ability to efficiently process the environment to reorient in space is an integral part of navigating the world, but possible impairments in dyslexia have not been fully addressed. In this study, the ability of individuals both with and without dyslexia to use auditory information in a spatial reorientation task was examined to further explore the processing deficits involved in dyslexia. Participants with and without dyslexia did not perform significantly differently when learning (training trials) and during probe test trials. Additionally, individuals found to have auditory processing disorder did not perform at a significantly lower level of accuracy. Results are discussed based on limitations of the study and potential clinical implications for our understanding of dyslexia.
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In loving memory of my Oscar
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Dyslexia is "a hereditary temporal processing defect, associated with impaired magnocellular neuronal development, that impacts selectively on the ability to learn to read, leaving oral and non-verbal reasoning powers intact" (Stein, 2018, pg. 9). In more concise terms, it is a learning disorder that affects many areas surrounding language, and affects up to 1 in 5 individuals in some capacity. Common issues that individuals with dyslexia struggle with include, but are not limited to: learning letters, acquiring spoken language skills, reading ability, reading comprehension, and organizing language in both written and spoken forms (The International Dyslexia Association, 2017). These deficits, especially when an individual is experiencing more than one, can negatively influence language acquisition and comprehension to the point that developmental milestones are not reached at the appropriate ages. It can often be detected in early to middle childhood, but some milder cases may not begin to exhibit problematic signs until later in adolescence, or even adulthood. Individuals with dyslexia tend to be much slower readers compared to their non-dyslexic counterparts (Norton, Beach, & Gabrieli, 2015). This often becomes more problematic with increased age in school, where academic demands are higher and coursework is more difficult, i.e., having to read longer or denser passages, or more chapters than in previous classes. But for some, by this time, the brain has discovered ways to compensate for these deficits, despite the fact that the underlying problems still persist (The International Dyslexia Association, 2017). Many individuals with dyslexia are able to reach levels of higher education due to early intervention or finding ways to adapt, although many may still need special accommodations such as longer testing time, or separate rooms for testing.
Neurobiology of Dyslexia

Research investigating the etiology of dyslexia is ongoing, but a great deal has already been learned about the heredity and extensive neurobiological underpinnings of the disorder. Many genes implicated in the disorder are responsible for multiple aspects of cerebral function. Individually, these genes may not cause dyslexia or its symptoms, but when combined they can affect performance of many cell types in multiple areas of the brain (Mascheretti et al., 2016; Neef et al., 2017). Some of these genes are underexpressed, specifically ones responsible for coding for proteins that aid in neural signaling, and have been shown to be crucial in cell migration during brain development (Stein, 2014). Others affect memory, as well as the ability for auditory processing and visual discrimination (Mascheretti et al., 2016).

Pernet, Poline, Demonet, & Rousselet (2009) suggest that there are six potential theories explaining dyslexia, but only the two that are most pertinent in explaining visual deficits will be discussed here. The first, known as the visual magnocellular theory, states that there are lowered visual abilities due to abnormal thalamic magnocellular cells. These magnocells, which are neurons larger than the surrounding cells (as their name suggests), are responsible for recognizing where things are, such as a word on a page (Stein, 2018). Individuals with dyslexia have been shown to have smaller and therefore less effective magnocells, affecting their abilities to notice or focus on words.

The second theory suggests that dyslexia may be a specific disorder where the individual has an impaired ability to automatize the higher-order sensorimotor skills needed for reading, which implies dysfunction in the cerebellum since it is the brain structure responsible for coordinating movement and programming muscles for both
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gross and fine motor function (Stein, 2001; Pernet, Poline, Demonet, & Rousselet, 2009). The cerebellum is strongly implicated in the sensory system, and has many afferent and efferent magnocellular pathways, especially those responsible for aiding coordinated eye movements. Individuals with dyslexia have been found to have decreased cerebellar activation compared to non-dyslexic control groups (Stein, 2001).

A large number of other brain structures have been identified as being implicated in dyslexia, with a majority being located in the temporal and parietal regions (Richards et al., 2008; Mascheretti et al., 2017; Paulesu, Danelli, & Berlinger, 2014). A multitude of imaging studies have been conducted to pinpoint the specific structures that are activated during reading or other language-related activity. Richards et al. (2008) found in a diffusion tensor imaging study that individuals with dyslexia had fewer and weaker functional connections in both the left and right inferior front gyri than non-dyslexic individuals, which suggests a more global implication that previous functional magnetic resonance imaging studies. All lobes were also found to be implicated in dyslexia, but the right parietal and occipital lobes showed stronger connections than their left hemisphere counterparts (Richards et al., 2008).

A systematic review by Mascheretti et al. (2017), resounds the results found by Richards et al., also determining that many regions of the brain from each hemisphere and lobe may be involved in the dysfunction that occurs in dyslexia, suggesting an overall or global dysfunction. Finn et al. (2014) investigated whole-brain connectivity in both children and adults with dyslexia, and is yet another study that finds more connectivity issues than previous research had detected. In multiple areas and pathways most frequently implicated in reading or language comprehension, the functional
connectivity was markedly altered or diminished compared to healthy or non-impaired individuals (Finn et al., 2014).

In younger children who have not yet been tested for dyslexia, it may appear as if they have an attentional disorder. Often times due to the individual’s frustration with not being able to process information in a quick or efficient manner, they may present with an inability to focus, especially on schoolwork, or an inattention to details, which can create serious academic issues. These behaviors map onto those commonly shown by individuals with attention deficit hyperactivity disorder (ADHD) (Serrallach et al., 2016). ADHD can be a comorbid diagnosis with dyslexia, because this disorder is developmental in nature. Serrallach et al. (2016) suggest that these disorders may share brain regions and pathways, providing some insight as to why they may present in similar manners and affect some of the same structures in the brain.

**Visual Perception Deficits**

As referenced by Pernet, Poline, Demonet, & Rousselet (2009) and explained by Stein (2018), the phonological theory of dyslexia is one of the strongest explanations of the disorder, despite still being incomplete and in need of further research. It proposes that dyslexic individuals do not learn how to read well as children due to an inability to gain the skill and ability to separate the syllables and sounds in words (called phonemes) in such a manner that matches how the word appears on paper, and is known as phonemic awareness (Stein, 2018). Phonemic awareness deficits can occur regardless of etiology, and children who will go on to develop dyslexia have a harder time learning to read, including learning the essential parts of reading such as how to visually recognize different letters of the alphabet, and what sound each letter makes. This ultimately results
in a diminished ability to visually recognize words, the letters that make up any particular word, and the correct sequence of those letters (Stein, 2018). Deficits and difficulties in acquiring this knowledge around the age of entering kindergarten is the “strongest predictor of later problems with learning to read” (Stein, 2018).

