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Temporal Dynamics in Auditory Perceptual Learning: Impact of Sequencing and Incidental Learning

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Abstract

Training can improve perceptual sensitivities. We examined whether the temporal dynamics and incidental versus intentional nature of training are important. Within the context of a birdsong rate discrimination task, we examined whether the sequencing of pre-testing exposure to the stimuli mattered. Easy-to-hard (progressive) sequencing of stimuli during pre-exposure led to more accurate performance with the critical difficult contrast and greater generalization to new contrasts in the task, compared to equally variable training in either a random or anti-progressive order. This greater accuracy was also evident when participants experienced the progressively-sequenced stimuli in a different incidental learning task that did not involve direct auditory training. The results clearly show the importance of temporal dynamics (sequencing) in learning, and that the progressive training advantages cannot be fully explained by direct associations between stimulus features and the corresponding responses. The current findings are consistent with a hierarchical account of perceptual learning among other possibilities, but not with explanations that focus on stimulus variability.

Keywords

perceptual learning; cognitive training; discrimination; fading

The ability to distinguish perceptual events often depends on experience. This is known as perceptual learning (Goldstone, 1998). Perceptual learning is often enhanced by progressive training. Early experience with an easy discrimination can facilitate subsequent learning of a difficult version (e.g. Lawrence 1952). This phenomenon (referred to as the easy-to-hard effect, transfer along a continuum, or fading) directly contradicts the classical prediction that learning transfer should be optimal when testing exactly matches training (Morris, Bransford, & Franks, 1977). The advantages of progressive training have been demonstrated with a variety of species and sensory domains (e.g. Walker, Lee, & Bitterman, 1990).

Although, few studies have directly examined this phenomenon in humans (e.g. Liu, Mercado, Church, & Orduña, 2008; McLaren & Suret, 2000; Orduña, Liu, Church, Eddins, & Mercado, in press), this approach has been integrated into various procedures to maximize training. Progressive training has been used for speech discrimination (Tremblay & Kraus, 2002), non-native phonemic discrimination (McCandliss, Fiez, Protopapas, Conway, & McClelland, 2002), cognitive skills (Anderson, Corbett, Koedinger, & Pelletier, 1995), and attention (Shalev, Tsal, & Mevorach, 2007), to mention a few. Researchers interested in maximizing learning in humans have often assumed that progressive training is advantageous (for a counter example see Spiering & Ashby, 2008).

Why progressive training may be advantageous is debated. Early explanations based on associative learning hypothesized more efficient trade off relationships between excitatory and inhibitory response gradients (e.g. Logan, 1966). Elemental-associative and selective-attention theories assume that progression aids either the associative learning or attentional reweighting of the relevant features (e.g. Jameison & Morosan, 1989; McLaren, Kaye, & Mackintosh, 1989). Both theories assume that learning requires links between the perceptual inputs and responses. Progressive learning is advantageous because it aids the formation of the most useful associations, or directs attention to the most relevant features for responding. Hierarchical perceptual learning theories, on the other hand, assume that tasks of different difficulty initially engage different cortical levels – progressive training engages higher cortical areas early in training, changing their influence on perceptual learning as the task becomes harder (Ahissar & Hochstein, 1997). This view assumes that progressive training changes the way that stimuli are perceptually represented, and the representations guided by higher cortical levels are believed to be more distinguishable than representations formed at lower levels without higher level input. This view has many similarities to theories of selective-attention. However, because the higher level guidance can still be within the perceptual system, associations with responses are not necessary. All three views predict that progressive learning is advantageous. However, only the hierarchical view predicts that progressive exposure will be advantageous even when the stimuli and responses are not linked.

Unlike the previous perspectives, not all theorists are convinced that the sequence of training difficulty is important. Some have suggested that reports of an advantage simply reflect less frustration during training (Eisenberger, 1992; see Liu et al, 2008, for counter). Others suggest that progressive advantages only occur when they aid the discovery of the task relevant dimension. If humans are told what features are relevant, the sequence of training is un-important (Casale & Pashler, 2011). A number of recent studies that informed participants about the relevant dimension suggest this hypothesis cannot fully explain the findings (Liu et al, 2008; Orduña et al, in press). However, a somewhat more viable alternative explanation of progressive effects assumes that the advantage actually comes from using more variable stimulus sets during progressive training.

