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Discrimination learning induced by training with identical stimuli

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Sensory stimuli become easier to detect or distinguish with practice. It is generally assumed that the task-relevant stimulus dimension becomes increasingly more salient as a result of attentively performing the task at a level that is neither too easy nor too difficult. However, here we show improved auditory frequency discrimination following training with physically identical tones that were impossible to discriminate. We also show that learning transfers across tone frequencies and across modalities: training on a silent visuospatial computer game improved thresholds on the auditory discrimination task. We suggest that three processes are necessary for optimal perceptual learning: sensitization through exposure to the stimulus, modality- and dimension-specific attention, and general arousal.

Practice-related improvement in performance is observed in most, if not all, auditory[1–5] and visual[6–10] tasks. In both animal[11] and human[12,13] studies of visual perception, improvement in task performance is observed during incremental, 'easy-to-difficult' training, but when the task is too difficult at the outset, training may fail to begin. Taken together with the view that listeners need sufficient exposure to signal levels at which an auditory task is difficult in order to learn the relevant cues[14], it seems that the optimal training strategy should be one that starts at an 'easy' signal level, and yet provides enough exposure to 'difficult' signal levels. Indeed, training in perceptual skills almost invariably uses adaptive training techniques, starting with stimuli that are easily detectable or discriminable and gradually making them less so[15,16]. However, whereas an easy signal level is clearly one for which performance is at or near 100% correct, it is unclear how difficult a signal level should be to optimize cue learning. We addressed this question by systematically varying the level of difficulty at which listeners performed a pure-tone frequency discrimination task.

RESULTS

We assessed frequency discrimination thresholds using short probe blocks[17] for ten groups of listeners before, during and after training, using various strategies (**Fig. 1a**). We found a highly significant ($P <$ 0.001) difference in learning between training groups (**Fig. 1b**). However, the second training session (T5–T8) did not result in significant changes in threshold beyond the first session (T1–T4). A group of listeners that received no training, and typically read a book during the time allocated for training blocks, showed no significant improvement in frequency discrimination ('None'; **Fig. 1c**, $P = 0.17$). In three groups, we manipulated the degree of difficulty of adaptive training by varying the frequency difference between two standard 1-kHz tones and a comparison tone so that participants performed at either 50% (difficult), 75% or 95% (easier) correct. All three adaptive training groups showed significant learning ($P < 0.001$, corrected for multiple comparisons unless stated), but did not differ significantly from one another. Thus, varying the level of difficulty in adaptive training had no clear effect on learning.

To test whether adaptive training has an advantage over training using an unvarying stimulus, we trained three further groups using a constant frequency difference throughout the training blocks. One group trained on a frequency difference of 400 Hz, at which the performance of all participants was at ceiling (listeners unable reliably to discriminate 1 kHz and 1.2 kHz, a 200-Hz frequency difference, were excluded from this study). Another group trained on a frequency difference of 7 Hz, which was found previously[18] to be the average threshold achieved after approximately 1,000 trials of training. The third group trained on a task where there was no frequency difference between the tones (0 Hz), to ensure performance at chance level for all listeners. The constant 400-Hz group showed significant learning ($P = 0.036$). We were surprised to find that not only the very difficult 7-Hz training task, but also the impossible task—trying to discriminate between three identical sounds—yielded strong learning effects (both $P < 0.001$) that did not differ significantly from those produced by any of the adaptive training tasks.

These results could be simply accounted for if learning was driven by bottom-up activation evoked by exposure to the stimuli, independent of the task. Listeners were repeatedly exposed to tones close to the trained frequency (1 kHz), except in the constant 400-Hz-difference condition, where one-third of the stimuli heard had a rather different frequency (1.4 kHz). The reduced exposure to the 1-kHz stimuli in this group may account for the trend to decreased learning compared to the constant 7-Hz group ($P = 0.046$; uncorrected).