These deficits are understood to be caused by temporal processing issues, specifically in how accurately or quickly the brain of an individual with dyslexia is able to shift attention to different components of a word while reading (Stein, 2018). The brain must be able to see and remember each letter, both in sequence and in relation to the other letters in the word. Magnocells, which were briefly mentioned in a previous section, are the primary neurons that facilitate the processing of this information. As aforementioned, magnocellular neurons are larger than neighboring cells, and therefore are more efficient and quicker in synaptic transmission. They are responsible for noticing the words on a page, as opposed to the individual letters that comprise the words, as well as moving attention to each word and directing eye movement so that the eye may position the word in the field of vision, specifically to the retina’s center of high focus known as the fovea centralis, in such a way that it may be focused upon and the detail can be distinguished. While they may not be able to directly discern an “i” from an “l,” magnocells have a much faster response time so as to keep moving the eyes and shifting attention to where it is needed (Stein, 2018).

There are two pathways in which this information is fed to centers where the sensory information can be processed. The first is the dorsal stream, also called the “Where” stream (Stein, 2018). Composed of almost all magnocells (with the exception of approximately 10%), this pathway carries visual information from the middle temporal
area to the posterior parietal cortex and ends at the prefrontal cortex. It is also the stream that coordinates and informs eye movements, as well as where the eyes should attend (Stein, 2018). The second pathway is the ventral stream, or the “What” stream. Responsible for discerning and identifying the objects in the field of vision, it contains the visual word form area found in the temporal cortex, which is critical to acquiring and developing the ability to read. The ventral stream often receives information from the dorsal stream, and therefore the streams often work in tandem. The dorsal stream signals where to look, and the ventral stream attends accordingly in order to identify and process the stimulus (Stein, 2018).

In dyslexia, the magnocellular neuronal response is diminished in both the lateral geniculate nucleus, a structure located in the thalamus that has afferent axons towards the primary visual cortex, and the retina, where specialized cells for vision are found. A majority of individuals with dyslexia have been found to exhibit lower function in the dorsal stream, as a result of impaired magnocellular function (Stein, 2018). Individuals with dyslexia also have less-precise control over eye movement in general. As previously stated, magnocells preside heavily over eye movement control, and whereas dyslexic individuals have compromised magnocellular function to begin with, it follows that they will have a diminished ability to maintain a pace of attentional shifting that might be necessary for whatever task they may be engaging in at the time, such as reading a sentence or solving a math problem. When reading or searching a page, the eyes try to keep up with normal, compensatory movements called saccades. For individuals with dyslexia, these “jumps” decrease the individual’s ability to focus or fixate on letters, or even words as a whole. This binocular instability is why a commonly reported issue with
Dyslexia is a perception of letters or words moving or flipping around on the page (Stein, 2001). The individual’s eyes may be darting or moving around in unintentional or uncoordinated movements, trying to keep up as the ability to shift attention lags, creating the appearance of moving text (Stein, 2001; Stein, 2018).

**Auditory Perception Deficits**

Dyslexia not only affects the individual’s ability to perceive written words or texts. It also extends to auditory function, with a genetic underpinning shown in both human and animal models (Norton, Beach, & Gabrieli, 2015). When researching the auditory system in regard to the causes of dyslexia, there are currently two main neurobiological theories. The first is a cognitive, or top-down, abnormality. An individual with dyslexia shows abnormal cortical function when a speech sound is introduced, which causes abnormal feedback, and therefore an abnormal auditory brainstem response (ABR) (Banai, Nicol, Zecker, & Kraus, 2005). This suggests that there is a higher-level loss in sensitivity that is causing deficits in the ability to process sounds, more specifically speech-related sound. Looking at mismatch negativity (MMN), a brain response that occurs at the cortical level to “acoustic change in a repetitive sound sequence,” individuals with learning disorders have a diminished or non-existent MMN (Banai, Nicol, Zecker, & Kraus, 2005). This inhibited response was found to be similar regardless of whether speech or non-speech stimuli were presented, indicating that there may be an overall deficit or inability to process sound correctly in the cortical regions of the brain in an individual with dyslexia (Banai, Nicol, Zecker, & Kraus, 2005).

The second theory suggests the opposite: a bottom-up abnormality originating with diminished or poor auditory brainstem timing. This lowered ability to correctly
perceive sounds results in a cortical inability to process sound correctly, efficiently, or, in some cases, at all (Banai, Nicol, Zecker, & Kraus, 2005). ABRs are an objective measure used to visualize the brain's response to hearing a sound, usually a click train played at different frequencies and decibel levels. Allowing a visual representation of the neuronal response, ABRs allow a real-time snapshot of how many brain structures acknowledge and pass along the signal. Ideally, the stimulus would ultimately reach a cortical level where it would be interpreted. Banai, Nicol, Zecker, & Kraus (2005) found that when tested against controls, approximately 40% of individuals with dyslexia exhibited abnormal ABRs. Using both speech and non-speech (in this case, a standard click train) stimuli, the abnormal ABRs were only observed during the speech sound portion and indicated a reduced cortical sensitivity to processing the sound. It was also observed that the individuals with abnormal ABRs have more severe learning disabilities and greater literacy problems, suggesting that this cortical insensitivity may involve more structures and pathways than just auditory ones (Banai, Nicol, Zecker, & Kraus, 2005).

According to the aforementioned phonological theory, individuals with dyslexia are not able, or have a diminished ability, to distinguish phonemes upon hearing them (Stein, 2018). In healthy individuals, phonemes are differentiated from one another by changes, or modulations, in the frequency and amplitude of the soundwaves (AM and FM, respectively) (Stein, 2018). These modulations are detected by cells in the auditory system which are homologous to the magnocells in the visual system. The neurons in the medial geniculate nucleus and left auditory thalamic nucleus, two structures heavily implicated in processing sound, have been shown to be reduced in size in dyslexic individuals compared to their non-dyslexic counterparts (Stein, 2018). The reduced size
and function in these structures may be a factor in the diminished ability to parse out and learn phonemes.

**Auditory Processing Disorder**

Auditory processing disorder (APD) is a learning disorder similar to dyslexia, but primarily affects the individual’s ability to listen or process sounds “despite displaying normal or near-normal hearing” (de Wit et al., 2016, p. 1). The effects of the inability to efficiently perceive auditory information extend to language, specifically vocabulary, grammar, and phonologic knowledge. APD is also commonly comorbid with other learning disabilities, such as specific learning impairment, autism, or dyslexia. It affects anywhere from 0.5%-7.0% of individuals across all age ranges, and twice as many males as females are diagnosed with APD (de Wit et al., 2016). Similar to dyslexia, researchers and professionals in the APD field are currently working to gain knowledge regarding whether it is a cognitive (top-down) or sensory processing (bottom-up) deficit. There is currently evidence for both, but it appears that the current literature may be revealing a multimodal nature spanning memory, language, attention, and cognitive deficits (de Wit et al., 2016).

In children with APD, both visual and auditory memory seem to be implicated. In multiple studies included in a systematic review by de Wit et al. (2016), individuals who had APD performed worse in tasks that tested visual memory. Additionally, despite being presented the words visually, children also exhibit auditory memory deficits (de Wit et al., 2016). One study found that poor auditory attentional abilities and cognitive deficits were strongly correlated with and predicted difficulties with listening. Children with APD
show a greater deficit in listening abilities if also experiencing a top-down deficit or unable to attend efficiently to auditory information (de Wit et al., 2016).

