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Frequency discrimination in children: Perception, learning and attention

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Abstract

It is generally believed that both sensory immaturity and inattention contribute to the poor listening of some children. However, the relative contribution of each factor, within and between individuals, and the nature of the inattention are poorly understood. In three experiments we examined the threshold and response variability of 6–11 y.o. children on pure tone frequency discrimination (FD) tasks. We first confirmed that younger children had both higher thresholds and greater within- and between-listener variability than older children and adults. Higher thresholds were mostly attributed to high response variability due to poor sustained attention. We next compared performance on the auditory FD task with that on visual spatial FD. No correlation was found between the thresholds or variability of individuals on the two tasks, suggesting involvement of modality-specific attention. Finally, we found lower thresholds for 8–9 y.o. children performing auditory FD training in a classroom than in the laboratory, possibly due to training session length or to a more familiar, motivating and focussed training environment. The adult-like performance of many younger children at times during their testing or training, together with the high response variability of immature performers, suggested that most elevated FD thresholds in children are due to inattention.

Keywords: Auditory processing; Vision; Development; Training; Mainstream school

1. Introduction

Children are generally considered to have poorer attention than adults, but attention is a construct that must be inferred indirectly from variations in performance on specific tasks (e.g. Manly et al., 2001). Psychoacoustic studies have long recognised the intervening effect of inattention on the assessment of hearing in children. In an attempt to separate auditory performance from attention, the properties of psychometric functions relating performance to stimulus level have been measured and modelled. These properties include the slope of the function (Allen and Wightman, 1994) and the extent to which performance at high stimulus levels falls short of perfection (Bargones et al., 1995). In more recent work, auditory spectral distractors (Stellmack et al., 1997; Oh et al., 2001) and informational masking approaches (Wightman and Kistler, 2005) have been used to show immature selective attention in children. Generic, non-psychoacoustic measures of attention, such as the TEA-Ch (Manly et al., 2001), have also revealed immature auditory attention in subtests aimed at specific attentional functions (e.g. sustained, selective and executive control). Psychoacoustic approaches have assumed that performance varies randomly (stochastically) over time; that the psychometric function is a 'snapshot' of both perception and attention. The generic approach assumes that attention is essentially a singular and multimodal function; that inattention will be simultaneously and rather indiscriminately manifest in a variety of tasks.

In this paper, we take several novel perspectives on the relation between attention and listening in children. We first examine how children's auditory performance changes over time. Our premise is that attention is constantly varying, both within and between tasks. The degree to which inattention is contributing to listening should be apparent as short- or medium-term changes

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in auditory abilities. Children who are attentive should, in a standard staircase adaptive procedure (Amitay et al., 2006), produce a consistent pattern of 'reversals' – levels of the stimulus that dynamically mark the upper and lower limits of threshold variability. Here, the staircase would be expected gradually to converge on a threshold, with little fluctuation around that point. Successive threshold determination 'tracks' should produce consistent estimates. Inattention, on the other hand, would be expected to lead to a greater degree of performance variability. This should manifest as higher thresholds and a greater range of reversals and inter-track differences. We might expect this to be particularly marked when measuring thresholds in noisy and/or otherwise distracting environments, such as a school classroom.

Leading models suggest that attention has both general (supra- or multi-modal) and modality-specific components (Spence, 2001). In a second experiment, we examine the relation between auditory and multimodal attention and children's listening by comparing individual performance on closely matched auditory and visual tasks. Previous work (Hawkey et al., 2004) used a similar technique to separate procedural and perceptual aspects of learning. Here, we reason that, if multimodal attention plays a significant role in the hypothesised attention drift described above, there should be a correlation between the auditory and visual tasks on measures of both performance and response variability. A lack of such a relation provides evidence for dominant unimodal influences.

Many studies have shown that auditory training improves performance on a variety of listening tasks, both in adults and children (Merzenich et al., 1996; Moore et al., 2005; Moore and Amitay, 2007; Wright and Zhang, 2006). We have suggested that attention makes a major contribution to such auditory learning by showing, for example, that training on a non-auditory task (the visuospatial computer game, Tetris®) can improve performance on an auditory frequency discrimination (FD) task (Amitay et al., 2006). Here we report and compare results of training children on FD tasks in the lab (Halliday et al., 2007) and in a school environment. Because of the possible interfering effect of noise on attention, we predicted that the school environment would be less conducive to learning than the quiet of a laboratory sound chamber. We also present data on the variability in children's performance on the trained task that remains a major challenge for the understanding and control of children's attention in relation to auditory learning.

