International Journal of Audiology

ISSN: 1499-2027 (Print) 1708-8186 (Online) Journal homepage: http://www.tandfonline.com/loi/iija20

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To cite this article: Deborah Moncrieff, William Keith, Maria Abramson & Alicia Swann (2017) Evidence of binaural integration benefits following ARIA training for children and adolescents diagnosed with amblyaudia, International Journal of Audiology, 56:8, 580-588, DOI: 10.1080/14992027.2017.1303199

To link to this article: http://dx.doi.org/10.1080/14992027.2017.1303199

Published online: 27 Mar 2017.

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International Journal of Audiology 2017; 56: 580–588

International Journal of Audiology

Original Article

Evidence of binaural integration benefits following ARIA training for children and adolescents diagnosed with amblyaudia

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Abstract

Objective: The purpose of this study was to demonstrate the efficacy of Auditory Rehabilitation for Interaural Asymmetry (ARIA) to improve dichotic listening scores in children and adolescents diagnosed with amblyaudia and other binaural integration deficits. *Design*: The study is a field experiment without randomisation. *Study*: Participants placed into groups based on dichotic listening test scores received four sessions of ARIA training. Baseline scores were compared to performance during the final session of training and to scores obtained 2 or more months after completion of ARIA. *Sample*: A total of 125 children participated at five different clinical sites. *Results:* Dichotic listening scores improved across all participants. *Post hoc* analyses demonstrated highly significant gains in non-dominant ear performance and reductions of interaural asymmetry among participants diagnosed with amblyaudia at both post-ARIA measurements. Participants in other diagnostic groups also showed significant benefits for some post-ARIA measures. *Conclusions:* Results demonstrate that ARIA training is an effective method for improving binaural integration skills among children and adolescents identified with dichotic listening weaknesses during assessments for auditory processing disorder (APD), especially for those diagnosed with amblyaudia. Benefits achieved following ARIA training remain stable across several months.

Key Words: Auditory processing; amblyaudia; dichotic listening; behavioural measures; paediatric; psychoacoustics/hearing science; speech perception

Amblyaudia is a type of auditory processing disorder (APD) characterised by deficits in the binaural integration of verbal information (Moncrieff, 2010). The hallmark pattern of amblyaudia is an abnormally large asymmetry between the two ears during dichotic listening (DL) tasks with either normal or below normal performance in the dominant ear (Moncrieff et al, 2016). Children with listening, learning and reading difficulties have produced symmetrical deficits in binaural integration (Hynd et al, 1979; Keefe & Swinney, 1979; Pelham, 1979; Tobey et al, 1979; Harris et al, 1983; Roush & Tait, 1984; Grogan, 1986; Vanniasegaram et al, 2004; Pinheiro et al, 2010) as well as an abnormally large asymmetry during DL tasks due to low performance in their non-dominant ears (Ayres, 1977; Johnson et al, 1981; Dermody et al, 1983; Aylward, 1984; Berrick et al, 1984; Asbjornsen et al, 2000; Vanniasegaram et al, 2004; Moncrieff & Black, 2008). The structural model of DL (Kimura, 1961) predicts enhanced performance in the ear that is contralateral to the language dominant cortical hemisphere, which is the right ear in 65–80% of normal listeners (Hiscock et al, 2000; Moncrieff, 2011) and the left ear in others (Denes & Caviezel, 1981). Because either the left or right ear can be dominant during DL tests, a diagnosis of amblyaudia is based on comparison to norms developed without regard to which ear is superior (Moncrieff, 2011; Moncrieff et al, 2016).

When assessed under earphones, normal listeners can readily identify information presented to their non-dominant ear during DL tasks, long thought to be primarily through cortical connections via the corpus callosum because after sectioning of the corpus callosum, a listener's ability to identify material presented to the non-dominant ear is extinguished (Sparks & Geschwind, 1968). In those patients, however, the performance improves following a reorganisation of the auditory pathways despite the absence of callosal transmission (Milner et al, 1968; Levitsky & Geschwind, 1968; Springer et al, 1978). This suggests that binaural integration of dichotic material engages both contralateral and ipsilateral

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(Received 15 July 2016; revised 4 February 2017; accepted 15 February 2017)

ISSN 1499-2027 print/ISSN 1708-8186 online © 2017 British Society of Audiology, International Society of Audiology, and Nordic Audiological Society
DOI: 10.1080/14992027.2017.1303199

ascending pathways, probably starting in the brainstem. During most listening experiences, individuals must fuse acoustic cues that are similar and separate cues that are different between the two ears in a process that is similar to binaural integration because we rarely process sounds from an isolated single source without the influence of competing acoustic signals. We use interaural timing and intensity differences from binaural cues for spatial listening and localisation, the capacity of our auditory system to interpret information arriving along different paths, through processes that are mediated by excitatory and inhibitory mechanisms in the superior olivary complex of the brainstem (Middlebrooks & Green, 1991; Blauert, 1997). Binaural spatial hearing is a process that is labile during early development (Keating & King, 2013) but may stabilise by age 4 to 5 years (Litovsky, 2011), which could be why children begin to perform DL tasks at age 5 (Moncrieff, 2011). By young adulthood, normal binaural integration is characterised by strong performance in both ears with only a small interaural asymmetry, indicating that cues from both ears are processed effectively during these challenging listening tasks. DL performance is also related to global top-down factors such as verbal working memory, attention, receptive language and neurophysiologic maturation that depend on bottom-up auditory processing.