In summary, a great amount of research is still needed to create a more solid and complete picture of dyslexia. Many imaging studies have provided information about how many and to what extent different brain structures are implicated, and many have tried to develop theories on the etiology of this learning disorder. While there are many current theories attempting to explain it, a consensus among researchers and professionals in the field is yet to be agreed upon. Whether dyslexia is a separate but comorbid disorder with APD, or if a general auditory processing deficit should be included in the criteria for a dyslexia diagnosis, is yet another area where more research is required.

**Spatial Reorientation**

Spatial reorientation is the ability to find or relocate our position in the world in order to perform common tasks, including navigating around our own living spaces (Sutton & Newcombe, 2014). Humans have the ability to utilize a multitude of information during this process, including geometric and non-geometric cues. Geometric cues provide information on the shape of the environment, such as a square, rectangle, hexagon, etc. Many studies have investigated the effects of how the relative lengths of a shape's sides affect performance in reorientation tasks (Nardi, Newcombe, Shipley 2011). Humans and non-human animals have been shown to use geometric cues to reorient (Keinath et al., 2017; Nardi, Newcombe, Shipley 2011; Newcombe & Cheng, 2005). Non-geometric, or feature, cues include information such as the color of a wall, a sign, or a sound – anything that can act as a landmark (Nardi, Newcombe, & Shipley, 2011). This type of information is routinely used for reorientation and navigation (Newcombe & Cheng, 2005).
Furthermore, although with contrasting views (see Twyman et al., 2013), it has been proposed that language can help reorientation guided by feature (landmark) information. Previous studies have indicated that humans (and non-human animals) tend to rely on geometric cues and disregard features cues unless language is involved (for a review, see Newcombe & Cheng, 2005). When able to use language, adults used both feature and geometric cues. But when limited in language use, they used exclusively geometric cues (for a review and counterarguments, see Twyman, Nardi, & Newcombe, 2013). Human toddlers, as well as rats, have been shown to use geometric cues more easily than feature cues—at least in some instances. This suggests that language, and the ability to use it, might be beneficial in reorienting when using feature cues.

Individuals with dyslexia or APD, who have developmental issues acquiring or developing language skills, may therefore be at a disadvantage during spatial reorientation tasks.

Even though vision has received most attention, many sensory modalities can be used to reorient, including audition. The scarce literature on auditory-based reorientation has focused on healthy human participants (Viaud-Delmon & Warusfel, 2014; Nardi, Anzures, Clark, Griffith, 2018) and rodents (Rossier, Haeberli, & Schenk, 2000; Watanabe & Yoshida, 2007). It has been proposed that there might be a crucial difference with visual-based reorientation that makes audition suitable for acquiring large scale spatial representations. Vision is a directionally-dependent sense, meaning that in order to gather visual information, one must be looking at or facing in a certain direction. For this reason, vision is stored in an egocentric reference system.
Audition, however, is not directionally-dependent. Humans can hear and encode sounds without having to face or look at what is making sound in order to process it. This creates a stable landmark in the brain's spatial map, which Viaud-Delmon and Warusfel (2014) suggest is a key component of allocentric encoding. In their study, the researchers sought to explore whether humans can develop cognitive maps of their environment using non-visual information, specifically auditory and sensorimotor (Viaud-Delmon & Warusfel, 2014). By using different-sounding auditory cues to signify different areas of the search space, including a target area, and manipulating the amount and location of each cue, they could assess how well the participants learned the search space by measuring the amount of search time before finding the target. It was found that that even without the ability to use vision, participants were able to learn and utilize the auditory cues and sensorimotor information in order to create their own mental spatial representations of the search environment, as evidenced by a statistically significant reduction in the time spent searching as the trials progressed. By allowing the use of both auditory and sensorimotor inputs, participants were able to create more accurate spatial maps (Viaud-Delmon & Warusfel, 2014).

There is a surprisingly large lack of research regarding the abilities or impairments of individuals with dyslexia in regards to spatial localization and navigation. Although there is one study (Castro-Camacho et al., 2014) that found the ability of individuals with dyslexia to localize sound and discriminate words to be deficient compared to non-dyslexic controls, there currently are no studies investigating the ability of a clinical population to use these cues in a spatial reorientation task. Much is still unknown about how these individuals use different cue types, or navigate their
environment. While it may be reasonably assumed that individuals with dyslexia might be predisposed to have an impaired ability to reorient due to the aforementioned visual and auditory processing issues, there is currently no research or evidence supporting or denying this relationship.

The Current Study

This study aimed to investigate the abilities, or lack thereof, of individuals with dyslexia or APD to utilize an auditory cue to successfully remember the location of and replace a target in a spatial reorientation task. It was beneficial in two-fold: it enhanced the current understanding and knowledge of dyslexia and the extent of dyslexic individuals' abilities to utilize auditory information, as well as enhanced the current understanding of both clinical and non-clinical populations' ability to use non-visual cues to reorient in space. As previously stated, there has been only scarce research on the abilities of individuals with dyslexia to localize auditory stimuli, and none on the ability to encode the stimuli to complete a reorientation task. There are a handful of studies that have conducted spatial awareness experiments where dyslexic participants were able to use visual information to assess their visual learning and memory. When participating in a visual search task, individuals with dyslexia found a target significantly faster when a tone pip was played. Van der Burg, Olivers, Bronkhorst, and Theeuwes (2008) proposed that this pip made the target "pop out" in the search field, aiding the individual in the task. This "Pip and Pop" paradigm has been used to observe how reaction and search times improve in individuals with dyslexia during visual search tasks, and mirror times of non-dyslexic participants, when the tone pip signal is used (de Boers-Schellekens & Vroomen, 2012; Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2008). The combining
of vision and hearing was enough to help individuals with dyslexia compensate for oculomotor deficiencies, as well as the temporal and attentional issues normally experienced in dyslexia.

The current study intended to test the abilities of dyslexic individuals to use only auditory information, as they were blindfolded, in a spatial reorientation task. It was unique in a few ways: first, again, it was the first study to test this clinical population in a reorientation task. Additionally, this was one of few studies to use a search space that is a circle, and not quadrilateral as other paradigms have used (e.g. Nardi, Newcombe, & Shipley, 2011); this allows for greater sensitivity in detecting the error because the measure is continuous, as opposed to just choosing one of the four corners.