The studies reported here thus had three specific aims. First, to examine the influence of attention on children's FD listening by examining the time course of performance variation. Second, to examine whether changes in children's listening over short time periods are influenced by multimodal or unimodal mechanisms. And third, to examine whether FD training in children is influenced by the environment in which the training takes place.

2. Materials and methods

2.1. Experiment 1: auditory frequency discrimination in children

All testing was conducted in a sound-attenuating chamber (IAC). Three age groups of audiometrically typical ($\leqslant$20 dB HL, 0.5–4 kHz, bilaterally) children (6–7 y.o., $n = 17$; 8–9 y.o., $n = 25$; 10–11 y.o., $n = 20$) were recruited from local schools. A comparison group of young adults ($n = 21$) was recruited from within the University of Nottingham and the Queen's Medical Centre. FD thresholds were estimated using an adaptive, three-interval, three-alternative ('odd-one-out') forced-choice paradigm. In each trial, two of three intervals contained a standard, 1 kHz tone (200 ms including 10 ms ramps, separated by 500 ms), and the third, randomly determined interval contained a higher frequency 'target' tone, the frequency of which varied adaptively from trial to trial. The listener's task was to detect the interval that contained the target. Note that a judgement about the relative properties of the tones, other than same-different, is unnecessary in this task.

In a familiarisation phase, five 'easy' trials were presented (standard: 1 kHz; target: 1.5 kHz). The criterion for successful completion was that at least 4/5 of these 'easy' trials were identified correctly by the listener. If more than one trial was answered incorrectly, the track was repeated until the examiner was satisfied the participant had understood the task instructions. In the initial trial phase, the frequency of the target tone was adaptively varied on each trial using a staircase procedure. The initial ΔF was 50% higher than the standard frequency. An initial "lead-in" 1-down 1-up rule was used to speed up approach to the ΔF region of interest. During this phase, ΔF was halved after each correct response, until the first error occurred. The staircase then followed a 3-down 1-up rule. During this second phase, ΔF was multiplied or divided by a factor of $\sqrt{2}$. In this phase, two successive increases in target frequency resulted in a doubling of the step size (a 'boost factor'; after Litovsky, 2005) to encourage increased attention from the added salience of an easier trial. For a few children, this lead to a ceiling level of performance (2 kHz target).

Tests were delivered via child-friendly computer games (Fig. 1A) in which each interval corresponded to an event on the computer screen. Trials were visually cued. Participants were given an unlimited time to respond. A response, via a purpose-built button box, initiated a new trial. Visual feedback was provided for all correct responses and an indicator of progress through the track was provided by a character at the top of the screen.

Trials continued until a total of three reversals were obtained in the second phase of the staircase, and the threshold estimate was calculated as the geometric mean of the difference between the standard and target frequency at the last two track reversals. Measurements were obtained from two consecutive tracks. If, in any one track,