Management recommendations for APD have included a variety of bottom-up auditory skill training strategies focussed on sensory detection and discrimination without specificity for the type of auditory deficit diagnosed (Chermak et al, 1999). Critics of a speech-based auditory training programme proposed for children with any type of APD and/or language difficulties argued that those kinds of programme primarily influence sustained attention and fail to generalise beyond trained skills (Moore, 2011). Auditory Rehabilitation for Interaural Asymmetry (ARIA) is a clinical training regimen designed to specifically rehabilitate the DL deficit behind amblyaudia. In Phase I clinical trials conducted at the University of Florida in 2000–2001 (Moncrieff & Wertz, 2008), participation in ARIA led to reduced interaural asymmetry from DL tasks in children with binaural integration deficits consistent with amblyaudia. In addition, some children also attained grade-level performance in listening comprehension after ARIA, a skill that was not specifically trained. ARIA initially involved a 30-minute training session three times per week for a period of 4–6 weeks. To increase access during the school year, ARIA was modified in 2008 to provide two 20 min sessions divided by a 20 min rest break at four weekly appointments. A comparison of the three-per-week versus one-per-week modes of conducting ARIA demonstrated results that were similar to and in some cases, better, under the new mode of administration (Russo et al, 2014).

Researchers have reported improvements in DL scores in normal young adults (Tallus et al, 2015) and in children identified with APD (Tawfik et al, 2015) following a training protocol that presented dichotic material at the same intensity to both ears. In another study, children who received integrative auditory training with diotic and dichotic speech-based materials in quiet and in noise showed improvements compared to children who did not receive the treatment (Putter-Katz et al, 2008). During ARIA, a clinician systematically adjusts the relative intensity of input to the two ears during DL exercises presented through sound-field speakers. The training is conducted in sound field to increase ecologic validity with situations similar to those encountered in daily listening experiences (Jerger et al, 2000) and to differentiate the exercises from presentations made under earphones during diagnostic assessment. The approach is similar to constraint-induced physical therapies for stroke patients and visual training for patients with amblyopia whereby performance from the dominant side is suppressed during targeted exercises, resulting in enhancement on the non-dominant side. The relative intensity between the two ears must be carefully controlled throughout training to avoid over-training to a reversed condition of amblyaudia whereby the non-dominant ear becomes excessively dominant over the formerly dominant ear as inadvertently demonstrated in one study utilising a similar method (Denman et al, 2015). Because of a risk of over-training to a reversed abnormal interaural asymmetry, ARIA requires individualised treatment by an audiologist with access to audiometric equipment and appropriate training in the methodology.

The purpose of this study was to evaluate the efficacy of ARIA at several clinical sites in the hands of trained audiologists. At each site, participants were assessed for APD and were enrolled in ARIA treatment based on results from DL tests. We hypothesised that participants would demonstrate benefits from ARIA intervention with improvements in non-dominant ear performance after training.

Methods

Children and adolescents ages 5 to 19 years ($n = 125$) were enrolled in ARIA at five clinical sites: Children's Hospital of Pittsburgh, Pittsburgh, PA; the Auditory Neurophysiology Laboratory at the University of Pittsburgh, Pittsburgh, PA; SoundSkills APD Clinic in Auckland, New Zealand; HearNow Abramson Audiology in Laguna Niguel, CA; and Auditory Processing Center in Clinton, MS. Demographic information regarding the participants enrolled in the study is shown in Table 1. All were enrolled in ARIA following APD assessment if they demonstrated weaknesses across at least two tests of auditory processing (including at least one DL test), had reported difficulties listening and learning at school, and had normal hearing sensitivity for pure tones <25 dB HL from 500 to 4000 Hz. All children were proficient speakers of English.

Participants were assessed with the Randomized Dichotic Digits Test (RDDT) (Strouse & Wilson, 1999), the Dichotic Words Test (Moncrieff, 2011) and/or the Dichotic Digits Test (Musiek, 1999), all administered under earphones through a clinical audiometer set to 50 dB HL bilaterally. Results were compared to normative information according to the protocol used to diagnose amblyaudia (AMB), dichotic dysaudia (DD), and amblyaudia plus (AMB+) (Moncrieff et al, 2016). 81 (65%) were given diagnostic labels AMB ($n = 58$), AMB + ($n = 16$), or DD ($n = 7$). Of the remaining 44 participants, 19 of them produced abnormal results on two DL tests, but performance patterns were mixed (MIX). The remaining 25

Table 1. Demographic information for subjects enrolled in ARIA.

Age	*n*	*M*	*F*	*AMB*	*AMB+*	*DD*	*MIX*	*UND*
5–6	11	6	5	7	1	0	2	1
7	25	15	10	8	4	4	2	7
8	20	16	4	10	2	1	3	4
9	25	14	11	13	5	0	3	4
10	16	12	4	9	0	0	4	3
11–12	14	14	0	4	2	2	2	4
13–15	8	6	2	4	1	0	2	1
16–19	6	4	2	3	1	0	1	1
Total	125	87	38	58	16	7	19	25

AMB: amblyaudia; AMB+:amblyaudia plus dichotic dysaudia; DD: dichotic dysaudia; MIX: mixed pattern; UND: undiagnosed.

produced abnormal results on only one DL test and were therefore undiagnosed with respect to binaural integration alone (UND). Participants in the UND category also performed below normal on another test of auditory processing so they qualified for a diagnosis of APD based on ASHA (2005) and AAA (2010) standards.

