Development and Validation of a Virtual Moving Auditory Localization (vMAL) Test among Healthy Children

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Abstract: *Introduction*: The ability to localize sound sources is crucial for humans. Due to specific hearing disorders, the affected individuals may have problems to accurately locate the sound sources, leading to other unwanted consequences. Nevertheless, a simple auditory localization test (that employs moving auditory stimuli) is currently lacking in clinical settings. Essentially, the objectives of the present study were to develop a virtual moving auditory localization (vMAL) test that is suitable for assessing children and assess the validity and the reliability of this test.

Materials and Methods: This study consisted of two consecutive phases. In phase 1, the required stimulus and the test set up for the vMAL test were established. Two loudspeakers were employed to produce five virtual positions, and eight different moving conditions were constructed. In phase 2, 24 normal-hearing Malaysian children (aged 7-12 years) underwent the vMAL test. The validity and the reliability of this test were then assessed using several validation measures. Fleiss Kappa and Spearman correlation analyses were used to analyse the obtained data.

Results: The vMAL test was found to have good convergent validity (kappa = 0.64) and good divergent validity (kappa = -0.06). Based on the item-total correlation and Spearman coefficient rho results, this test was found to have good internal reliability (rho = 0.36-0.75) and excellent external (test-retest) reliability (rho = 0.99).

Conclusions: in this study a new vMAL test was developed and proven to be valid and reliable accordingly for its intended applications. This test can be useful in clinical settings since it is simple to administer, cost-effective, does not take up much room, and can assess auditory localization performance in children. The outcomes of the present study may serve as preliminary normative data as well as guidelines for future auditory localization research.

Keywords: Binaural hearing, Auditory localization, Moving, Virtual auditory space, Validity, Reliability.

1. INTRODUCTION

Ear is a delicate part of the sensory systems in humans [1]. Having intact ear functions enables individuals to hear conversations and maintain postural control appropriately [1-5]. Normal hearing abilities consist of several listening skills that help people to enjoy their daily communications. Binaural hearing is a skill that is achieved using two ears. Beginning from the auditory brainstem region, the sounds perceived by left and right ears are integrated to be further processed by the auditory cortex [6]. For normal-hearing people, listening with two ears helps them to localize sounds from their sources (i.e., auditory localization ability) accurately. Having two ears also helps them to understand conversations in noisy environments. These binaural hearing abilities are crucial as they reflect an intact function of the central auditory nervous system, which is typically compromised in those with hearing disorders [6, 7]. It is evident that individuals with unilateral hearing loss (one ear is normal and the other ear is abnormal) and those with central auditory disorders have problems in localizing sound sources [8-11]. The impaired auditory localization ability may lead to communication problems (particularly in the noisy environments), social withdrawal (e.g., low self-esteem) or even motor vehicle accident (MVA) [12].

Typically, the auditory localization ability is measured by having many loudspeakers (located at specific locations) in a dedicated sound-proof room. Specific auditory stimuli are then presented via the loudspeakers (in a random order) and the listeners are required to indicate their perceived position (e.g., by pointing to the loudspeaker using their hand). This conventional method, however, has many limitations including the need of a big space and it is not cost-effective (the need to purchase many expensive loudspeakers) [6].

Alternatively, there has been a growing interest to employ the virtual auditory space (VAS) concept in auditory localization studies [13-17]. In a study by Távora-Vieira and colleagues on sixteen cochlear implant (CI) users, eleven “virtual” auditory positions were simulated with the use of only 2 speakers (placed at -60 and +60 degrees azimuth from the listeners) [15]. While the stimulus (narrow band noise centred around 4 kHz) was presented randomly, the listeners were instructed to indicate their response by verbally

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informing the speaker that delivered the signal. This virtual technique is clearly cost-effective, sensitive and can be conveniently implemented in typical audiology clinics (as a big space is not required).

Apart from determining the auditory localization ability involving stationary sound sources, tracking auditory stimuli that are in motion can also be implemented with the use of virtual method [16, 17]. In everyday situations, since many people would spend more time "dealing" with moving objects, assessing the ability of localizing sounds by tracking moving auditory signals seems to be more realistic [16]. Furthermore, a simple test employing the auditory motion concept (that can be potentially used in clinical settings) is currently lacking and more research efforts are needed for assessing those with spatial hearing disorders [6, 16].