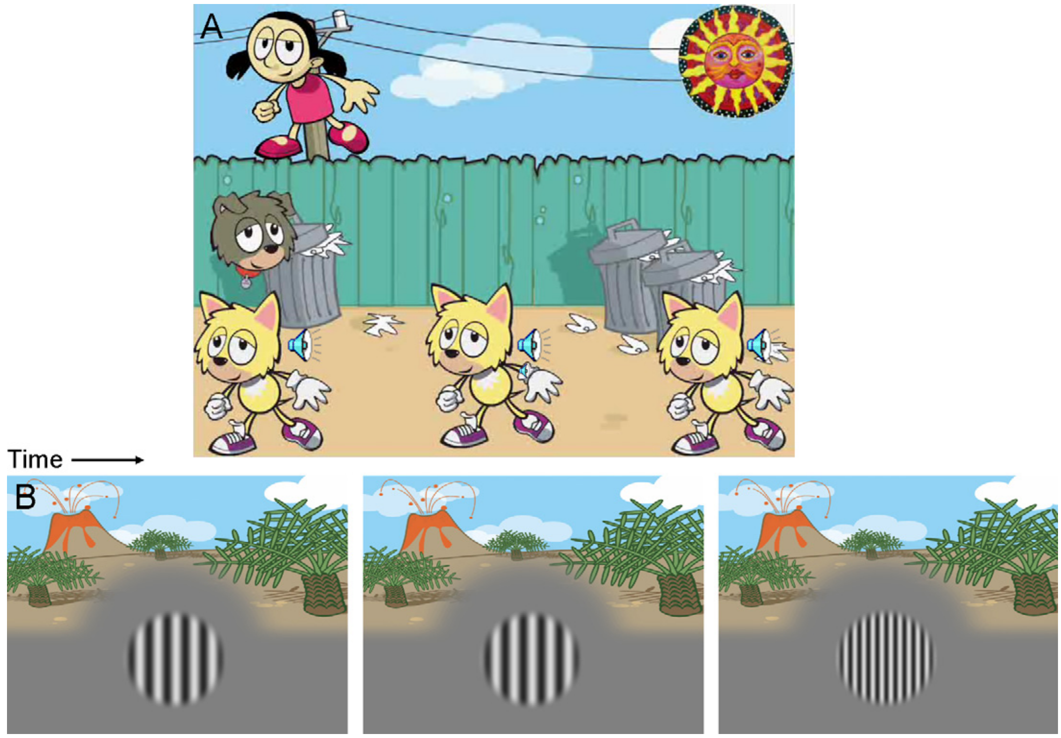

Fig. 1. Stimulus presentation screen shots. (A) Auditory presentation. Trials were cued by the dog lifting an ear. The three sound intervals were marked by each of the cats jumping up in turn. Correct responses were indicated by the selected cat doing a dance and the girl (top left) advancing from left to right. (B) Visual presentation. The three successive presentation gratings were as shown, with the higher frequency grating (right) appearing randomly in any of the three intervals. A fixation screen (small red cross in centre of where the grating would appear) preceded the first interval.

40 trials were presented without achieving three reversals, or if the discrepancy between the two track threshold estimates was greater than $\Delta F = 10\%$, a further track was collected. FD threshold data presented are the means of the estimates derived from the two tracks. Where a third track was obtained, the threshold was the mean of the closest two thresholds. An estimate of response drift, the inter-track threshold difference (ITTD), was the (unsigned) difference between the threshold measure derived from each of the first two tracks (even when a third track was obtained), irrespective of track threshold discrepancy.

Data were log transformed prior to statistical analysis in all experiments.

2.2. Experiment 2: auditory and visual frequency discrimination

A second group of children (6–7 y.o., $n = 8$, 8–9 y.o., $n = 12$, 10–11 y.o., $n = 8$) with typical hearing and (corrected) visual acuity was recruited and the procedure for auditory FD threshold estimation described above was repeated. Subsequently, each child was tested for visual spatial frequency discrimination using a near-identical procedure. The children were asked to direct their attention to a grey area near the foot of the image (Fig. 1B). On each trial, following a visual cue (a red cross that appeared near the centre of the grey area), three circular sine-wave contrast gratings of equal mean luminance to the surrounding grey area (Fig. 1B) were each shown successively for 1500 ms (500 ms ISI) at a viewing distance of 0.6 m (0.1 m diameter = 10° viewing angle. Ilyama Vision Master Pro 510, 20" CRT Monitor contrast = 77%). As for auditory FD, a target grating had a higher spatial frequency (initially of 0.75 c/deg) than two standard gratings (0.5 c/deg) and the frequency of the target was adaptively varied on each trial using the same staircase procedure and step sizes described above.