All participated in ARIA during four weekly one-hour appointments that involved 20 min of dichotic training followed by 20 min of rest and then followed with another 20 min of dichotic training. Dichotic training material was comprised of words (digits, monosyllables and spondees) spoken in standard American English presented in a sound-treated booth or quiet room through soundfield speakers. Each dichotic presentation was aligned at onset and normalised for average RMS amplitude across its duration. The intensity of output directed toward the non-dominant ear was held at 50 dB HL while the intensity of output directed toward the dominant ear was adjusted throughout each training session. As the purpose of the training is to minimise interaural asymmetry while listening to dichotic material, the goal with each presentation was to maintain differences between the two ears close to or below 10%. Clinicians selected a list of dichotic words and measured performance after 15–25 presentations. The order of material was not specified and if a child had more difficulty with one type of material (words, digits), training was usually more focussed on that material than the other (digits, words), but both types of material were always used. Intensity was reduced for the dominant ear when relative performance was better on that side by more than 10% and increased when relative performance on the other side was better by more than 10%. Adjustments to intensity were made in steps of 1 dB while continually monitoring performance differences in the two ears as detailed previously (Moncrieff & Wertz, 2008).

At the fourth training session, scores for most of the participants were recorded from one list of dichotic words ($n = 119$) and one list of two-pair dichotic digits ($n = 116$). A subset of these ($n = 70$) returned to the clinic at least 2 months following the end of the treatment and were reassessed for their DL skills. Scores from the pre-ARIA assessment, the fourth training session, and the post-ARIA assessment were used to measure task-specific outcomes from training.

Statistical methods

The Kolmogorov–Smirnoff test determined that DL scores were not normally distributed, even after applying rationalised arcsine transforms to the raw data. Therefore, DL scores for the dominant and non-dominant ears and values of interaural asymmetry were subjected to nonparametric analyses of variance. Between-participant factors of age were compared for significant differences prior to ARIA training. Scores before and after ARIA treatment were compared across all participants and within each diagnostic group for significant effects at the fourth training session and at the post-ARIA assessment. Comparisons were made between scores obtained at the fourth session and the post-ARIA assessment to determine if gains were maintained or if regression had occurred.

Results

Effect of age and diagnosis on pre-ARIA DL scores

Based on results from the Jonckheere–Terpstra test, non-dominant ear scores and interaural asymmetry were significantly different for age group (Table 2). Dominant ear scores were significantly

Table 2. Significant effects of age group on individual scores.

Test	*Score*	*J–T statistic*	*Levels*[a]	*p*
RDDT	Non-dominant ear	5.20	6	<0.001
	Dominant ear	4.65	6	<0.001
	Interaural asymmetry	−2.92	6	0.004
DWT	Non-dominant ear	2.66	4	0.008
	Dominant ear	1.28	4	0.201
	Interaural asymmetry	−1.95	4	0.051

RDDT: Randomized Dichotic Digits Test; DWT: Dichotic Words Test; J-T Statistic is from the Jonckheere–Terpstra Test.
[a]Levels refers to the number of age groups in the analysis.

different only for digits and scores for interaural asymmetry were minimally significant for words. As shown in Figure 1, dominant (dom) and non-dominant (nondom) ear scores increased and values for interaural asymmetry decreased with maturation. Results are displayed within age groups defined for establishing normative data for scores from each test. Average ear scores and interaural asymmetry are separated by diagnostic category and displayed in Figure 2. The large asymmetry between the two ears that is the hallmark pattern of amblyaudia is apparent in the lower non-dominant ear scores and large values for interaural asymmetry in the AMB and AMB + groups. Participants in the other diagnostic groups (DD, MIX and UND) demonstrated abnormal but higher non-dominant ear scores and lower values of interaural asymmetry.

Effect of ARIA training on DL scores at fourth week

Scores from the pre-ARIA evaluation were compared to scores during the fourth session by the Wilcoxon signed ranks test. Scores were significantly different except for dominant ear scores during the words test as detailed in Table 3. A separate analysis for significant differences within each diagnostic group was done by the Wilcoxon signed ranks test with Bonferroni's correction to adjust significance level to $p < 0.01$ for five separate groups. As shown in the left column of Figure 3, non-dominant ear scores improved significantly for participants in the AMB, AMB + and MIX groups for both words and digits. Participants in the UND diagnostic group demonstrated significant improvement for digits only. The goal of ARIA training was to improve non-dominant ear performance, especially among those whose interaural asymmetry was largest because of non-dominant ear weakness. As expected, the greatest gains in non-dominant ear performance and reductions in interaural asymmetry were seen in the AMB and AMB + group whose non-dominant ear performance was lowest at diagnosis (see Figure 2). The only group that showed a significant improvement in their dominant ears (not shown) were those in the UND group who demonstrated a significant increase with digits at the fourth training session, $Z = -2.70$, $p = 0.007$.

Effect of ARIA training on DL scores after several months

A subset of 70 participants returned to three clinical sites for a post-ARIA follow-up evaluation (35 AMB, 11 AMB+, 3 DD, 7 MIX and 14 UND). All were assessed with 2-pair digits and 67 were assessed with dichotic words at a time between 2 and 12 months following completion of training, with most done between 3 and 6 months. Post-ARIA scores were significantly higher than pre-ARIA diagnostic scores for dominant ear and non-dominant ear and were