The current study used participants both with and without dyslexia, and consisted of two portions. The first portion was an auditory assessment, conducted by an audiologist from the department of Communication Disorders and Sciences, so as to test each participant’s hearing and the possible presence of an auditory processing deficit. If the participant showed any indication of hearing damage or loss, they were excluded from the study. As previously stated, individuals with dyslexia and/or APD tend to have normal hearing as the disorder or deficit is not caused by a difficulty or an inability to hear. The second portion was a behavioral task (reorientation task) and was carried out approximately one to two weeks after the auditory assessment. The behavioral task involved encoding the location of a target and then replacing it in a circular search space using only an auditory cue (white noise).
Method

Participants

Participants were comprised of undergraduate students attending Eastern Illinois University. Non-dyslexic participants ($n = 11$) were students enrolled in the Introductory Psychology Participation Pool and received research participation credit. They were recruited through the SONA online registration system. Participants were excluded from this group if the auditory assessment revealed hearing impairment. Dyslexic participants ($n = 5$) were volunteers recruited from Eastern Illinois University’s Office of Student Disability Services through flyers, or from a pool of students who had previously been diagnosed with dyslexia and were invited to participate through email or phone call. The criteria for inclusion for the dyslexic group were a current diagnosis of dyslexia and a current status as an undergraduate at EIU.

The description of the study for recruiting non-dyslexic individuals that was posted on SONA provided the summary and purpose of the study and instructed participants to contact the chair of this thesis for scheduling two appointments: one for the auditory assessment and one for the behavioral (reorientation) task. The description of the study for recruiting individuals with dyslexia was posted as flyers around the EIU Speech-Language-Hearing Clinic on the second floor of the Human Services building. The flyers included a summary and purpose of the study, and informed prospective participants that they would need to be available for the two appointments of the auditory test and behavioral task. Prospective participants were instructed to contact Dr. Heidi Ramrattan to schedule their auditory portion.
A goal of collecting 24 dyslexic and 24 non-dyslexic participants was set for the study, for a total of 48 participants. A priori power analyses indicated that this study would achieve a statistical power of 0.52 when having 24 participants per condition. But, due to issues with scheduling the audiological testing and difficulty recruiting dyslexic participants, the actual sample size was much smaller. As previously mentioned, only 16 participants total were collected—11 control and five dyslexic.

**Materials**

**Auditory assessment.**

The full audiological evaluation included pure-tone air- and bone-conduction audiometry and speech assessments (NU-6 word recognition tests). The APD test battery consisted of the following tests: Dichotic Digits, Duration Pattern, Tap Test, Gap Detection, Pitch Pattern, Competing Sentences, Low Pass Filtered Words (750 Hz), Time Compressed Speech, Monaural Selective Auditory Attention Test, and Staggered Spondaic Words. A case history questionnaire was also distributed.

**Reorientation task.**

The experiment took place in a room measuring 3.8 m x 3.7 m. The room was quiet, and the experimental apparatus was located in the center (Figures 1 and 2), and consisted of a circular PVC pipe (215 cm in diameter, 2.3 cm thick) laid on the floor. The circular pipe was the search space, and the target object (a hairclip measuring 9 cm) was to be clipped onto it. A swivel chair (base: 46 cm diameter; seat height: 59 cm), was used to disorient participants, located in the center of the circle of pipe. A CD player (SONY model CFD-S01) was placed on ground, in a corner (distance of the speaker from the center of the apparatus: 140 cm). The CD player generated either white noise or a
recording of multi-talker babble noise (four different people talking layered over one another) (Auditec Four Talker Babble (FT)), both at a volume of approximately 55 dB measured from the center of the search space (Sound Meter, Abc Apps). See Figure 1 for a schematic representation of the apparatus. It should be noted that the location of the target object was always located on the circular pipe, 90° away counterclockwise from the CD player; therefore, with respect to the auditory signal, the target was always in a consistent, certain position.

Procedure

Informed consent was obtained from all participants before commencing the experiment. Participants were informed that they were free to withdraw from the current study at any point in time without repercussion. The procedure followed the guidelines generated by the American Psychological Association and was approved by the University’s IRB.

All participants took the auditory assessment first, followed by the behavioral task. The two sessions were scheduled separately with, on average, a week in between.

Auditory assessment.

Participants were tested individually, and one experimenter (Dr. Ramrattan) ran the auditory assessment. Subjects were given a standard comprehensive audiological evaluation, including the NU-6 Word Recognition test, to determine the lowest decibel level that speech could be understood 50% of the time. If the subjects passed the audiological component of the evaluation, then a standard APD evaluation was given. The APD evaluation was also administered by Dr. Ramrattan and took approximately two hours to complete in one sitting. A written case history was taken via a questionnaire.
as a routine part of the comprehensive audiological evaluation and used to identify pre-existing conditions. If the subject tested positive for APD, the subject was counseled and educated regarding possible interventions and resources. Resources included a list of services provided in the area, including those provided at the Eastern Illinois University Speech-Language-Hearing Clinic. Two participants from the non-dyslexic group and one participant from the dyslexic group were found to have APD.

**Reorientation task.**

**Training trials (Trial 1-4).** Participants were tested individually. One experimenter ran the study. Upon arrival in the experimental room located in the Physical Science building, the CD player was turned on and generated white noise. Participants read and signed the consent form, and then the experimenter explained and showed the following procedure step-by-step, and the participant was given time to familiarize with the apparatus and practice the procedure before starting. Most importantly, during the explanation of the task, the participant was explicitly instructed to use the white noise to help them complete the task. This was emphasized to the participant because a previous study indicated that participants fail to spontaneously use a similar auditory cue for reorientation unless they were explicitly told to use it (Nardi et al., 2018). The target was in a fixed location relative to the CD player for all participants and in all trials (90° counterclockwise with respect to the auditory cue; see Figure 1) (reference memory paradigm). However, the location of the CD player – and thus the correct location for the target – varied with respect to the room. From trial to trial, it alternated between two diametrically opposite locations. The purpose of this was to ensure that participants learned to localize the target only with respect to the auditory cue, and not use alternative,
confounding cues that may be potentially present in the room (e.g., a sound coming from the hallway).

The participant sat down on the swivel chair, was given a blindfold, and instructed to keep it on for the duration of the session. They were then given the wireless headphones to wear (JLab Neon Bluetooth On-Ear Headphones with Universal Mic, model no. HDTW130XC3C10), and music was played through them so as to mask the sound of the auditory cue. Once the participant had both the blindfold and headphones on, they were gently spun around in the swivel chair in order to lose their sense of orientation (disorientation procedure). The disorientation lasted for approximately 60 seconds and included varying speeds and at least one change in direction. The facing direction of the chair after spinning changed pseudo-randomly each time the participant was spun, with the constraint that the same facing direction could not be repeated within three iterations.

After being disoriented, the participant was instructed to remove the headphones, stand up, keep one hand on the back of the swivel chair for balance, and walk around the platform in order to find the target on the circle. The experimenter gave clues as to how close they were getting to the target ("cold, warm, hot"). When near the target, the participant was instructed to kneel and feel around for the hairclip target on the circular search space, and instructed to remember where it was in relation to the white noise. They were allowed time to listen for the noise, if they chose to. When ready, they picked up the clip and sat back down on the chair. After replacing their headphones and being spun again, they were instructed to stand up and put the clip back on the circle as close as possible to where they retrieved it. After the participant replaced the clip on the circle, the
location was recorded by the experimenter, and the participant was given feedback on how close or far from the target they placed the clip. The clip was then moved by the experimenter from the location that the participant placed it to the target location, and the participant was allowed to find it again and pick it up. This was the first training trial (Trial 1). The trial was repeated (disorientation, replacement, feedback) three more times (total of four training trials).