2.3. Experiment 3: auditory frequency discrimination training

2.3.1. Laboratory study

Participants were a group of pre-screened, audiometrically typical (⩽25 dB HL, 0.5–4 kHz, bilaterally), 8–9 y.o. children ($n = 29$) who were able reliably to discriminate between a 1.0 and 1.5 kHz tone. They were trained over a long (∼3 h, including breaks) single session in a laboratory sound-attenuating chamber. Training was delivered via eight blocks of 75 trials, comprising three interleaved tracks running concurrently. For each track, stimuli, adaptive procedures, step sizes and computer graphics were broadly the same as those for the auditory components of Experiments 1 and 2. However, there was no 'boost factor', the maximum (ceiling) frequency was 1.5 kHz, the familiarisation phase was a screen to determine ability to discriminate 1.0 and 1.5 kHz, and responses were made via a touch screen. As before, participants were given an unlimited time to respond but, here, the initiation of each new trial was self-paced. Visual feedback was again provided for all correct responses and tokens accumulated at the bottom of the touch screen as a measure of past performance success. Progress through the track was not monitored.

2.3.2. School study

A single group of 8–9 y.o., audiometrically screened (⩽25 dB HL, 0.5–4 kHz, bilaterally) children ($n = 10$) who were able reliably to discriminate between a 1.0 and 1.5 kHz tone were recruited from a local primary school. They were trained in an auditory FD task within the school's library, simultaneously with and alongside the other children. Three experimenters were at hand to assist. The procedure was similar to that used in Experiment 3, but with the following noteworthy exceptions. Training was conducted in half-hourly sessions, thrice-weekly, for 4 weeks. There were 11 standard frequencies of the tone (0.57–2.92 kHz, including 1 kHz), varied from one 25 trial track to the next. Children completed 4–6 tracks of each frequency throughout the whole experiment. The graphics displays were more interesting and children received tangible rewards (stickers and prizes) contingent on their participation. The training was therefore presented in shorter, but more numerous tracks, was dispersed across frequencies and training days, and was otherwise more interesting, making direct comparison with the laboratory study difficult. Nevertheless, we have extracted the 1 kHz data from the remainder, and we present below the results separately for the 1 kHz and the total data set.

All experiments were approved by the Nottingham NHS Research Ethics Committee.

3. Results

3.1. Experiment 1: auditory frequency discrimination in children

Children's response patterns to the adaptive presentation of the tone discrimination task were quite variable. However, we were able to discern three basic types. The most common was a 'good performer' (Fig. 2A). This pattern was characterised by a lead-in sequence in which a succession of correct responses resulted in a rapid approach to a level that was close to that at which subsequent staircase reversals occurred. These performers generally achieved the criterion number of reversals in a relatively small number of trials. A second test track typically had the same characteristics as the first and resulted in a similar threshold estimate that indicated acute discrimination relative to others of the same age (Fig. 3). A second pattern was similar to the first, except that these 'genuine poor performers' (Fig. 2B) had much less sensitive thresholds. This pattern was seen only rarely, by the simple criteria used in this analysis (Table 1), and the example shown is the most consistent of this type we found. Nevertheless, in broader studies of children's hearing development (Cowan et al., 2005; Ferguson et al., 2007) we have found several examples across a variety of listening tasks. A third pattern, seen in a larger number of children, especially younger children, was characterised by very poor, or ceiling level (Figs. 2C and 3) thresholds. As shown by the example in Fig. 2C, these children often performed quite accurately and consistently during the lead-in trials, suggesting that they could both do the task and discriminate the stimuli. However, when they began to make mistakes for difficult discriminations, their performance declined, and they subsequently made mistakes for discriminations they had formerly achieved with ease. In a few extreme cases, such as that shown in Fig. 2C, they performed at ceiling but, more typically, their performance varied cyclically, with large excursions of performance during the course of a test track. Their performance also often varied dramatically between tracks. This behaviour, which we call 'non-compliant', always resulted in the poorest thresholds (Fig. 3), where these could be measured, and was presumably due to fluctuations of attention. The proportion of non-compliant performers was considerably higher in the 6–7 y.o. group than in any of the other groups, by the relatively liberal cri-