Any newly developed assessment tools must be tested for their validity and reliability prior to their intended applications [18-20]. Validity is simply defined as the ability of an assessment tool to measure what it claims to measure [18]. There are many validity measures including convergent validity and divergent validity. The convergent validity refers to the degree to which an assessment tool is related to others that measure the same constructs. The divergent validity, on the other hand, represents the extent to which a measurement tool is unrelated to others that measure different constructs. In addition to being valid, a particular assessment tool also needs to be reliable i.e., it consistently produces the same outcome under the same conditions [19, 20]. Among others, internal reliability and external reliability are typically assessed when new measurement tools are developed [18-20]. The internal validity represents the consistency of results across items within an assessment tool. Meanwhile, a particular measurement tool is said to have good external reliability (or test-retest reliability) when it shows consistent results when repeated between different sessions. Essentially, the present study was carried out to develop a simple virtual moving auditory localization (vMAL) test that is suitable when assessing children (phase 1). Subsequently, the validity and the reliability of this test were tested using several validity and reliability measures (phase 2).

2. METHODS

2.1. Phase 1 (Development of vMAL Test)

In this phase, the set up and the required stimulus for the vMAL test were developed. As illustrated in Figure **1**, two loudspeakers with built-in amplifiers (Logitec MX, Switzerland) were placed in a soundproof room (with distance of 214 cm between them). A black curtain was used to cover the loudspeakers and numbered from "1" to "5" (to indicate the virtual positions). The participant would be seated on a specific position with distance of 70 cm directly in front of number "1" position (0º azimuth). Based on this distance, the difference in degrees between the simulated positions was about 27^{o} azimuth (Figure **1**).

The stimulus was a broadband noise (150 ms duration with 20 ms rise and fall times) synthesized with Audacity software (version 3.1.3, USA). To develop the five virtual positions, an interaural difference (ITD) approach was employed. In particular, the virtual positions were simulated by delaying the stimulus onset (with specific time differences) for either loudspeaker. For number "3" virtual position, the stimulus onset for both loudspeakers was set to be equal (leading to "central" perception). To simulate number "2" virtual position, the onset of stimulus for the right loudspeaker was delayed relative to the onset of stimulus for the left loudspeaker. On the other hand, to simulate number "4" position, the onset of stimulus for the right loudspeaker was made earlier compared to the onset of stimulus for the left loudspeaker. Bigger time differences between the stimuli were used to simulate numbers "1" and "5" positions. A preliminary observation involving ten normal-hearing young adults found that the time differences employed were sufficient, i.e., 100% accuracy was obtained for each simulated position. the test set up and the design of stimuli were considered optimum (and no changes were required).

In the vMAL test (aiming to assess the perception of moving auditory stimuli), 8 different moving conditions were constructed: "1-2-3-4-5" (left-right, leading to "right" perception), "5-4-3-2-1" (right-left, leading to "left perception"), "1-2-3" (left-right), "3-4-5" (left-right), "3-2-1" (right-left), "5-4-3" (right-left), "2-3-4" (left-right) and "4-3-2" (right-left). For each moving condition, the time interval between simulated positions was fixed at 500 ms. Whereas between the moving conditions, the time interval was 5 s.

2.2. Phase 2 (Validation of vMAL Test)

In this phase, the validity and reliability of the newly constructed vMAL test were determined. To achieve this objective, 24 healthy Malaysian children were enrolled based on the inclusion criteria. In particular, all