To examine stimulus-driven influences in the absence of task-specific attention, a further group of listeners ('Passive') was exposed to a

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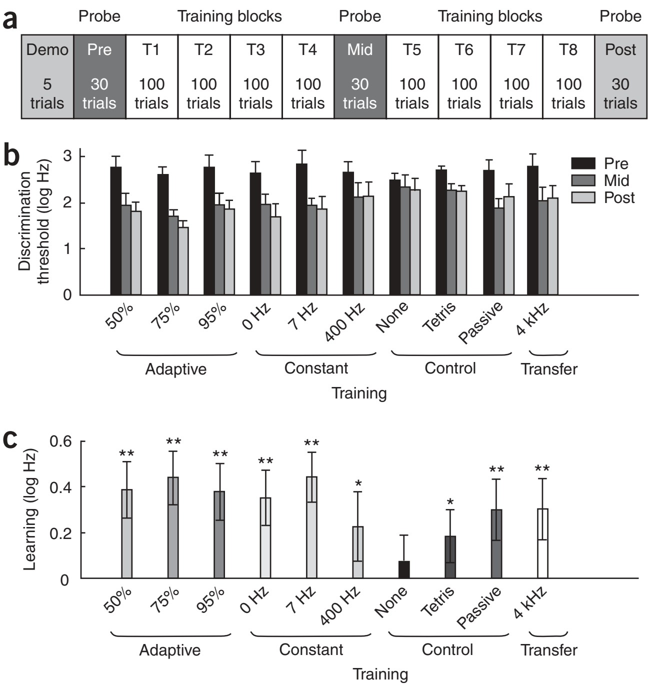

Figure 1 Improvement in frequency discrimination with different types of training tasks. (**a**) Experimental design. A short demonstration was followed by a frequency discrimination threshold assessment (pre-training probe). This was followed by four training blocks, a mid-training probe, four more training blocks and a final post-training probe. The only difference between the groups was the content of their training blocks. (**b**) Log-transformed frequency discrimination thresholds (mean + s.e.m.) at 1 kHz for the pre-, mid- and post-training probes in the ten experimental groups. Pre-training thresholds varied considerably between groups. There was a significant effect of training group ($P < 0.001$), but no significant difference between the learning effects at mid- and post-training probes ($P = 0.15$). (**c**) Overall learning effect size (mean ± 95% confidence interval) in the different training groups. Asterisks mark significant learning (Bonferroni corrected for ten multiple comparisons). $^*P < 0.05$, $^{**}P < 0.001$.

playback of the stimuli used in training one of the listeners in the adaptive 75% training group. Listeners were instructed to ignore the sounds while playing a silent visuospatial game ('Tetris'). To ensure that they had, we monitored their performance on Tetris and compared it with that of a group who played Tetris but were not exposed to the auditory stimuli. Both Tetris-playing groups showed significant improvements in frequency discrimination (Passive: $P < 0.001$; Tetris: $P = 0.019$, **Fig. 1b,c**). Tetris improvement for both groups together was correlated with improvement in frequency discrimination performance ($r_p = 0.50$; $P = 0.013$; see **Supplementary Fig. 1** online), but the passive group scored better at Tetris than the Tetris group (two-tailed *t*-test: $P = 0.026$), suggesting that, despite exposure to sounds, the passive group were attending to the game rather than to the stimuli. Similar results have been shown in studies of visual perception, where learning was observed for unattended, not consciously perceived visual stimuli[19].

The final group in this experiment trained at a remote frequency (4 kHz), using an adaptive task that tracked 75% correct performance. This group showed significant transfer of learning to the 1-kHz probe task ($P < 0.001$). A separate experiment (**Supplementary Fig. 2** online), however, showed that off-frequency training (with a 0-Hz difference) was less effective than same-frequency training.

DISCUSSION

The most surprising result of this study was that frequency discrimination learning occurred in the absence of a discriminable difference between the stimuli during training. This shows that perceptual learning need not involve fine-tuning a stimulus comparison mechanism. Instead, we suggest that training might improve the ability to attend to a task-specific stimulus dimension and the ability to access a low-level representation and make it available for further processing. A correlate of this phenomenon has been found in an animal study: changes in the frequency tuning of auditory cortex neurons in guinea pigs trained on a frequency discrimination task are similar whether or not the animals can behaviorally discriminate the stimuli[20].

Our results suggest a learning process that, when working most efficiently, has at least three influences. The first, supported by the partial frequency specificity, is primarily bottom-up and consists of response enhancement to the standard stimulus. Rapid, early learning does not transfer from an intensity discrimination task to a frequency discrimination task, even when the standard stimulus is identical for both discriminations[21]. We suggest that the second component in learning is top-down, switch-activated and dimensionally selective attention, as evidenced by the benefit of active engagement with the specific task. This would presumably exert its influence on hearing at a relatively low level of the system where neurons retain frequency selectivity. Changes in scalp-recorded event-related potentials and neuromagnetic fields, whose source was localized to the auditory cortex, have been observed while subjects are selectively attending to auditory pitch[22] or intensity[23,24] changes, compared to an unattended condition (ignoring the sounds). Such changes occur as early as 20 ms after stimulus onset[23], suggesting attentional influences on processing within the ascending central auditory system. A recent animal study showed rapid changes in the receptive field properties of primary auditory cortex neurons resulting from selectively attending to task-related cues in a target-frequency detection task[25].