**Testing trials.** After the training trials, three test trials were carried out. During the testing phase, participants were notified that they would no longer receive feedback from the experimenter. The sequence of test trials was as follows and was the same for all participants. For each test trial, participants were disoriented and instructed to replace the target using the general procedure of the training trials, but with the following differences:

*Multi-talker Babble test (Trial 5).* The CD player was switched from playing the white noise CD to a multi-talker babble noise cassette tape. Participants were instructed that they needed to use the babble noise in the same manner that they had previously been using the white noise to perform the trial. The purpose of this test was to assess if participants were able to use an unintelligible speech signal to reorient.

*No-blindfold test (Trial 6).* The CD player was switched back to playing white noise, but in this trial they were instructed to remove their blindfold after being disoriented and before they replaced the clip, therefore allowing the use of vision. The purpose of this test was to assess whether or not their performance improved when they were able to use vision to complete the task.
Sound localization test (Trial 7). Participants were instructed to replace their blindfold, and after being disoriented were instructed to place the clip where the white noise was coming from, not the target location they had been finding in all previous trials. This served to determine a baseline of accuracy for noise source localization. Once this trial concluded, so did the experiment.

Debriefing. Participants were asked what information they used to remember the location of the target and to replace it where it used to be. They were also asked how difficult the task was, and their age, and academic major. They were then debriefed about the details and purpose of the study.

None of the phases of the study were timed, and participants were told to take as much time as they need. The overall duration of the experimental session was expected to last, on average, 50 minutes.

Statistical Analysis

The dependent variable was the absolute angular error in replacing the target, measured as the difference between the participant’s response and the correct location. This could range between $0^\circ$ (perfect replacement) and $180^\circ$ (largest error), with the average response at chance being $90^\circ$. One-sample t-tests were used to compare the average participants’ error with chance in each trial. The dyslexic and non-dyslexic conditions were compared in each test trial using between-subjects t-tests (see Figure 3 and Figure 4, respectively). For the training trials, a mixed-factorial ANOVA was performed (see Table 3). The within-subject factor was the training trial, and the between-subjects factor was the condition (dyslexic and non-dyslexic participants). Additionally, since three participants were found to have APD, all aforementioned statistical analyses
were repeated, this time comparing the APD and non-APD participants’ performances (see Figures 5 and 6, and Tables 4-6).

**Results**

**Audiological Assessment**

The results from the audiological assessment revealed that all of subjects’ hearing thresholds were within normal limits (20 dB and above). The NU-6 Word Recognition Test results were within normal limits and verified the pure tone audiometry results. Three participants were found to have Auditory Processing Disorder (APD): two in the dyslexic group and one in the non-dyslexic group.

**Reorientation Task**

**Non-dyslexic vs. dyslexic.**

*Training.* Replacement errors during training were analyzed relative to the auditory cue, based on which performance at chance would yield an average error of 90° (Figure 1). For the control condition (n = 11), the average replacement errors were: Trial 1 (M = 63.41; SEM = 18.24), Trial 2 (M = 54.82; SEM = 18.56), Trial 3 (M = 48.07; SEM = 19.47), and Trial 4 (M = 50.11; SEM = 20.04) (see Figure 3). One-sample t-tests revealed that the average error was not significantly smaller than chance for Trial 1 (t(10) = -1.46, p = 0.176, d = 0.44), but was marginally smaller than chance for Trial 2 (t(10) = -1.89, p = 0.09, d = 0.57), Trial 3 (t(10) = -2.15, p = 0.06, d = 0.65), and Trial 4 (t(10) = -1.99, p = 0.08, d = 0.60). A one-way within-subject ANOVA was conducted to analyze the errors during training (Table 1). There was not a significant effect of trial, $F(3, 30) = 0.226, p = 0.878, \eta_p^2 = 0.02$. 
For the dyslexic condition ($n = 5$), the average replacement errors were: Trial 1 ($M = 63.00; SEM = 25.78$), Trial 2 ($M = 16.65; SEM = 4.64$), Trial 3 ($M = 16.20; SEM = 3.29$), and Trial 4 ($M = 18.45; SEM = 6.84$) (see Figure 3). One-sample t-tests revealed that the average error was not significantly smaller than chance for Trial 1 ($t(4) = -1.05, p = 0.35, d = 0.47$), but was significantly smaller than chance for Trial 2 ($t(4) = -15.76, p < 0.001, d = 7.06$), Trial 3 ($t(4) = -22.42, p < 0.001, d = 10.03$), and Trial 4 ($t(4) = -10.46, p < 0.001, d = 4.68$). A one-way within-subjects ANOVA on errors during training revealed that there was a marginally significant effect of trial, $F(3, 12) = 3.17, p = 0.06, \eta^2_p = 0.44$ (Table 2).

The average error between dyslexic and control condition was compared with a 2 (condition) by 4 (trial) mixed ANOVA (Table 3). There was no significant effect of trial, $F(3, 42) = 1.59, p = 0.21, \eta^2_p = 0.10$, no significant effect of condition, $F(1, 14) = 1.29, p = 0.28, \eta^2_p = 0.08$, and no significant interaction, $F(3, 42) = 0.54, p = 0.66, \eta^2_p = 0.04$.

**Multi-talker babble test.** For the Multi-talker Babble test, the average replacement errors were: control ($M = 50.32; SEM = 15.99$) and dyslexic ($M = 16.20; SEM = 5.88$). One-sample t-tests revealed that the average error of both the control condition ($t(10) = -2.48, p = 0.03, d = 0.75$) and the dyslexic condition ($t(4) = -12.54, p < 0.001, d = 5.61$) was significantly smaller than chance ($90^\circ$) in the multi-talker babble test. The difference between the conditions was not statistically significant, $t(14) = 1.394, p = 0.19, d = 0.88$ (see Figure 4).

**No-blindfold test.** For the No-Blindfold test, the average replacement errors were: control ($M = 43.16; SEM = 15.65$) and dyslexic ($M = 25.20; SEM = 7.51$). One-sample t-tests that the average error of both the control condition ($t(10) = -2.99, p = 0.01, d = 0.90$)
and the dyslexic condition ($t(4) = -8.63, p = 0.001, d = 3.86$) was significantly smaller than chance (90°) in the no-blindfold test. The difference between the conditions was not statistically significant, $t(14) = 0.74, p = 0.47, d = 0.46$ (see Figure 4).

**Sound localization test.** For the Sound Localization test, the average replacement errors were: control ($M = 6.75; SEM = 2.04$) and dyslexic ($M = 5.40; SEM = 1.68$). One-sample t-tests revealed that the average error of both the control condition ($t(10) = -40.87, p < 0.001, d = 12.33$) and the dyslexic condition ($t(4) = -50.18, p < 0.001, d = 22.47$) was significantly smaller than chance (90°) in the Localization test. The difference between the conditions was not statistically significant, $t(14) = 0.41, p = 0.69, d = 0.25$ (see Figure 4).