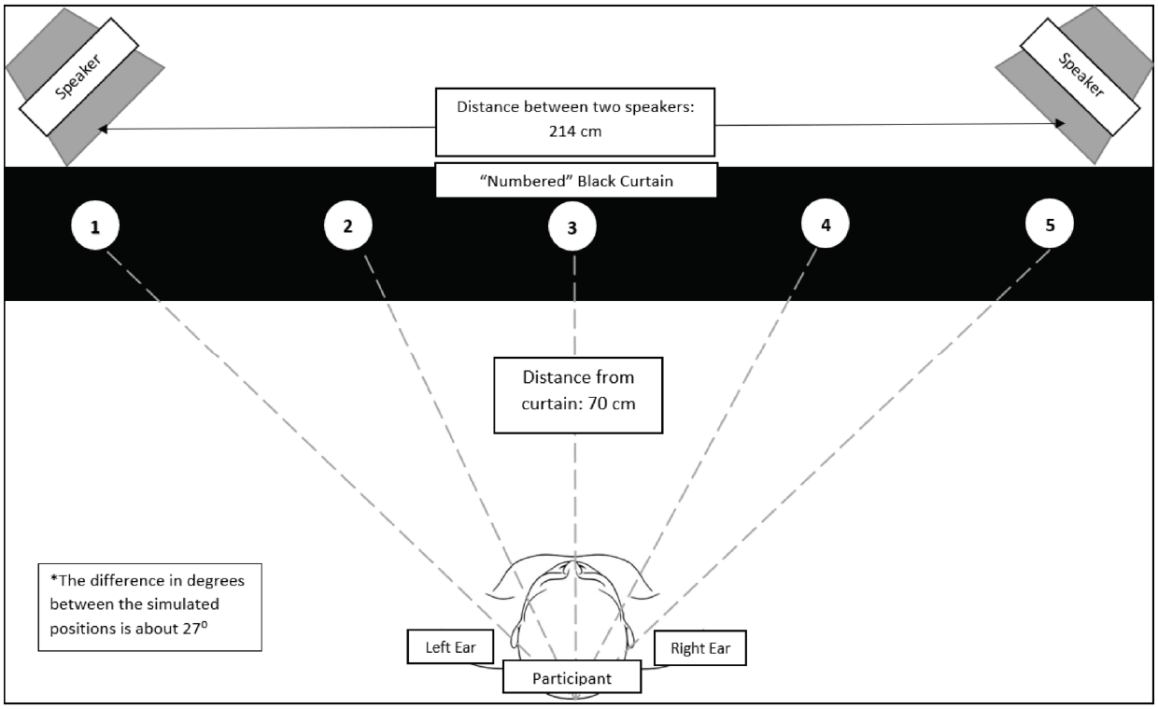

Figure 1: An illustration of the set up for virtual moving auditory localization (vMAL) test.

of them had normal hearing bilaterally (pure tone thresholds ≤ 20 dB HL at frequencies between 250 and 8000 Hz with no significant air-bone gaps), normal middle ear function for both ears (as indicated by a type A tympanogram) and no history of ear and hearing problems (as reported by parents). Prior to the data collection, an ethical approval was obtained from the respective institutional review board, which is in line with the 1975 Declaration of Helsinki and its later amendments.

After obtaining the consent forms from the respective parents, the children were invited to come to the Audiology Clinic, University Hospital to undergo the vMAL test. Clear instructions were given to each child before the test began. While seating comfortably on a height-adjustable chair, the child was instructed to face forward (0º azimuth) (Figure **1**), and not to move his/her head during the testing. He/she was then required to listen to moving auditory stimuli presented by the loudspeakers, and to say aloud whether the auditory moving perceived was either "left" or "right". As mentioned earlier eight different moving conditions were to be assessed. For example, for condition "1-2-3-4-5" (left-right), the expected response should be "right" (as the sound "moves" from left to right simulated positions). Conversely, for condition "3-2-1" (right-left), the expected response should be "left". It is worth stating that for each child, the moving conditions were presented randomly (and repeated three times for each condition). All stimuli were presented at an intensity level of 65 dBA, and short practice was given to each child before the start of the testing. The duration of the testing was about nine minutes for each child (including the practice session). Additionally, to specifically measure the external reliability of the vMAL test, all children were invited to come again to undergo the testing within two weeks after the first visit.

2.3. Statistical Analyses

Both descriptive and inferential statistics were used to analyse the data. Mean, standard deviation (SD), confidence interval (CI) and percentage were expressed as applicable. In the vMAL test, the data obtained were presented in two ways, i.e., perceived moving sound direction ("left" or "right") and percentage of correct perceived moving sound direction. The multiple-interrater Fleiss kappa analysis was employed to assess the convergent validity and the divergent validity of the test. The kappa value of > 0.80 indicates almost perfect agreement, 0.61-0.80 as substantial agreement, 0.41-0.60 as moderate agreement, 0.21-0.40 as fair agreement, 0.00-0.20 as slight agreement, and < 0.00 as no agreement [21]. For assessing the internal reliability of the test, item-total correlation approach (by means of Spearman rank correlation analysis) was used. The Spearman correlation method was also employed to determine the external (test-retest) reliability of the vMAL test, in which the test

results were compared between first and second sessions. The data analyses were conducted using the SPSS software version 24 (SPSS Inc, Chicago, IL).