Researchers have focused on the critical role of variable training in maximizing learning. Recent interest in the perceptual variability of training sets arose within studies training phonemic contrasts in second languages (e.g. Lively, Pisoni, & Yamada, 1994). More recently, the issue of greater generalization with stimulus variability has also been addressed in animal learning (e.g. Wright & Katz, 2007), second-language vocabulary (e.g. Bancroft & Sommers, 2005), frequency discrimination (e.g. Amitay, Hawkey, & Moore, 2005), category learning (e.g. Hahn, Bailey, & Elvin, 2005), mathematical problem solving (e.g. Sanders, Gonzalez, Murphy, Pesta, & Bucur, 2002), and even tennis (Douvis, 2005). These studies show that the effects of stimulus variability depend on the type of task (Bancroft & Sommers, 2005; Hahn et al., 2005) and individual/group differences (Amitay et al., 2005; Sanders et al., 2002). In general, training variability leads to better learning of second-language contrasts and is comparable to progressive training (Iverson, Hazan, & Bannister, 2005). However, though variable training increases generalization, retention, and overall skill (Douvis, 2005; Sanders et al., 2002), it also slows initial learning, (Hahn et al., 2005) and is more helpful to some than others (Amitay et al., 2005; Sanders et al., 2002).

Only one previous study has directly compared the effectiveness of variable and progressive training. Iverson et al. (2005) trained Japanese speakers to learn the English /r/ - /l/ phoneme contrast using different procedures. One procedure progressively trained listeners to discriminate the third formant (F3) crucial for distinguishing this phoneme contrast. Another procedure simply used variable training with multiple speakers. Both procedures were found

to be equally advantageous, despite their vast differences. It remains unclear whether non-progressive but equally variable training along the F3 dimension would have produced the same efficiency. It is important to disentangle this because progressive training is by definition more variable than constant training. Therefore, the benefits of progressive training may result from the increased variability. The hierarchical, elemental-associative, and selective-attention accounts clearly predict that the temporal sequencing, not just the variability of the training, is vital. However, of these three accounts, only the hierarchical account clearly predicts that this will continue to be true when the discrimination is not trained.

Experiment 1

In experiment 1, we examined people's ability to discriminate birdsongs played-back at varying rates. Four types of training (progressive, constant, random, and anti-progressive) were compared to dissociate the impact of progressive sequencing from increased variability. Half of the participants in each learning condition were intentionally trained (asked to discriminate birdsong rates) and half were incidentally exposed to the stimuli (asked to judge whether or not they thought they would recognize the particular birdsong during a memory test). This incidental learning procedure is similar to the learning phase of artificial grammar (e.g., Reber, 1967) and dot distortion categorization tasks (e.g., Knowlton & Squire, 1993) where participants are exposed to stimuli, but are not asked to focus on the relevant aspects of the stimuli. This allowed us to determine whether associations between the stimuli and responses were necessary for a progressive advantage.

The theory of reverse hierarchy predicts that progressive training will produce the best performance because perceptual learning is guided by higher cortical areas, producing more differentiated representations. The constant and random conditions should fall somewhere in between because neither will recruit higher level processes, and the anti-progressive group should show the worst performance because higher cortical levels are being recruited at the wrong time. In addition, because the progressive advantage should reflect changes in stimulus representation as a result of apparent contrast, rather than an association with a response, the theory predicts that progressive sequencing should show a similar advantage, whether the discrimination is trained or incidentally exposed. There may be an overall advantage of training, but the pattern of advantage across sequencing types should be the same. On the other hand, if the "progressive" advantage is actually produced by stimulus variability, the progressive, random, and anti-progressive conditions should be similar, all sharing an advantage over the constant condition. If associations or selective attention are necessary, then only the intentionally trained conditions should show a progressive advantage.

Method

Participants—Ninety-nine introductory psychology students from the University at Buffalo, SUNY, participated as partial fulfillment of their course requirements. Twelve participants were assigned to each of the eight between-participants conditions (2 learning presentation by 4 sequencing type). Three participants were dropped and replaced for having missing values for more than 6 trials. Final data analyses included 96 participants.