We obtained evidence from the Tetris-playing groups for the contribution to learning of a third, broadly based arousal mechanism that is supra-modal but that can nevertheless exert an influence via tasks related to the training (for example, computer use). The small improvement in performance of the None control group, while nonsignificant, may also be attributed to some listeners in that group maintaining arousal through the training phase by, for example, reading.

We hypothesized that optimal learning will be achieved by using a training task that is neither too easy nor too difficult. Whereas our results support the first part of this hypothesis—reduced learning on the easy 400-Hz task—they do not support the latter. Rather, they suggest that effective auditory training tasks cannot be made too difficult, provided that sufficient, task-appropriate attention is engaged during learning.

METHODS

Subjects. We recruited 120 subjects from the University of Nottingham undergraduate population. Subjects all lacked previous experience in psychoacoustic experiments. They were recruited through advertisements and notices posted on public university notice boards and were paid for their participation. Listeners were excluded from participation if they failed to pass audiometric screening (20 dB HL or less bilaterally, at 0.5 kHz, 1 kHz, 2 kHz and 4 kHz), administered in accordance with the British Society of Audiology (BSA) standard, method A (ref. 26), or if they were unable reliably to discriminate 1 kHz and 1.2 kHz. There were no other exclusionary criteria. Informed consent was obtained from all participants. Both experiments were approved by the University of Nottingham, Department of Psychology Ethics Committee.

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Equipment. Listeners were tested individually in a sound-attenuating chamber and responded on a touch screen, which also visually cued the test intervals and provided positive and negative visual feedback for each trial. All experimental blocks were self paced. Stimuli were digitally generated using custom software running on a PC that also controlled the experiment. Stimuli were presented diotically via Sennheiser HD 25-1 headphones.

Procedure. Ten groups of 12 listeners were tested before (pre), during (mid) and after (post) eight 100-trial blocks (T1–T8) of frequency discrimination training (see **Fig. 1a**). In three training groups, the frequency difference between standard (1 kHz) and comparison tones was varied adaptively to track 50%, 75% and 95% correct levels of performance. In three other groups, the frequency difference was held constant throughout training at 0 Hz, 7 Hz and 400 Hz. One group underwent no training at all (None); these listeners were probed at half-hour intervals (time normally required to complete four training blocks). One group played a silent visuospatial game (Tetris; the game was a free download from http://sivut.koti.soon.fi/sodacan) and were probed on the auditory task at half-hour intervals. One group passively listened to a playback of a session from one of the 75% adaptive group listeners while playing Tetris (Passive); listeners were instructed to ignore the sounds and concentrate on the game. The final group trained at a standard tone of 4 kHz (adaptively tracking 75% correct performance), to test for frequency specificity of training. Training and probe trials used a three-interval, three-alternative forced choice ("oddball") protocol. Listeners were instructed to pick the odd-one-out of three consecutive sounds. Each of the three tones was 100 ms long (10-ms rise-fall times), and the tones were separated by a 500-ms silent interval. The interval containing the oddball was chosen randomly in each trial. Probes and adaptive training blocks used a maximum-likelihood algorithm[27]. Probe blocks targeted the 79%-correct point on the psychometric function, previously shown to yield thresholds quickly and reliably[17].

Statistical analysis. Initial comparison of the training groups using a General Linear Model (GLM) revealed an inhomogeneity of variance. We therefore used a Generalized Least Squares (GLS) model. GLS allows the homogeneity assumption of the GLM to be relaxed while still benefiting from the power of the distributional characteristics. This method was combined with a random-effects model to allow for significant between-subject variance. A more detailed description of the statistical analysis used can be found in the **Supplementary Methods** online.

Note: Supplementary information is available on the Nature Neuroscience website.

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AUTHOR CONTRIBUTIONS
S.A. and D.R.M. designed the study and prepared the manuscript, and all authors contributed to planning the experiments. A.I. collected most of the data. S.A. analyzed the data.

COMPETING INTERESTS STATEMENT
The authors declare competing financial interests (see the *Nature Neuroscience* website for details).

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