3. RESULTS

3.1. Demographics of Participants

In the present study, 24 eligible Malaysian children were recruited to validate the vMAL test with ages ranging from 7 to 12 years (with a mean of 9.04 ± 1.80 years). In terms of ethnicity, all of them belonged to the Malay ethnic group. Boys and girls made up the equal proportion of the study participants (i.e., 12 boys and 12 girls). It is worth stating that all children had completed the vMAL test successfully.

3.2. The Convergent Validity of vMAL Test

In the present study, the convergent validity of the vMAL test was assessed by measuring the agreement between the perceived moving sound directions and the actual moving sound directions. the Fleiss kappa analysis was used as the data were of categorical type and three repetitions were made for each moving condition., the kappa value was found to be 0.64 (95% CI: 0.60, 0.70) indicating a substantial agreement between the variables [21]. This suggests that the vMAL test has good convergent validity.

3.2. The Divergent Validity of vMAL Test

The divergent validity of the vMAL test was determined by making a comparison between the perceived movingn sound direction for “left” moving condition and the perceived moving sound direction for “right” moving condition. In this respect, it was expected that no agreement would be observed between them (since “left” and “right” moving conditions produced different results). Likewise, the Fleiss kappa was used for this analysis. The resultant kappa value was -0.06 (95% CI: -0.12, -0.01) suggesting the absence of agreement between “left” and “right” moving conditions. This implies that the vMAL test has good divergent validity.

3.3. The Internal Reliability of vMAL Test

As there were eight moving conditions, and three repetitions were made for each moving condition the listeners would be given 100% score if they correctly perceived all three trials. Table **1** reveals the mean percentage of the correctly perceived moving sound direction for each moving condition. As depicted, the mean score was the lowest for the “5-4-3” moving condition (“left” perception) (i.e., 51.3%). Both “1-2-3-4-5” condition (“right” perception) and “5-4-3-2-1” condition (“left” perception) produced the highest mean score (i.e., 93.1%).

The item-total correlation analysis was used to assess the internal reliability of the vMAL test. That is, the correlation between the mean score (for each moving condition) and the total mean score (the sum of mean scores for all moving conditions) was measured. Since the data were found not to be normally distributed ($p < 0.05$ by Shapiro-Wilk test), the non-parametric Spearman correlation was employed. As shown in Table **2**, the coefficient rho values ranged from 0.36-0.75, which were within the acceptable value (i.e., ≥ 0.30) [22, 23]. This indicates that the vMAL test has good internal reliability.

3.4. The External Reliability of vMAL Test

All children (n = 24) were able to participate in the second session of the testing (separated by a two-

Table 1: Mean and Standard Deviation (SD) of Score (in Percentage) for each Moving Condition of the Virtual Moving Auditory Localization (vMAL) Test

Moving condition	Mean (%)	SD (%)
“1-2-3-4-5” (“right” perception)	93.1	17.0
“5-4-3-2-1” (“left” perception)	93.1	17.0
“1-2-3” (“right” perception)	79.3	19.1
“3-4-5” (“right” perception)	80.7	29.3
“3-2-1” (“left” perception)	87.5	25.6
“5-4-3” (“left” perception)	51.3	29.6
“2-3-4” (“right” perception)	83.3	29.5
“4-3-2” (“left” perception)	84.7	29.5

week period from the first visit). Since the data were not normally distributed ($p < 0.05$ by Shapiro-Wilk test), the Spearman correlation was again used to determine the test-retest reliability of the vMAL test. It was then found that the mean scores of the test were strongly correlated between the first and second sessions (rho = 0.99). This renders the vMAL test to be highly repeatable and reliable for its intended applications.

Table 2: Item-Total Correlation for each Moving Condition of the Virtual Moving Auditory Localization (vMAL) Test

Moving condition	Rho
"1-2-3-4-5" ("right" perception)	0.64
"5-4-3-2-1" ("left" perception)	0.36
"1-2-3" ("right" perception)	0.74
"3-4-5" ("right" perception)	0.73
"3-2-1" ("left" perception)	0.68
"5-4-3" ("left" perception)	0.61
"2-3-4" ("right" perception)	0.69
"4-3-2" ("left" perception)	0.75

4. DISCUSSION

The ability to locate the direction of sound sources and enjoy communications in noisy environments are among the advantages of having intact binaural hearing [6]. If the binaural hearing ability is compromised (e.g., impaired auditory localization skill), many negative impacts would be observed [12]. Therefore, research efforts in the field of binaural hearing are imperative.