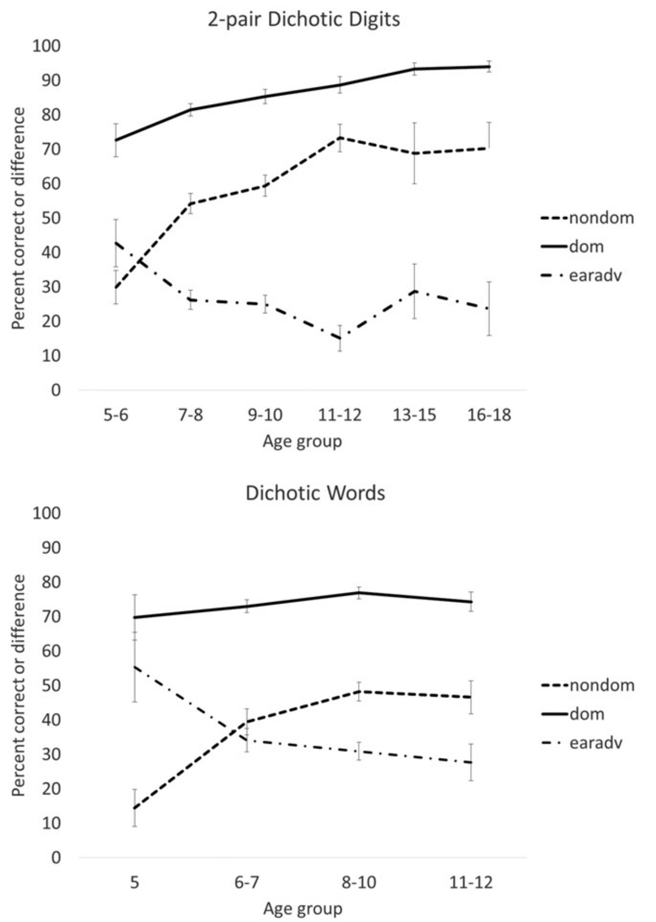

Figure 1. Age-related changes in scores in the non-dominant (nondom) ears (dashed lines) and dominant (dom) ears (solid lines) for the two-pairs condition of the Randomized Dichotic Digits Test (RDDT) (top) and the Dichotic Words Test (DWT) (bottom). Age-related changes in interaural asymmetry (earadv) for both tests are displayed by the dash-dot lines. Age groups are defined by the ranges used for establishing normative values for each *t*.

significantly lower for interaural asymmetry across both tests as shown in Table 3. Results within each diagnostic group demonstrated significantly better post-ARIA non-dominant ear scores among the AMB, AMB + and UND groups for digits and among the AMB and AMB + groups for words as shown on the right side of Figure 3. Post-ARIA improvements in the dominant ear were also significant for the UND group with digits, $Z = -2.67$, $p = 0.007$, and words, $Z = -2.95$, $p = 0.003$ (not shown). Participants in the AMB group showed significant reductions in interaural asymmetry with both digits and words, but those in the AMB + group showed significant reductions only with words. There were no significant post-ARIA changes in interaural asymmetry in the DD, MIX or UND groups.

Comparison of scores at initial diagnosis, fourth session and at post-ARIA evaluation

For those whose performance was measured on all three occasions (pre-ARIA, fourth session and post-ARIA), scores were compared

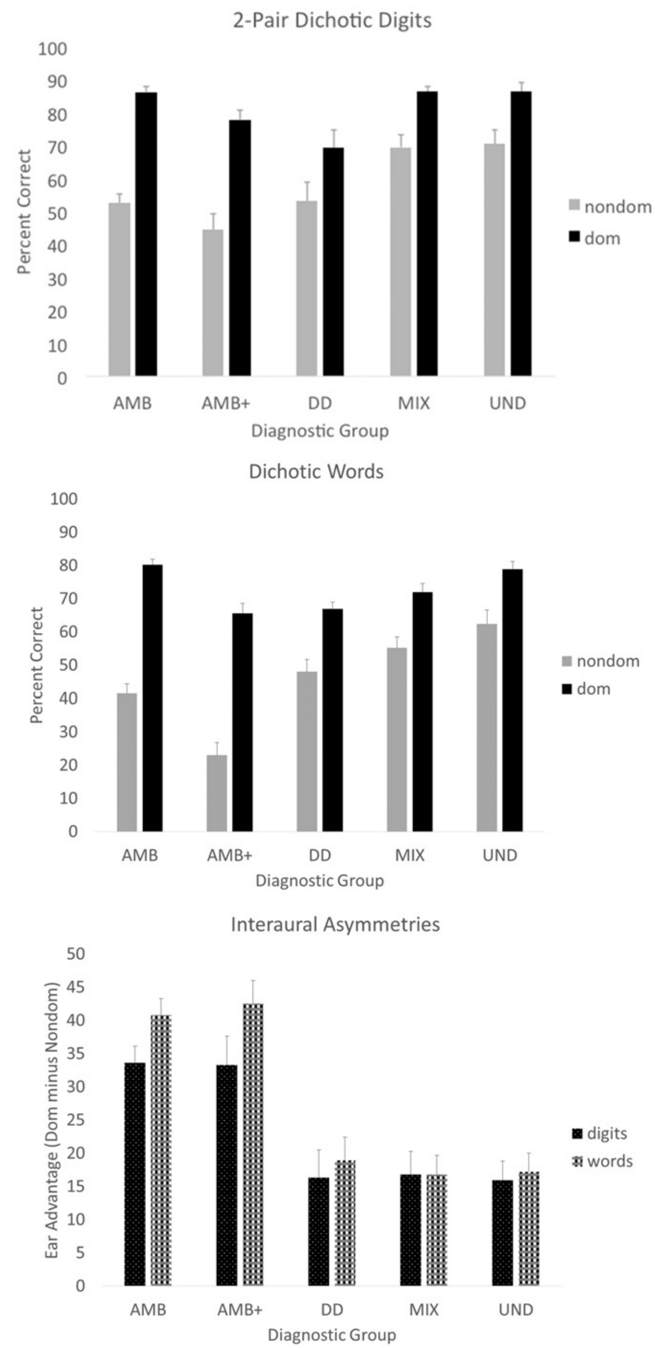

Figure 2. Average scores in the non-dominant (nondom) (grey bars) and dominant (dom) (black bars) for the digits test (top) and words test (bottom) for participants in each diagnostic group. AMB: amblyaudia; AMB+: amblyaudia plus dichotic dysaudia; DD: dichotic dysaudia; MIX: mixed; UND: undiagnosed.

by the Friedman test, a non-parametric analysis of repeated measures. Significant differences were found across all measures as shown in Table 4. To determine which intervals resulted in significant differences, *post hoc* analyses with Wilcoxon signed ranks tests with Bonferroni's adjustment were run with the significance level adjusted to $p < 0.017$ to accommodate three intervals. As detailed in Table 5, non-dominant ear and interaural

Table 3. Main effects of ARIA on dichotic listening scores.