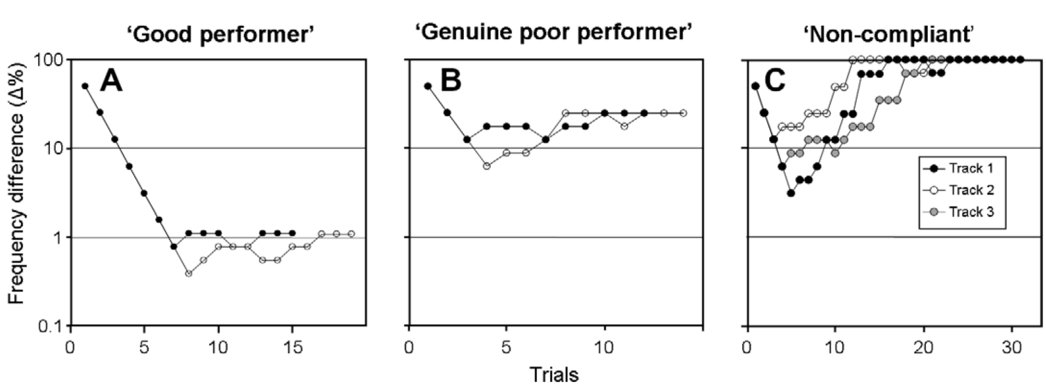

Fig. 2. Examples of performance sub-types in Experiment 1. Each figure shows the results of successive, 3-down, 1-up staircase, adaptive tracks of trials. The ordinate shows the frequency difference between the standard and target stimuli. (A) Good performers produced consistent responses at low threshold levels. (B) Genuine poor performers were consistent, but had elevated thresholds (>2 s.d. above their age mean). (C) Non-compliant responders generally performed well in the first few trials of each track, but performance then declined, either to ceiling level (as here) or to a level close to, or above the starting level of the track. Performance often recovered towards the end of the track. The examples shown are from (A) a 10 y.o., (B) 9 y.o., and (C) 8 y.o. child. Further details in the text.

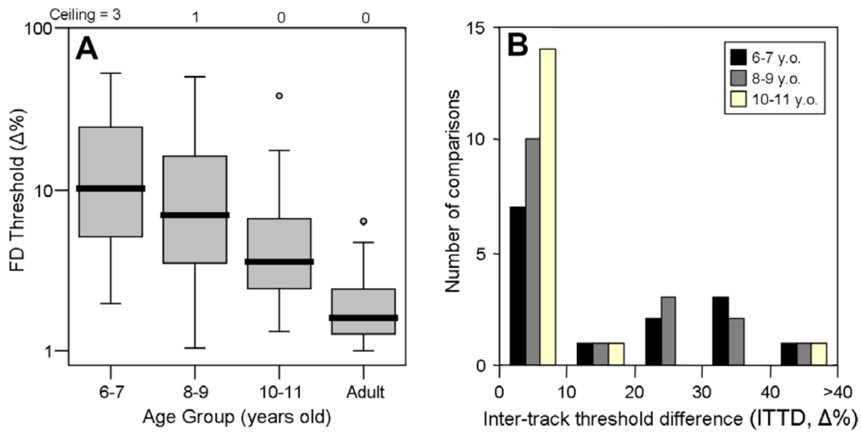

Fig. 3. Experiment 1 group results. (A) Box plots showing auditory frequency discrimination (FD) thresholds as a function of age. 'Ceiling' indicates the number of children in each group whose performance was beyond the scaling of the ordinate. Data from these children were not included in the box plots. (B) The distribution of the (unsigned) inter-track threshold difference (ITTD) for each child across age groups. See text for details.

Table 1
Classification of performance sub-types in Experiment 1 (see Fig. 2)

Age (y.o.)	Good	Genuine poor	Non-compliant
6–7	24% ($n = 4$)	12 (2)	64 (11)
8–9	56 (14)	4 (1)	40 (10)
10–11	84 (16)	5 (1)	11 (2)

Every trial ΔF in each track for the good performers and genuine poor performers was within 50% of the standard frequency. Most were much closer than this. For the non-compliant performers, the ΔF for at least one trial (usually many) was greater than 50%.

teria used here (Table 1) and, among this group, non-compliance in FD was more prevalent than in any of ten other listening tasks (Cowan et al., 2005).