Stimuli & Apparatus—The stimuli were constructed from a publicly available recording of superb lyre bird's song from the Macaulay Library at the Cornell Lab of Ornithology. A one second section was selected containing various frequency and amplitude modulations. Variants of the original were created using the time stretch function in Cool Edit Pro 2.0, to make stimulus versions that were 10%, 20%, 30%, 40%, 50%, and 70% faster than the original. Increasing rate in this fashion led to a number of concurrent changes, such as

shorter stimulus duration and steeper frequency and amplitude modulations. Such complex changes resulted in a variety of acoustic cues that could be used for discrimination. Spectrograms of the original stimulus and the 20% faster version are shown in Figure 1.

Stimuli were presented, and keyboard responses collected, using DMDX (Forster & Forster, 2003) running on IBM-compatible desktop computers. Audio-Technica ATH-M40fs headphones presented the stimuli at normal conversational levels.

Design & Procedures—A 2 (learning presentation: training versus exposure) $\times$ 4 (sequencing type: progressive, constant, random, and anti-progressive) between-participants design was used. The dependent variable was discrimination performance with either the critical experienced contrast or novel contrasts not heard during learning.

All participants completed one learning session followed by a test with a break for instructions. Participants were presented with birdsongs and asked to make a two-alternative forced-choice response for each stimulus. During the test and the intentional training, participants decided whether the presented song was the “slow” birdsong (the original recording) or a faster version. Participants responded with keyboard presses, and they were told to guess if unsure. They received no feedback during test. Participants in intentional training conditions received accuracy feedback regarding their trial performance, and the first trial was their first exposure to any stimuli. Participants in incidental exposure conditions heard the same birdsongs, but were asked to judge whether they were likely to recognize the stimuli during a later memory test. No feedback was given in exposure conditions. Participants had 5 seconds to respond to all trials. The inter-trial interval was 1.5 seconds.

Learning sessions had 60 trials, half were “slow” (the original recording; one speed only), and half were “fast” (faster versions; varied depending on training type). During constant training, the “fast” stimuli were always the 20% faster version. During progressive training, participants cycled through 4 stages of 15 trials. Each stage compared the “slow” trials with a different speed of “fast” trials, from 70%, 50%, 30%, to 20% faster in the last stage, with no breaks indicating the transitions between stages. During random training, participants heard the same stimuli, but the stimuli were presented in a random order rather than stages. During anti-progressive training, participants heard the stimuli in the opposite order (20%, 30%, 50%, and 70% faster).

The test was identical across conditions. Half the 100 trials were “slow” and half “fast”. Three versions of “fast” stimuli – 10%, 20% and 40% faster – were used during testing. This allowed examination of the effects of sequence on the most difficult experienced discrimination (the critical contrast), and both easier and harder novel discriminations. All items within learning stages and test were presented in a pseudorandom order (no more than five identical stimuli in a row).

Results

All significance tests were two-tailed using an α level of .05. Percent correct and the discriminability index (d') for each group's test performance on the critical contrast (20% rate difference) and the novel contrasts (10% and 40% rate difference) are presented in Table 1. To correct for potential response biases, all statistical comparisons used d' as the dependent measure.¹

¹Hit rates and false alarm values were corrected following Wixted and Lee (2004). False alarms of zero were replaced by $1/(2 \times \text{total trials})$. Hit rates of 100 were replaced by $1 - [1/(2 \times \text{total trials})]$.

A 2×4 between-participants analysis of variance (ANOVA) on the critical contrast found a significant main effect of sequencing type, $F(3, 88) = 11.663$, $p < .001$, $\eta^2 = .276$. The main effect of learning presentation was marginally significant, $F(1, 88) = 3.59$, $p = .061$, $\eta^2 = .028$, suggesting a small advantage of intentional training. The interaction was not significant, $F < 1$. Two planned non-orthogonal contrasts were performed to determine whether the data fit the patterns of performance with the different sequencing types predicted by the reverse hierarchy (RH) (progressive > constant = random > anti-progressive) and the variability hypotheses (VH) (progressive = random = anti-progressive > constant). The contrast testing the RH trend was significant, $F(1, 88) = 34.045$, $p < .001$, $\eta^2 = .269^2$. The contrast testing the VH trend was not, $F < 1$. Planned comparisons between conditions showed that the progressive groups performed better than the constant groups, $t(46) = 3.256$, $p = .002$, *Cohen's d* = 0.961, and the random groups performed significantly better than the anti-progressive groups, $t(46) = 2.093$, $p = .039$, *d* = 0.616. The constant groups were numerically but not statistically better than the random groups, $t < 1$.