In sum, during training, the control condition did not perform at a level significantly above chance by trial 4 (only marginally), whereas the dyslexic group did perform above chance; however, the difference between conditions was not significant. In the test trials, both conditions performed above chance, but the difference between groups was not statistically significant. Post-hoc power analysis indicated that this study had 0.13 achieved power, and that to attain a 0.80 achieved power, 140 participants per group (280 total) would have been needed.

**APD vs. non-APD.**

Even though the sample of participants with APD was very small ($n = 3$), for exploratory purposes I analyzed the difference with non-APD participants ($n = 13$).

**Training.** For the non-APD group, the average replacement errors were: Trial 1 ($M = 67.67; SEM = 18.53$), Trial 2 ($M = 47.25; SEM = 17.84$), Trial 3 ($M = 42.92; SEM = 18.21$), and Trial 4 ($M = 45.35; SEM = 18.21$) (see Figure 5). One-sample t-tests
revealed that the average error was not significantly smaller than chance for Trial 1 ($t(13) = -1.37, p = 0.19, d = 0.36$) and Trial 3 ($t(13) = -1.76, p = 0.10, d = 0.78$), but was significantly smaller than chance for Trial 2 ($t(13) = 3.05, p = 0.01, d = 0.72$) and Trial 4 ($t(13) = 2.489, p = 0.03, d = 0.72$).

A one-way within-subjects ANOVA was conducted to analyze the errors during training and revealed there was a significant effect of trial, $F(3, 36) = 7.06, p = 0.001, \eta^2_p = 0.37$ (Table 4). At an alpha level of 0.05, post-hoc contrast results of Sidak corrections revealed that the pairwise comparison between Trial 2 and Trial 3 ($p = 0.05$) was significant. All other pairwise comparisons were not found to be statistically significant.

For the APD group, the average replacement errors were: Trial 1 ($M = 44.25; SEM = 18.07$), Trial 2 ($M = 24.00; SEM = 1.54$), Trial 3 ($M = 17.25; SEM = 2.09$), and Trial 4 ($M = 18.00; SEM = 7.26$). One-sample t-tests revealed that the average error was not significantly smaller than chance for Trial 1 ($t(2) = -2.65, p = 0.12, d = 1.13$), but was significantly smaller than chance for Trial 2 ($t(2) = 7.99, p = 0.02, d = 19.20$), Trial 3 ($t(2) = -6.43, p = 0.02, d = 15.53$), and Trial 4 ($t(2) = 13.93, p = 0.005, d = 4.44$) (see Figure 5).

A one-way within-subjects ANOVA on errors during training revealed that there was a statistically significant effect of trial, $F(3, 6) = 89.81, p < 0.001, \eta^2_p = 0.98$ (Table 5). At an alpha level of 0.05, post-hoc contrast results of Sidak corrections revealed that the pairwise comparisons between Trial 2 and Trial 3 ($p = 0.02$), and Trial 3 and Trial 4 ($p = 0.005$) were statistically significant. Additionally, the pairwise comparison between Trial 1 and Trial 2 was marginally larger than chance ($p = 0.06$). All other pairwise comparisons were not found to be significant.
I compared the average error between the participants found to have Auditory Processing Disorder (APD) and the participants who were not found to have APD with a 2 (condition) by 4 (trial) mixed ANOVA (Table 6). There was a significant effect of trial, \(F(3, 42) = 14.05, p > 0.001, \eta^2_p = 0.50\), but, crucially, no significant effect of condition, \(F(1, 14) = 0.05, p = 0.83, \eta^2_p = 0.003\) or significant interaction, \(F(3, 42) = 1.65, p = 0.19, \eta^2_p = 0.11\).

**Multi-talker babble test.** For the Multi-talker Babble test, the average replacement errors were: non-APD (M = 43.96; SEM = 15.37) and APD (M = 21.00; SEM = 6.07). One-sample t-tests revealed that the average error of the APD participants \((t(2) = 6.63, p = 0.02, d = 0.90)\) was significantly smaller than chance, and for the non-APD participants \((t(12) = 2.06, p = 0.06, d = 6.07)\) the error approached statistical significance. The difference between the conditions was not statistically significant, \(t(14) = -0.77, p = 0.45, d = 0.62\) (see Figure 6).

**No-blindfold test.** For the No-Blindfold test, the average replacement errors were: non-APD (M = 38.60; SEM = 14.67) and APD (M = 33.00; SEM = 8.20). One-sample t-tests revealed that the average error of both the APD participants \((t(2) = -2.76, p = 0.11, d = 3.11)\) and the non-APD participants \((t(12) = -2.11, p = 0.06, d = 1.06)\) was not significantly smaller than chance \(90^\circ\) in the no-blindfold test. The difference between the conditions was not statistically significant, \(t(14) = 1.28, p = 0.22, d = 0.15\) (see Figure 6).

**Sound localization test.** For the Sound Localization test, the average replacement errors for each group were: non-APD (M = 6.06; SEM = 1.93) and APD (M = 7.50; SEM = 1.54). One-sample t-tests revealed that the average error of the APD participants \((t(2) =
3.84, \( p = 0.06, d = 24.00 \) approached statistical significance, and the average error of the non-APD participants (\( t(12) = 8.38, p < 0.001, d = 13.14 \)) was significantly smaller than chance (90°) in the Localization test. The difference between the conditions was not statistically significant, \( t(14) = 0.35, p = 0.73, d = 0.28 \) (see Figure 6).

In sum, during training, the non-APD condition reached a performance statistically above chance by trial 4, as did the APD condition. The difference between the conditions was not significant. During the tests, in the No-Blindfold trial, neither condition performed above chance. In the other test trials, both conditions performed significantly better than chance or approached statistical significance. The difference between conditions was not significant in any test.

**Discussion**

**Summary of Results**

The current study aimed to investigate the ability of individuals with dyslexia to use an auditory cue in a spatial reorientation task. Statistical analysis of the behavioral data indicated that the participants with dyslexia did not perform significantly worse than the non-dyslexic participants in any of the training and test trials. Even though only three participants were diagnosed with APD, the data also indicated that the individuals found to have APD did not perform significantly worse than the participants that did not have APD. Altogether, these findings do not support the initial hypotheses that the individuals with dyslexia would perform significantly worse than the control condition in the training trials, Multi-talker Babble test trial, and Sound Localization test trial. Therefore, no evidence of any difficulty for individuals with dyslexia or APD in spatial reorientation using auditory information was found.
Although this study lacks power because of the small sample size, if there really was no significant difference between the two groups, it would suggest that there is no impairment in individuals with dyslexia to utilize auditory information to perform a spatial task. If a significant impairment had been found in individuals with dyslexia, it may have indicated that these individuals have a lowered ability to use auditory information to navigate their environments.