A comparison of track thresholds across age showed that younger children had higher variability, both between (Fig. 3A) and within (Fig. 3B) individuals. Performance of more than 75% of the 6–7 y.o. was outside the 95% confidence intervals of the adult group. The mean threshold (transformed logarithmically) differed significantly ($p < 0.001$) between the four groups, with performance improving across each successive age group. However, half of the good performers in the three groups of children, including two in the youngest group, had thresholds that were within the confidence intervals of the adult group. One 7 y.o. had an FD threshold of 1.6%. The ITTD index (Fig. 3B) indicated that a higher proportion of the two younger groups had quantitatively greater response variability ($\chi^2 = 9.32$; $p < 0.01$), within the time frame of successive adaptive tracks (separated by about 2–5 min).

3.2. Experiment 2: auditory and visual frequency discrimination

Performance of the visual FD task (Fig. 4) differed qualitatively from that of the auditory FD task (Fig. 3A). Variability, both within and between children, was much reduced for the visual task. At the group level, we found the same trends seen in auditory FD (Fig. 4A). Younger children performed more poorly and more variably than older children, but none of the children showed

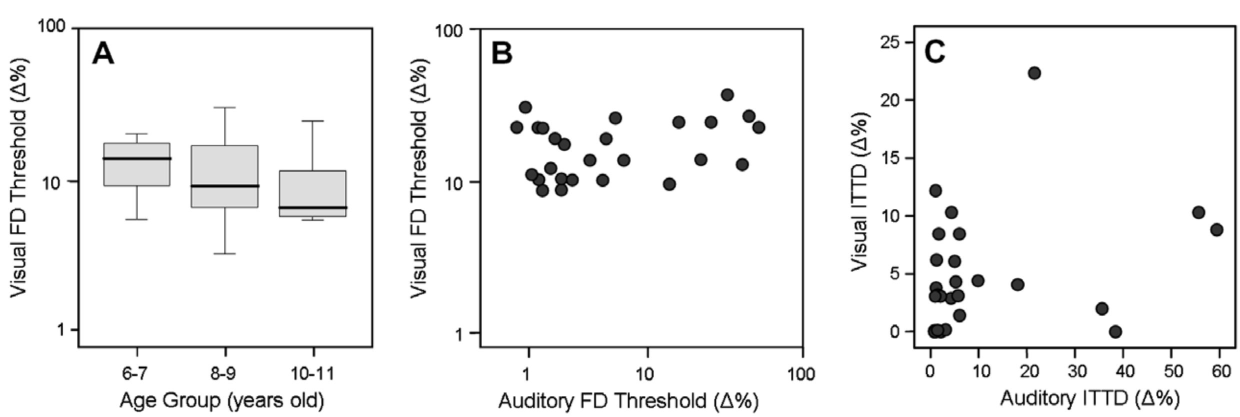

Fig. 4. Experiment 2 results. (A) Box plots showing age group visual frequency discrimination (FD) thresholds. (B) Comparison of visual and auditory FD thresholds. (C) Comparison of visual and auditory threshold variability (ITTD). For B and C, each point shows results for an individual child, all age groups combined.

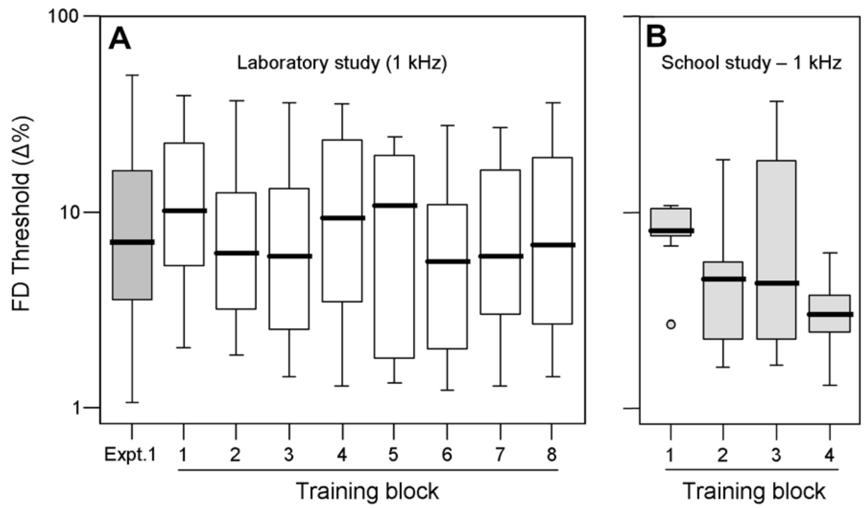

Fig. 5. Experiment 3 results. (A) Laboratory study of auditory FD training in 8–9 y.o., with thresholds at the end of each successive training block (1–8) shown as box plots. For comparison, results are also shown for the comparable age group (8–9 y.o.) from Experiment 1. (B) School study results for 1.0 kHz training in the first 4 (of 6) training blocks, shown as per A. Results are not shown for blocks 5 and 6 due to small numbers of children completing these later training blocks.