Even though there was no significant interaction between learning and sequencing type, ($F < 1$), it was theoretically important to know whether the RH predicted sequence type pattern was significant even when only the exposure condition was examined. To this end, a one-way ANOVA was performed on just the participants in the incidental condition. The main effect of sequence type was significant, $F(3, 44) = 4.934$, $p = .005$, $\eta^2 = .252$. Planned contrasts showed that the RH trend was significant, $F(1, 44) = 14.328$, $p < .001$, $\eta^2 = .243^3$, and the VH trend was not, $F < 1$. Planned comparisons showed that the progressive group performed marginally better than the constant group, $t(22) = 2.001$, $p = .051$, *Cohen's d* = 0.855, and the random group performed numerically but not statistically better than the anti-progressive group, $t(22) = 1.294$, $p = .203$, *d* = 0.552.

To evaluate how learning generalized to novel stimuli, we performed a $2 \times 2 \times 4$ mixed ANOVA on the *d's* for the 10% and 40% faster stimuli. Analyses revealed significant main effects of sequencing type, $F(3, 88) = 8.519$, $p < .001$, $\eta^2 = .054$, learning presentation, $F(1, 88) = 15.271$, $p < .001$, $\eta^2 = .032$, (higher in the trained groups), and stimuli, $F(1, 88) = 313.815$, $p < .001$, $\eta^2 = .540$, (better with 40% faster stimuli). There were also significant interactions between stimuli and learning presentation, $F(1, 88) = 6.380$, $p = .013$, $\eta^2 = .011$, and stimuli, learning presentation, and sequence type, $F(3, 88) = 3.586$, $p = .017$, $\eta^2 = .019$. All other interactions were non-significant, $F_s < 1$. Planned contrasts revealed a significant RH trend, $F(1, 88) = 5.596$, $p = .022$, $\eta^2 = .081^4$, but no VH trend, $F < 1$. Planned comparisons indicated better generalization in the progressive groups than in the constant groups, $t(46) = 3.555$, $p < .001$, *d* = 1.048. However, the random groups generalized numerically but not statistically better than the anti-progressive groups, $t < 1$.

To better understand the interaction between the stimuli and learning presentation and the three-way interaction, separate 2×2 between-participant ANOVA's were performed on the 40% and 10% faster stimuli. For the easier stimuli, there were significant main effects of sequencing type, $F(3, 88) = 4.393$, $p = .006$, $\eta^2 = .107$, and learning, $F(1, 88) = 16.838$, $p < .001$, $\eta^2 = .136$, (trained was better), and a non-significant interaction, $F(3, 88) = 1.822$, $p = .149$, $\eta^2 = .044$. To further understand the 3-way interaction, planned contrasts testing the sequencing hypotheses for each learning condition separately found a significant RH trend in the exposure, $F(1, 44) = 11.772$, $p = .001$, $\eta^2 = .206^5$, but not the trained group, $F < 1$. This

²The residual sequencing type main effect not explained by the RH trend contrast was not significant, $F < 1$, suggesting that the contrast largely explained the main effect.

³The residual sequencing type main effect not explained by the RH trend contrast was not significant, $F < 1$, suggesting that the contrast largely explained the main effect.

⁴The residual sequencing type main effect not explained by the RH trend contrast was significant, $F(2, 88) = 9.160$, $p < .001$, $\eta^2 = .115$, suggesting (like the three way interaction) that not all performance was explained by the RH trend.

probably reflects a ceiling effect in the better performing trained group with the easy stimulus contrast.

For the more difficult stimuli, there was a significant main effect of sequencing type, $F(3, 88) = 6.131$, $p < .008$, $\eta^2 = .161$. The main effect of learning, $F < 2$, and interaction, $F(3, 88) = 2.077$, $p = .109$, $\eta^2 = .054$, were non-significant. Planned contrasts for each learning condition found a significant RH trend for the trained, $F(1, 44) = 22.105$, $p < .001$, $\eta^2 = .310$ ⁶, but not the exposure group, $F < 2$. This may reflect a floor effect in the incidental condition with the most difficult contrast. No groups showed significant VH trends, all F s < 1 .