Test	*Score*	*Z score*	*n*	*p*
(a) Significant effects of ARIA on scores at fourth session.				
RDDT	Non-dominant ear	−8.24	116	<0.001
	Dominant ear	−2.54	116	0.011
	Interaural asymmetry	−7.34	116	<0.001
DWT	Non-dominant ear	−8.18	119	<0.001
	Dominant ear	−0.128	119	0.898
	Interaural asymmetry	−8.14	119	<0.001
(b) Significant effects of ARIA on scores at post-ARIA evaluation.				
RDDT	Non-dominant ear	−6.71	70	<0.001
	Dominant ear	−2.67	70	0.008
	Interaural asymmetry	−5.99	70	<0.001
DWT	Non-dominant ear	−6.01	67	<0.001
	Dominant ear	−3.92	67	<0.001
	Interaural asymmetry	−5.65	67	<0.001

RDDT: Randomized Dichotic Digits Test; DWT: Dichotic Words Test.
Z score is from the Wilcoxon signed ranks test.
n refers to the number of participants whose scores were analysed.

asymmetry measures were significantly different between the pre-ARIA evaluation and the fourth session in this subgroup of participants, with results that are highly similar to results obtained from the larger group of participants enrolled in the study (see Table 3). Scores between pre- and post-ARIA evaluations were also highly significant across all measures and similar to results from the larger group (see Table 3). The only scores that showed a significant change between the fourth session and post-ARIA were the dominant ear scores with words. This significant change in dominant ear performance with words did not represent post-training regression, however, but instead reflected a continued improvement in the participants' ability to process dichotic words in their dominant ears as shown in Figure 4.

The post-ARIA improvement in the dominant ear with words also led in some cases to an increase in interaural asymmetry. Within this subgroup for whom measures were obtained at all three times, average interaural asymmetry increased from under 12% to over 18% between the fourth session and the post-ARIA evaluation. Among those diagnosed as AMB and AMB+, nearly half of them demonstrated interaural asymmetry with dichotic words greater than 10% at their post-ARIA evaluations. This same pattern did not occur for participants in the DD, MIX or UND groups. This suggests that despite gains in non-dominant ears, there may be a residual degree of amblyaudia present among some of these participants resulting in a tendency for the dominant ear to suppress non-dominant ear performance. Pre- and post-ARIA values of interaural asymmetry for participants with amblyaudia when tested with dichotic words are displayed in Figure 5. All but three of the participants with amblyaudia showed reductions in interaural asymmetry, two participants (one 7-year-old and one 16-year-old) showed an increase in interaural asymmetry after training, and one 8-year-old showed the same value as before ARIA.

Discussion

ASHA (2005) recommends assessment of ''auditory performance in competing signals'' and the AAA Clinical Practice Guidelines recommend testing with ''Dichotic Listening (Speech) Tests'' for individuals suspected of having an APD. A survey of audiologists reported that a majority use DL tests to assess patients (Emanuel et al, 2011). DL tests have been utilised for over 50 years and new normative information is available for assessing performance in the non-dominant and dominant ears so that direction of ear advantage does not influence measures of interaural asymmetry (Moncrieff, 2011; Moncrieff, 2015). All study participants demonstrated binaural integration weaknesses and 65% of them were diagnosed following consistent patterns from two DL tests: 46% as AMB, 13% as AMB + and 6% as DD. Another 15% who demonstrated inconsistent abnormal performance were designated MIX and 20% who demonstrated abnormal performance on only one DL test were designated UND. The high prevalence of scores designating AMB or AMB + demonstrates that clinically significant DL deficits in the non-dominant ear are common among children and adolescents referred for APD assessment. Since the primary purpose of clinical assessment should be to direct remediation, training methods designed to improve binaural integration performance with competing signals are useful to treat the large number of children and adolescents suffering from the effects of amblyaudia.

Participants in other diagnostic groups also benefitted from participation in ARIA. Those diagnosed as DD from relatively symmetrical but weak performance in both ears during DL tests demonstrated higher ear scores and lower interaural asymmetry, but none of their results achieved significance. As there were only seven participants diagnosed with DD and only three for whom post-ARIA scores were measured, it is not known whether a larger number of participants with the DD diagnosis would have shown significant improvements following training. Those designated MIX demonstrated inconsistent but abnormal performance on two DL tests and showed significant improvements in their non-dominant ears at the fourth session, but not at the post-ARIA assessment when there were scores available for only seven of them. When examined individually, however, only one of them continued to demonstrate an abnormal asymmetry of 20% at the post-ARIA evaluation with words, a difference that was only 2% above the normal cut-off criterion for that age. This would suggest that for children and adolescents whose abnormal performance is inconsistent, ARIA may be able to provide improvement for their binaural integration skills. More data from a larger subset of participants with the DD diagnosis and MIX designation may better determine if they may significantly benefit from ARIA training.