a ceiling effect on the visual task. However, of most interest in this work was the comparison between performance on the two tasks. As shown in Fig. 4B, there was no significant correlation ($n = 27$; $r = 0.29$, $p > 0.1$); poor performers on the auditory task spanned the full range of performance on the visual task. The response variability index, ITTD, was similarly larger for the auditory than for the visual task (Fig. 4C). Note, however, that by this measure most children (21/27) performed consistently (ITTD < 12) on both tasks, as shown previously for a separate, larger group of children on the auditory FD task (Fig. 3B). Again, there was no significant correlation ($n = 27$; $r = 0.28$, $p > 0.1$) within individual children between performance variability on the auditory and the visual tasks.

3.3. Experiment 3: auditory frequency discrimination training

Children who repeatedly performed the FD task in the laboratory showed erratic performance across training blocks that did not differ significantly between blocks and thus provided no evidence of training (8–9 y.o., Fig. 5A). Their initial median performance level was comparable to, but slightly higher than the results obtained for the same aged children (8–9 y.o.) in the separate study reported here as Experiment 1. Note, however, that the latter group was also somewhat more variable, perhaps indicative of the much smaller number of trials they completed or the more restrictive cap on drift imposed in the training. Results of both these groups were well above the adult values but, as before, some children in the trained group performed as well as the adults. Overall, these results suggested that this amount of training in one session may be ineffective for 8–9 y.o. children.

Results from the first block of 1 kHz training in the school study (Fig. 5B) showed comparable performance levels to those of the other two studies (Fig. 5A). In this case, however, significant ($F_{3,32} = 3.75$, $p = 0.02$) training was seen across blocks 1–4 (log transformed), the only blocks for which 1 kHz data were available for at least 8 of the 10 children. The large fluctuations in the confidence intervals are presumably a reflection of this small sample (of both children and training blocks) and cannot be interpreted further. Median values from the much larger data set that included all 11 trained frequencies in the school study (Fig. 6) were comparable to the results at 1 kHz (Fig. 5B) but less than those from the laboratory based tests. Because of the different ways training was performed in the lab and classroom studies, quantitative blockwise

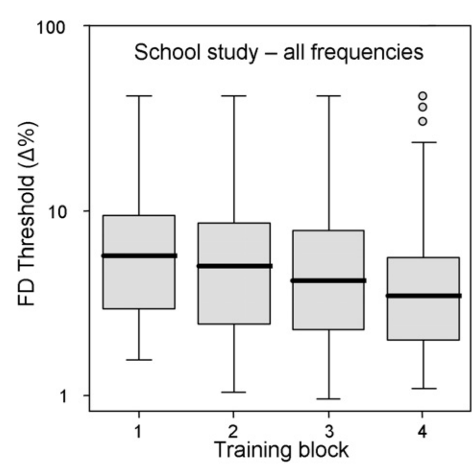

Fig. 6. Experiment 3 results. Box plots showing auditory frequency discrimination (FD) thresholds over the same 4 training blocks shown in Fig. 5B. Here, the results of all 11 training frequencies are pooled for each individual and combined for presentation.

comparisons are not possible. Nevertheless, the overall, track-by-track thresholds (log transformed) in the school study were, on average, lower than those in the lab study ($t_{638} = 4.07$, $p < 0.0001$). Threshold improvements (log transformed) with training in the school study were highly significant ($F_{3,421} = 6.25$, $p < 0.001$) across the four blocks. The smaller interquartile range of the multi-frequency data from the school study (Fig. 6) compared with the lab study (Fig. 5A) suggests less threshold variability while training in the school, but that result was statistically marginal ($F_{214,424} = 1.18$, $p = 0.08$).