Discussion

The results show that direct associations between relevant stimulus features and a particular response are not necessary for the progressive advantage to occur. Progressively exposed individuals showed a performance advantage even when they had no training about rate discrimination. The results also seem to support the idea that the sequence not just the variability of the exposure is important. However, there is one possible problem with this interpretation of the critical contrast results in the current experiment. There is a potential confound between the sequence of training and the probability that the last item heard during training was the fast item from the critical contrast. Though the probability of the last item being that item is the same for the progressive and constant conditions (50%), it is lower for the conditions with equal variability (0% for anti-progressive, and 12.5% for random). Though these complex sound stimuli are unlikely to be retained in a short-term memory buffer for more than 10–20 seconds (e.g. Cowan, 1984), and the delay for the participants to read the screen and press the space bar to begin the test requires more than 20 seconds, it is possible that some kind of priming for recent information could operate to give the progressive condition an advantage over the other variable conditions with the critical contrast. The operation of the combination of variability and an advantage related to the most recent stimulus could explain the current results with the critical contrast. How one explains the generalization results with this sort of priming from the most recent stimulus is less obvious. However, a less confounded interpretation of the critical contrast is important to understanding the progressive effect.

Previous research has shown that a progressive over constant training advantage is still evident after a one day delay (Liu et al, 2008), clearly showing that it operates on long-term learning not just performance in the short-term. However, this research cannot disentangle sequencing and variability of training. In order to assess this combined variability and priming hypothesis, we conducted experiment 2.

Experiment 2

In experiment 2, we compared equally variable training conditions with three different sequences (progressive, random, anti-progressive), while controlling the probability that the last training item was the stimuli used for the critical contrast.

Method

Participants—Thirty-one introductory psychology students from the University at Buffalo, SUNY, participated as partial fulfillment of their course requirements. Ten

⁵The residual sequencing type main effect not explained by the RH trend contrast was not significant, $F < 1$, suggesting that the contrast largely explained the main effect.

⁶The residual sequencing type main effect not explained by the RH trend contrast was not significant, $F(2, 44) = 2.613$, $p < .079$, $\eta^2 = .073$, suggesting that the contrast mostly explained the main effect.

participants were assigned to each of three between-participants conditions (progressive, random, and anti-progressive training). One participant was dropped and replaced for making one response more than 80% of the time. Final data analyses included 30 participants.

Design—The experiment employed a simple between-participants design. The independent variable was sequencing type (progressive, random, and anti-progressive). The dependent variables were discrimination of the critical difficult contrast and the novel contrasts.

Stimuli & Procedures—The stimuli and procedures were the same as experiment 1 except: 1) for simplicity of comparison and to maximize statistical power, only three intentionally trained conditions were used (progressive, random, anti-progressive); 2) in every condition, the last six items during training had a 50% probability of being the 20% faster item. Overall and relative number of times the particular stimuli were played was identical across conditions and to experiment 1.

Results and Discussion

Percent correct and the discriminability index (d') for each group's test performance on the critical contrast and novel contrasts are presented in Table 2. All statistical comparisons used d' as the dependent measure.

A one-way ANOVA on the critical contrast found a significant main effect of sequencing type, $F(2, 27) = 5.796$, $p = .008$, $\eta^2 = .300$, showing differences in participants' discrimination ability after different sequences of training. A planned contrast revealed that the data fit the RH predicted linear trend (progressive > random > anti-progressive), $F(1, 27) = 11.265$, $p = .002$, $\eta^2 = .292^7$. Planned comparisons between conditions showed that the progressive group performed better than the random group, $t(18) = 2.174$, $p = .039$, *Cohen's d* = 1.025, and the random group performed numerically but not statistically better than the anti-progressive group, $t(18) = 1.18$, $p = .247$, *Cohen's d* = .557.