The auditory localization test developed in the present study was based on the VAS approach. This virtual technique was preferable due to its notable advantages [6, 15]. In particular, it is cost-effective, and a big space is not required as by using only two loudspeakers, five simulated positions had been constructed in the study. In another study by Mohd Sobri Chew [24], seven simulated positions were used to assess the auditory localization performance among normal-hearing adults. As reported, notable localization errors were found implying that it was not "easy" to accurately perceive the seven simulated positions [24]. Therefore, it was decided to use only 5 simulated positions in the present study as an attempt to have better study outcomes when testing children. Furthermore, rather than asking the listeners to localize sounds coming from stationary sound sources, the auditory motion concept was chosen as an effort to assess auditory localization abilities in a more natural manner [16].

It is imperative for a newly developed assessment tool to be tested for its validity and reliability. Once proven to be valid and reliable, it can therefore be used for its specific applications [19, 20]. As revealed in the present study, the newly designed vMAL test was found to be valid and reliable based on the results of specific validation assessments. In particular, based on the high agreement result between the perceived moving sound directions and the actual moving sound directions (kappa = 0.64), it was proven to have good convergent validity [21]. Likewise, its divergent validity was also good as no agreement was found between "left" and "right" moving perceptions (kappa = -0.06). When assessing the divergent validity of a specific assessment tool, poor agreement (or correlation) with other measures is expected to support the notion that they measure different constructs [18].

In the present study, both internal validity and external validity assessments were carried out to determine the reliability of the vMAL test. Based on the item-total correlation results (rho = 0.36-0.75), its internal reliability was considered good. As reported elsewhere, an assessment tool is said to have good internal reliability if the item-total correlation is at least 0.30 [22, 23]. As such, items deletion is recommended if this condition is not fulfilled [18]. Owing to this, all eight moving conditions of the vMAL test were considered "equally" valid and retained (and no changes were required). It is worth mentioning that for the "5-4-3" moving condition ("left" perception), the score was the lowest (i.e., 51.3%). Sensibly, when assessing subjects who are healthy and have normal hearing, getting a score of around 80% is the ultimate aim [25]. Nevertheless, this moving condition should still be retained as its item-total correlation value was reasonably high (rho = 0.61). It is also crucial for a new assessment tool to have good external (test-retest) reliability. In the present study, when the test scores were compared between the first and second sessions, the correlation value was notably high (rho = 0.99). This implies that the vMAL test is highly repeatable and reliable to be used in clinical settings. Particularly, this virtual localization test is potentially useful to assess the benefits of hearing amplification devices and/or the implementation of a specific auditory rehabilitation program in children with hearing loss. To the best of our knowledge no comparable studies have been

carried out till date(that thoroughly validate the virtual auditory localization test employing moving auditory stimuli), thus making comparisons with other studies challenging.

However, the present study was not without limitations. Firstly, a modest sample size was used and perhaps better study outcomes could be obtained if more subjects were recruited. Secondly, only children aged 7-12 years were tested. In this respect, future studies should include other age groups to provide more comprehensive data regarding the auditory localization skills in children. Lastly, only those with normal hearing were enrolled in the present study. To further support the clinical usefulness of this test, having subjects with hearing disorders can be advantageous. That is, the ability of the test to discriminate between normal and hearing-impaired groups (i.e., discriminant validity) can be assessed, and this is subject to further research.

5. CONCLUSIONS

Due to the lack of a simple auditory localization assessment for paediatric patients in clinical settings, the present study was carried out to develop and validate the virtual moving auditory localization (vMAL) test. The required stimulus and the test set up were established accordingly. Subsequently, the validity and reliability of this newly developed test were tested using two validity tasks and two reliability measures. As revealed, this test was found to be valid and reliable for its intended applications. Collectively, having this test in clinical settings can be advantageous as it is simple to administer, cost-effective (only two loudspeakers are needed), does not require a big space and most importantly, it is able to assess the auditory localization performance that is not typically tested in routine audiology clinics. The present study's findings may serve as preliminary normative data as well as guidelines for future auditory localization research. Further studies are welcome to ascertain the outcomes of the present study.

DISCLOSURE STATEMENT

All authors declare that they have no conflicts of interest.

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