Those designated UND demonstrated abnormal performance on only one DL test, either with words or with digits. They demonstrated significant improvements in non-dominant ears with digits at the fourth training session and the smaller subgroup of them who returned for a post-ARIA assessment demonstrated significant improvements in non-dominant ears with both digits and words. It was anticipated that significant gains would be observed only among those participants who demonstrated a consistent pattern of weakness across both DL tests and not among those whose weakness was apparent on only one DL test. A majority of UND group participants who returned for post-ARIA evaluations had produced the AMB or AMB + pattern on the one DL test that was abnormal (9 of the 14). The significant improvements seen in this subgroup suggests that even when DL testing falls below normal for only one test, children and adolescents diagnosed with APD who show the AMB or AMB + pattern on one DL test may still benefit from enrolment in ARIA. Others in the UND group demonstrated the DD pattern on one DL test and all showed large

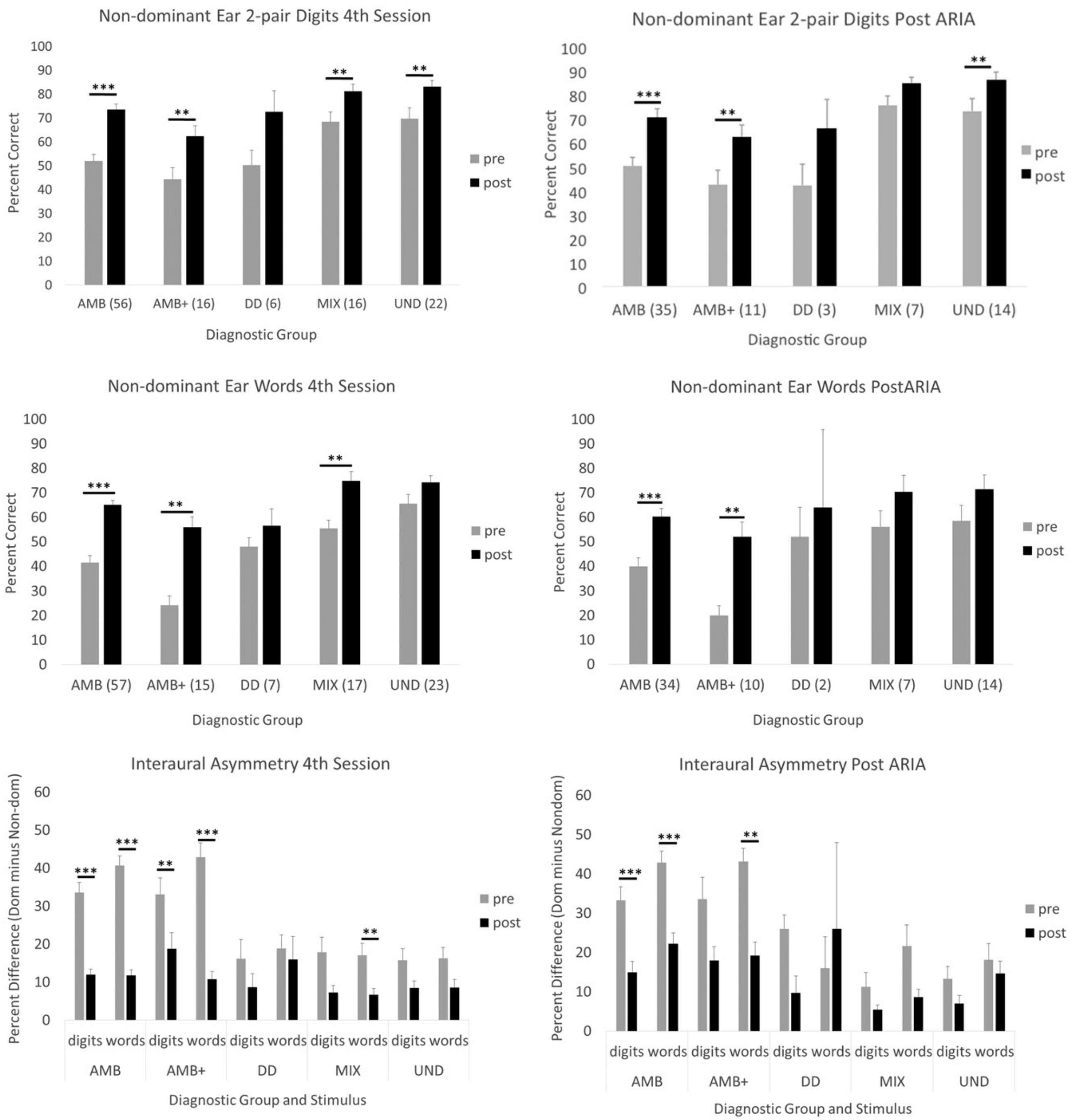

Figure 3. Left column displays results from the group of participants whose scores were measured at the fourth session of ARIA (words, $n = 119$; digits, $n = 117$): Outcomes measured during the pre-ARIA evaluation (grey bars) and during the 4th ARIA session (black bars) for participants in each diagnostic group (a) for non-dominant ears from the 2-pairs condition of dichotic digits; (b) for non-dominant ears from dichotic words and (c) for interaural asymmetry measured from digits and words; Right column displays results from the subgroup of participants whose scores were measured at pre-ARIA (grey bars) and post-ARIA (black bars) evaluation (words, $n = 67$; digits, $n = 70$); (d) for non-dominant ears from the 2-pairs condition of dichotic digits; (e) for non-dominant ears from dichotic words; (e) for interaural asymmetry measured from digits and words. Significance values are represented by bars, $p < 0.001$***, $p < 0.01$**, $p < 0.05$*.

gains in both ears following ARIA training, suggesting that children and adolescents who perform poorly and symmetrically on DL tests may also benefit from participation.