In the current study, if it was solely an issue of using speech-like sounds specifically, the individuals with dyslexia would have performed significantly worse on the Multi-talker Babble test trial. Additionally, if it were solely an issue of general auditory processing abilities, the APD individuals would have performed significantly worse that their non-APD counterparts. However, these were not the observed results of the study. As previously mentioned, the current study used white noise which ran continuously throughout the study, with the exception of the Multi-talker Babble test trial, and was explicitly identified by the researcher to participants as the information they should use to successfully complete the task. It is unclear from the current study whether this continuous non-speech sound is processed differently than sounds of shorter duration. But if there truly was no significant impairment of the dyslexic group in this study investigating auditory-based reorientation using a non-speech sound, and if the dyslexic group were to have performed significantly worse on the Multi-talker Babble test trial, it would suggest that the pattern of impairment in dyslexia is limited to speech-related sounds, or sounds lasting less than a few hundred milliseconds, or—perhaps more broadly—to non-spatial processing. Altogether, this study will add to the ever-evolving clinical definition of dyslexia and will further the understanding of this disorder.
Limitations

There are quite a few possible explanations as to why there were no significant differences between conditions. One of the greatest limitations of this study is the small sample size. The original intention was to recruit more participants overall, especially those in the dyslexic condition. However, recruitment for the dyslexic condition was more difficult than anticipated. The proposed sample size of 48 participants, 24 per each condition, was not met. Eleven non-dyslexic and 5 dyslexic individuals were tested, for a total of 16 participants.

Additionally, there were considerably large individual differences in performance. The largest standard deviation values for the control (non-dyslexic) condition and dyslexic condition were 62.05 and 40.40 degrees of error, respectively. Previous studies testing similar populations did show large standard deviations (Castro-Camacho et al, 2014; Messaoud-Galusi, Hazan, & Rosen, 2011), and these large differences may be why the average error in the control condition training trials failed to be statistically smaller than chance. Had the individual differences been smaller, a significant difference between conditions, as well as a significant difference compared to chance, would have been more likely to be detected.

Anecdotally, some participants appeared to give more effort during the behavioral task than others. All participants were encouraged to try their best before the task began and were explicitly instructed that the white noise cue would be the key to doing well during the task. However, it was apparent that some participants were guessing or did not know where they were spatially, but it was unclear whether this confusion was due to being genuinely disoriented and finding the task difficult, or if they were apathetic
towards doing well in the task. Therefore, the lack of motivation in some participants may be a contributing factor to the large individual differences. The differences in motivation could be related to the differences in compensation between the groups. The control group received course credit for the Introduction to Psychology course, whereas the dyslexic condition received $20 financial compensation, likely a stronger incentive. Although this information was not disclosed to any participants, differing levels in performance due to differing levels of compensation is not uncommon. In the current study, this is illustrated by the fact that the dyslexic group performed numerically better than the control group in training trials 2, 3, and 4, as well as the Multi-talker Babble test trial. It should be noted that large individual differences in performance in this task, with some participants performing very poorly, was also found in Nardi, Anzures, Clark, and Griffith (2018), which used a larger sample size of only healthy participants.

Additionally, the individuals in the dyslexic group may have been using compensation techniques that they had learned or developed throughout the years of schooling they received. Since dyslexia is a learning disability, they may have been allowed to have certain accommodations for their schoolwork. Some participants may have also received therapy to teach them techniques to help them work at a faster pace or to at least prevent anger or frustration they might experience when completing schoolwork. Also, these students were attending higher education, which is not always a possibility for individuals with dyslexia, so it may be reasonably assumed that these participants’ skills allowed them to succeed academically. These extra skills could have proven beneficial or advantageous during the behavioral task, which may have been a factor as to why no significant difference were observed between the two groups. A few
Dyslexic participants were asked about their accommodations or disorder history as part of the debriefing conversation, but their responses were not recorded. It would have been interesting to see how many of the dyslexic participants had some sort of compensatory skills.

**Future Research**

This study would have greatly benefitted from having a more robust sample size. Ideally, a sample size of at least 48, split evenly between the two conditions, would be obtained. This would increase statistical power making up for the wide range of individual differences that were observed in this study. In addition to collecting a larger number of participants, another test trial could be added using an “environmental” noise cue, meaning noises heard in one’s everyday environment, such as traffic sounds or bird calls. Viaud-Delmon and Warusfel (2014) used a cicada sound in their study investigating the ability of humans to encode a spatial map via audition. Other sounds, such as the sound of traffic or a busy city, bird calls, or bell tower may be useful as they can be common sounds to the participant depending on his or her geographical location. Since their brain may be more accustomed to hearing and using those auditory cues to navigate their everyday environment, the participants might be able to use environmental sounds more effectively than white noise.

Another change to the study could involve a secondary Multi-talker Babble test trial. This would involve three additional speakers, with one located in each of the remaining corners, and each speaker would play one voice talking with each voice being different from the others. The participant would be instructed attend to only one of the four voices (chosen by the experimenter) to replace the target. This would challenge the
ability of each participant to choose a voice, be able to discern it from the other three, and then attempt to utilize it to complete the trial. This would theoretically be more difficult for the individuals with dyslexia and/or APD, and it would be expected that those participants would have significantly higher errors during that trial compared to the participants without those disorders. Adding this trial would provide a more in-depth probe into the ability or lack thereof of individuals with dyslexia to use speech sounds to complete the spatial reorientation task.

The final change to the study would be to add two to four additional training trials with the goal of increasing the amount of time the participant is allowed to continue learning the task without significantly extending the total length of the exercise. More training trials would also allow for more chances for the participant to receive feedback from the experimenter on their performance.

This study was the first to address the issue of dyslexia-related impairments in sound localization and memory. After conducting an extensive literature review, no previous studies were found investigating the abilities of individuals with dyslexia or APD to use non-visual information in a spatial reorientation task. Additionally, this study was interdisciplinary in nature, as it was a collaboration between the EIU Psychology and Communication Disorders and Sciences departments. This allowed for auditory testing by a trained professional (Dr. Ramrattan) of participants to ensure that their performance in the behavioral task was not affected or mediated by any deficit in hearing. It also allowed for conducting the APD screening in order to compare the performance of individuals with and without APD, as relatively little is known about APD as a learning disorder.
Although no significant deficits of performance in the dyslexic condition were found in the current study, future studies should follow up using the improvements mentioned in the Study Improvements section. This was a small-scale, pilot study limited in time and number of participants, but a full-scale study with more time and greater resources to obtain more participants would be more likely to detect an effect. Large individual differences were found in the current study, as have many previous similar studies, but a larger sample size should compensate for the effects of largely differing individual performances. Much is known about dyslexia and other processing disorders, but there are still many areas that are yet to be investigated and questions to be answered. Further studies, especially those like the current study, would provide more insight and information, and altogether make a more complete clinical picture of dyslexia.
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Appendix A

The APD test battery consisted of the following tests: dichotic digits, duration pattern, tap test, gap detection, pitch pattern, competing sentences, low pass filtered words, time compressed speech, monaural selective auditory attention test, and staggered spondaic words.