4. Discussion

Individual performance ability and variation on auditory frequency discrimination may arise from time-related changes in low-level sensory processing or in higher level cognitive processing. The data we present here suggest that, while individual differences in sensory processing undoubtedly exist, and are clearly demonstrated by the cases of 'genuine poor performers', fluctuations of auditory attention account for most of the poor FD performance seen in audiometrically typical children. The finding that most of these children can show sensitive discrimination at some time(s) during testing or training, typically in the early stages, within about a minute of starting a 'track' or 'block' of trials, is strong evidence for this hypothesis. Another is that the best listeners in each age group of children had FD thresholds that were consistent over time; up to two orders of magnitude better than their peers and very similar to those of adults. In terms of the time course of attention change, we routinely observed drifting performance in the order of tens to hundreds of seconds, consistent with an explanation in terms of sustained attention (Manly et al., 2001). However, others have demonstrated selective attention problems when more complex stimuli, and appropriate tasks, are used (Oh et al., 2001; Wightman and Kistler, 2005). It would be interesting to know if the same children showed both types of inattention.

Relatively rapid drifts in performance argue against a primary influence of memory. However, we have found in our wider surveys of auditory processing in children (e.g. Cowan et al., 2005; Ferguson et al., 2007) that FD appears to present unique difficulties, especially for very young children, compared with the many detection tasks we have examined. This difference between tasks may be because FD poses a greater challenge to memory. Detection and ordering of a difference in the nature of the tone may be a cognitively more demanding task than detection and ordering of a single tone.

This study revealed a much larger proportion of non-compliant listeners than most other studies of the development of hearing (e.g. Allen and Wightman, 1994; Wightman et al., 1989). We attribute this to design considerations rather than to any particular abilities of the children we tested. Because training was an independent variable of interest, we gave the children the absolute minimum exposure to the stimulus before we started measuring their listening (see Hawkey et al., 2004). That, combined with the small number of trials in each track, inevitably leads to considerable variability, especially in children. However, we wanted to capture as much as possible how listeners actually perform when they hear sounds for the first time – as they would perform under natural listening conditions. These factors, combined with the need to keep test sessions brief, especially for very young children, presumably contributed to the high level of 'non-compliance'. A second reason for the apparently high level of non-compliance may have been differences between studies in data inclusion and/or exclusion criteria.

We used a visual spatial frequency discrimination task to examine the modality-specificity of attention influences. Results on the visual task were comparable with other recent data (Patel, 2007) from young children. However, there was no correlation between threshold or variability on this task and threshold or variability on the auditory FD task for the same individuals. If we assume that performance of the visual task is, like the auditory task, highly dependent on attention, these results suggest that each modality of task uses at least partially separate, unimodal attention resources. This hypothesis is consistent with leading models of attention that posit separate, but interacting auditory and visual attention modules (see Spence, 2001).

FD performance was compared under three different listening conditions – in the lab as a quick part of an auditory processing test battery, in the lab as the outcome of a longer auditory learning study, and in a school library as part of a group learning exercise. The two lab-based experiments yielded similar thresholds, but most striking was the lower thresholds and variability (interquartile range) seen in the school studies. The differences between overall performance in the lab and school could be due to greater attention drift during lab training, possibly due to the larger number of trials in a block (75) than in the school study (25) and the much longer test sessions. Children find it difficult to sustain attention across a single long session. Since we know that, in adults, attention facilitates, or may be required for auditory learning (e.g. Amitay et al., 2006), the highly variable results of the children in the lab study are perhaps unsurprising. However, neither threshold nor variability (between individuals) in the first block of the lab study were less than those in the subsequent blocks. If the long length of the training sessions in that study had led to progressive inattention, we would have predicted declining performance and greater variability across successive blocks.

In contrast to our initial expectation, children working in the noisier school environment had reduced mean thresholds. Thus, rather than being impaired by the additional noise in a group testing environment, it appears that most children were able to focus their attention, possibly because of some additional motivation of peer interaction, or possibly because of the more naturalistic surroundings of a familiar environment. It would be interesting to perform further research that compared more systematically performance using identical methodology in these two environments and in the home, both under parental guidance and under full individual control. Conversely, it would be useful to compare differing levels and types of distracters while training in a fixed environment.

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