Results from this study suggest that ARIA training benefits individuals whose performance on a DL test falls below normal which is not surprising since the training focuses on dichotic tasks. Benefits are maximal, though, for children and adolescents whose binaural integration skills are consistently weak across two different DL tests, especially when the pattern leads to the diagnosis of amblyaudia. As the ARIA training paradigm requires that the clinician continually adjust the relative intensity of material presented through the sound-field speakers, participants with poor

Table 4. Significant differences between scores at initial evaluation, fourth session and post-ARIA.

Test	*Condition*	X^2	*df*	*n*	*p*
RDDT	Non-dominant ear	67.99	2	70	<0.001
	Dominant ear	9.33	2	70	0.009
	Interaural asymmetry	26.82	2	70	<0.001
DWT	Non-dominant ear	51.54	2	67	<0.001
	Dominant ear	18.73	2	67	<0.001
	Interaural asymmetry	54.87	2	67	<0.001

RDDT: Randomized Dichotic Digits Test; DWT: Dichotic Words Test.
X^2 score is from the Friedman test, a nonparametric alternative to repeated measures ANOVA.

Table 5. *Post hoc* analyses of differences between scores at initial evaluation, fourth session and post-ARIA.

Test	*Score*	*Test interval*	*Z score*	*n*	*p*
RDDT	Non-dominant ear	Pre-ARIA to session 4	−5.61	66	<0.001
	Dominant ear		−2.23		0.026
	Ear advantage		−5.12		<0.001
DWT	Non-dominant ear		−5.99	66	<0.001
	Dominant ear		−0.99		0.320
	Ear advantage		−6.08		<0.001
RDDT	Non-dominant ear	Pre-ARIA to post-ARIA	−6.71	70	<0.001
	Dominant ear		−2.67		0.008
	Ear advantage		−5.99		<0.001
DWT	Non-dominant ear		−6.07	68	<0.001
	Dominant ear		−3.89		<0.001
	Ear advantage		−5.71		<0.001
RDDT	Non-dominant ear	Session 4 to post-ARIA	−0.75	66	0.453
	Dominant ear		−0.42		0.676
	Ear advantage		−0.33		0.743
DWT	Non-dominant ear		−0.19	64	0.852
	Dominant ear		−4.10		<0.001
	Ear advantage		−3.34		0.001

RDDT: Randomized Dichotic Digits Test; DWT: Dichotic Words Test.
Z score is from the Wilcoxon signed-ranks test.

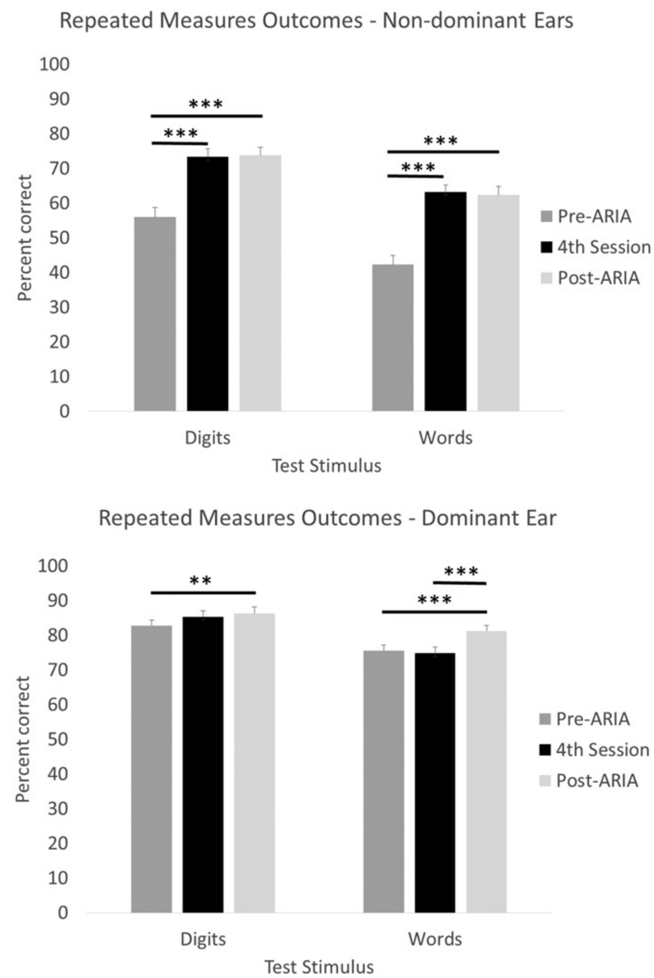

Figure 4. Average results for participants who were assessed at all three intervals. Top panel shows non-dominant ear scores for digits and words at each test time, pre-ARIA, fourth session and post-ARIA. Bottom panel shows dominant ear scores for digits and words at each test time. Significance values are represented by bars, $p<0.001$***, $p<0.01$**, $p<0.05$*.

but symmetrical DL performance can do most of their training work at relatively equal intensities throughout the training sessions. This individualised and adaptive approach allows the clinician to structure the training regimen to the specific performance characteristics of each participant in order to maximise gains across tasks with dichotic digits and words.