In the dichotic digits assessment, three numbers were presented simultaneously to each ear, which the listener was required to repeat. The dichotic digits test assessed the individual’s auditory memory and dichotic listening skills.

The duration pattern test was comprised of three 1000 Hz tones and two 300 millisecond intertone intervals. The tones lasted either 250 milliseconds or 500 milliseconds, and the listener indicated whether a short tone or long tone was presented (Musiek, 1994).

In the gap detection assessment, two tones were presented. A gap that varied by milliseconds separated the two tones, and the subject reported whether they heard one or two tones. The lowest interval at which the subject could distinguish two tones was recorded. The gap detection assessment screened the subject’s temporal processing skills.

In the competing sentences assessment, two sentences were presented to each ear at the same time. The listener was made to repeat both sentences. The competing sentences assessment provided information regarding dichotic listening and neuromaturation separation (Bellis, 2006).

In the staggered spondaic words assessment, two spondees were presented so that the last syllable of the first word was presented to one ear while the first syllable of the second word was presented to the opposite ear. A spondee is a two-syllable word with
even stress on both syllables. The staggered spondaic words assessment evaluated closure integration order and the ability to divide auditory attention, which is important for keeping information separated between the ears.

In the pitch pattern test, the listener discriminated the pitches of four consecutive tones. Pitch discrimination contributes to speech perception (Bellis, 2006).

In the tap test, multiple tapping sounds were presented at 120 millisecond intervals, and the listener reported the number of taps heard. This assessment evaluated the auditory system’s ability to gauge temporal measurements.

During the low pass filtered word assessment, 20 words were presented to both ears using a low pass filter at 750 Hz, which revealed information about auditory closure, discrimination, and filling in missing information.

In the monaural selective auditory attention test, the participant listened to and repeated words accompanied by background noise (Bellis, 2006). The dichotic digits, duration pattern, gap detection, competing sentences, staggered spondaic words, and pitch pattern assessments all evaluated the left hemisphere, right hemisphere, and corpus callosum. The low pass filtered word assessment and the monaural selective auditory attention test evaluated the primary auditory cortex (Bellis, 2006).
Figure 1. Schematic representation of the apparatus setup. The swivel chair was located in the center of the search space. The target was always located 90 degrees to the left of the speaker position. Speaker location and target were alternated between two opposite locations for each trial.
Figure 2. Participant in apparatus, with blindfold and headphones.
Figure 3. Dyslexic and non-dyslexic mean and standard error of the mean values for training trials when compared to chance (90°)

*p < 0.001.
Figure 4. Dyslexic and non-dyslexic mean and standard error of the mean values for test trials when compared to chance (90º)
* p < 0.05. ** p < 0.01. *** p < 0.001.
Figure 5. APD and non-APD mean and standard error of the mean values for training trials when compared to chance (90°).

*p < 0.05. **p < 0.01. ***p < 0.005.
Figure 6. APD and non-APD mean and standard error of the mean values for test trials when compared to chance (90°).

*p < 0.05. **p < 0.001.
Table 1

One-Way Within-Subjects ANOVA for Non-Dyslexic (Control) Condition During Training Trials

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between-Subjects</td>
<td>92384.20</td>
<td>10</td>
<td>9238.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within-Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Variable</td>
<td>1534.29</td>
<td>3</td>
<td>511.43</td>
<td>0.23</td>
<td>0.88</td>
</tr>
<tr>
<td>Residuals (Error Variance)</td>
<td>68032.97</td>
<td>30</td>
<td>2267.77</td>
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<td></td>
</tr>
</tbody>
</table>
Table 2

*One-Way Within-Subjects ANOVA for the Dyslexic Condition During Training Trials*

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between-Subjects</strong></td>
<td>4886.03</td>
<td>4</td>
<td>1221.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Within-Groups</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Variable</td>
<td>7914.53</td>
<td>3</td>
<td>2638.18</td>
<td>3.17</td>
<td>0.06</td>
</tr>
<tr>
<td>Residuals (Error Variance)</td>
<td>9985.63</td>
<td>12</td>
<td>832.14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3  
*Mixed-Factorial ANOVA Comparing Dyslexic and Non-Dyslexic During Training Trials*

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Between-Subjects</em></td>
<td>8960.40</td>
<td>1</td>
<td>8960.40</td>
<td>1.29</td>
<td>0.28</td>
<td>0.08</td>
</tr>
<tr>
<td><em>Within-Groups</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training</td>
<td>8855.34</td>
<td>3</td>
<td>2951.78</td>
<td>1.59</td>
<td>0.21</td>
<td>0.10</td>
</tr>
<tr>
<td>Training x Condition</td>
<td>2983.07</td>
<td>3</td>
<td>995.36</td>
<td>0.54</td>
<td>0.66</td>
<td>0.04</td>
</tr>
<tr>
<td>Residuals (Error Variance)</td>
<td>97270.22</td>
<td>14</td>
<td>6947.87</td>
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</tbody>
</table>
Table 4

One-Way Within-Subjects ANOVA for Non-APD Group During Training Trials

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between-Subjects</td>
<td>26059.42</td>
<td>12</td>
<td>2171.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within-Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Variable</td>
<td>27450.31</td>
<td>3</td>
<td>9150.10</td>
<td>7.06</td>
<td>0.001*</td>
</tr>
<tr>
<td>Residuals (Error Variance)</td>
<td>46629.19</td>
<td>36</td>
<td>1295.26</td>
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<td></td>
</tr>
</tbody>
</table>

*p < 0.001.
Table 5

*One-Way Within-Subjects ANOVA for APD Group During Training Trials*

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between-Subjects</td>
<td>1400.17</td>
<td>2</td>
<td>700.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within-Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Variable</td>
<td>26246.00</td>
<td>3</td>
<td>8748.67</td>
<td>89.81</td>
<td>0.00*</td>
</tr>
<tr>
<td>Residuals (Error Variance)</td>
<td>584.50</td>
<td>6</td>
<td>97.42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.001.
Table 6

*Mixed-factorial ANOVA Comparing APD and Non-APD During Training Trials*

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>(\eta^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between-Subjects</strong></td>
<td>95.41</td>
<td>1</td>
<td>95.41</td>
<td>0.05</td>
<td>0.83</td>
<td>0.003</td>
</tr>
<tr>
<td><strong>Within-Groups</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Training</td>
<td>47380.93</td>
<td>3</td>
<td>15793.64</td>
<td>14.05</td>
<td>0.000*</td>
<td>0.50</td>
</tr>
<tr>
<td>Training x Condition</td>
<td>5562.68</td>
<td>3</td>
<td>1854.23</td>
<td>1.65</td>
<td>0.19</td>
<td>0.11</td>
</tr>
<tr>
<td>Residuals (Error Variance)</td>
<td>27459.59</td>
<td>14</td>
<td>1961.40</td>
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</tbody>
</table>

*p < 0.001.