The systematic adjustments to intensity of presentations to the dominant ear throughout ARIA depended on the performance in the participant's non-dominant ear. The rationale behind this approach is based on the anatomical and physiological correlates of the duplex theory of sound localisation (Tollin & Yin, 2002). Interaural level differences (ILDs) produced by presenting information to the non-dominant ear at a higher relative intensity level should result in higher discharge rates in neurons in the ipsilateral lateral superior olive (LSO), leading to an enhanced sensitivity to information arriving at that side and reduced sensitivity to presentations at the contralateral ear (Boudreau & Tsuchitani, 1968). Neurons in higher level structures along the auditory pathway, i.e. the inferior colliculus, medial geniculate body, and auditory cortex, are sensitive to the neural patterns generated by ILDs and use them to encode spatial sensitivity and location. We hypothesise that the ILDs used during ARIA training promote increased activation along the non-dominant ear's auditory pathway, thereby inducing neuroplastic changes that lead toward more symmetrical binaural integration of verbal material.

Sound source location deficits have been reported following conductive hearing loss in several animal studies (Slattery & Middlebrooks, 1994; Hartley et al, 2003; Lupo et al, 2011). Even long after conductive hearing loss has cleared, children have been shown to have binaural localisation deficits (Hall et al, 1998; Roberts et al, 2004). Sound localisation depends on the integration of binaural cues, especially in environments with varied sound sources (Blauert, 1997). However, a clear relationship between chronic otitis media, sound localisation deficits, and performance on DL tests has not been established. Whether participants in this study had histories of chronic otitis media is not known, but information relating significant histories of conductive hearing loss with

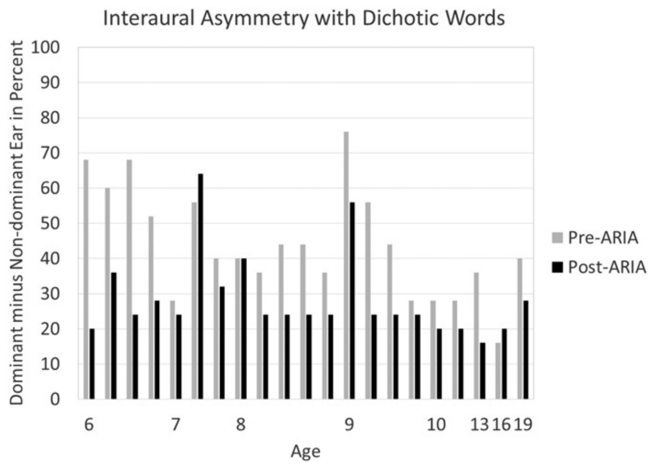

Figure 5. Individual scores for interaural asymmetry when tested with dichotic words for participants diagnosed with amblyaudia pre-ARIA (grey bars) and post-ARIA (black bars).

binaural integration test results would be of interest in managing deficits in children suspected of having APD.

Children with normal post-ARIA performance should be discharged from further treatment and those whose performance remains below normal should receive appropriate recommendations. Even with significant improvements following 4 weeks of ARIA, some scores may not achieve normal levels in children with severe pre-ARIA deficits. If interaural asymmetry remains high because of abnormally low performance in the non-dominant ear or abnormally high performance in the dominant ear, another 4-week session of ARIA is recommended. If interaural asymmetry is normal but performance is abnormally low in both ears, use of a remote microphone hearing aid (''FM'') system at school is recommended (Reynolds et al, 2016). A bilateral hearing assistive device is likely to be more beneficial for a child who does not have a large asymmetry when the two ears are placed in competition, so greater benefit may be achieved once the two ears are integrating binaural information more symmetrically. This recommendation for use of a bilateral hearing assistive device is based on clinical experience, so research evidence of greater benefit from remote microphone assistive devices following treatment with ARIA is needed.

Benefits derived from participation in ARIA across other auditory processing measures will be addressed in a subsequent manuscript. It is hypothesised that binaural integration deficits may underlie listening and learning difficulties and that ARIA training may result in improvements in other auditory processing skills that were found to be deficient during an initial evaluation for APD. Follow-up research will assess other auditory processing skills such as temporal resolution, speech perception in noise, spatial stream segregation, and pattern recognition for outcomes following ARIA training.

A limitation of this study is that not all of the clinical sites performed post-ARIA assessments. Clinicians providing ARIA should have patients return for a follow-up assessment at a time between 3 and 6 months following the end of the treatment and they should use the same tests at the diagnostic evaluation and the post-ARIA assessment in order to adequately compare outcomes across a variety of auditory processing skills. In the second initial trial of ARIA, the Brigance battery was used to assess listening comprehension, oral reading, and word recognition following ARIA (Moncrieff & Wertz, 2008) in order to evaluate listening and learning skills outside of those used during a standard APD assessment and/or during ARIA training. As this was a clinical study designed to show that multiple practitioners at several clinical sites could produce similar DL outcomes across children diagnosed with amblyaudia, it was beyond its scope to add additional outside evaluations of broader skills needed for classroom performance. A randomised controlled trial is an appropriate next step to evaluate the direct benefits of ARIA on DL performance and to further investigate how improvements might generalise to listening and language skills that can enhance learning in children diagnosed with amblyaudia. In such a trial, all training methods including the number of stimuli presented and the rules regarding changes to interaural intensity throughout ARIA training will also be standardised.

Conclusions

ARIA training produced significant gains in DL test scores across participants diagnosed with an APD with the greatest benefits observed among those diagnosed with amblyaudia. Given that the primary focus of ARIA is to enhance performance in the listener's non-dominant ear, it is not surprising that listening to dichotically presented words throughout 4 weeks of training led to better scores in these tasks. Scores at the fourth session are likely to reflect the highest levels of performance because they are derived from direct training-to-the-test, but even after intervals from 2 to 12 months, significant improvements in non-dominant ear scores were maintained. With words, dominant ear scores continued to improve following the end of ARIA training suggesting enhanced ability to process verbal material. Maintenance of binaural integration skills for months after training, as seen in those who returned for post-ARIA assessments, suggests that the training led to continuing benefit with minimal or no regression.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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