A 2×3 mixed ANOVA exploring the novel contrasts found significant main effects of sequence type, $F(2, 27) = 6.470$, $p = .005$, $\eta^2 = .048$, and stimuli, $F(1, 27) = 251.060$, $p < .001$, $\eta^2 = .838$. The interaction was not significant, $F(2, 27) = 2.152$, $p = .139$, $\eta^2 = .014$. The planned contrast revealed a significant RH linear trend, $F(1, 27) = 12.922$, $p = .001$, $\eta^2 = .324^8$.

These results show that participants who experienced a progressive sequence during training showed better discrimination of the critical contrast even when the probability of hearing it as the last item was equal across conditions. The progressive sequence not just whether it was the last item heard during training seems to be important.

General Discussion

The results support the idea that temporal dynamics (easy to hard sequencing) confer an advantage in learning. Among all sequencing types, progressive showed the highest discrimination of the critical contrast, as well as the best generalization to novel contrasts even when participants were not intentionally trained to discriminate rate. Most importantly, although participants experienced the exact same stimuli with identical stimulus variability

⁷The residual sequencing type main effect not explained by the RH trend contrast was not significant, $F < 1$, suggesting that the contrast largely explained the main effect.

⁸The residual sequencing type main effect not explained by the RH trend contrast was not significant, $F < 1$, suggesting that the contrast largely explained the main effect.

and equal probabilities of having the last trained item be the critical contrast, progressive still produced better learning than either anti-progressive or random sequencing. This makes it unlikely that the advantage of progressive training comes from increased stimulus variability. This was important to establish because previous research has confounded the temporal dynamics and the variability of training (e.g. Liu et al, 2008; McLaren & Suret, 2000), and variability and interleaved learning are both known to positively affect skill learning (e.g Schmidt & Bjork, 1992; Lively et al, 1994). Not only do random and anti-progressive sequencing lack the advantage of progressive, anti-progressive significantly hurts critical contrast discrimination compared to constant, and adding random variability does not increase performance compared to having more training with the hard discrimination. At least, in this context, increasing variability does not seem to be helpful.

Progressive sequencing also generalized best to novel discriminations, confirming past reports that progressive training with complex sounds can enhance discrimination of novel sounds (e.g., Merzenich, et al, 1996). Likewise, this advantage can't be explained by stimulus variability during training, because neither the anti-progressive nor the random groups showed greater generalization than constant groups. The findings highlight the importance of temporal sequencing for perceptual learning.

Finally, these results show that the advantage of progressive training cannot be explained by simple versions of either elemental-associative or selective-attention theories that assume the advantage is caused by learning task-relevant features. The fact that progressive sequencing improved rate discrimination with incidental exposure shows that associations between the stimulus properties and the relevant response are not necessary for learning.

Where does this leave our understanding of the temporal dynamics of perceptual learning? These results together with previous findings (Liu et al, 2008; Orduña et al, in press) make it clear that the sequence of exposure to the stimuli is important for improving resolution and generalizing distinctions to novel contrasts. These progressive effects don't seem to be explained by confounds with motivational factors (Eisenberger, 1992), attentional foci (Casale & Pashler, 2011), or stimulus variability.

Why is this sequence advantageous to perceptual learning? Elemental-associative and selective-attention theories have been important to our understanding of a variety of phenomena, and their ability to characterize a wide range of findings with relatively simple models has been illuminating (e.g. McLaren et al, 1989; Petrov, Doshier, & Liu, 2005). However, the current experiments suggest that they are not (in their most straightforward form) sufficient to fully explain the progressive advantage.

On the other hand, because reverse hierarchy theory (Ahissar & Hochstein, 1997) allows top down perceptual influences to play a role on lower level perception without the need for decision/response level processes, it can account for the current results. That does not mean that this theory can fully characterize all of the data relating to progressive learning. Because of the way that reverse hierarchy theory assumes top down processes influence perceptual differentiation, the "progressive" effect is really an "anchoring" effect. Unlike elemental-associative theories, all of the advantage of sequencing is carried by the initial experience with the easy discrimination and the rest of the progression should be relatively unimportant. Both early research with animals (e.g. Lawrence, 1952), and recent research with humans (Radell, Winiewski, Church, & Mercado, submitted) show that progressive produces better learning than anchored training. These findings indicate that like elemental-associative and selective-attention theories, reverse hierarchy theory is also not sufficient to fully explain the progressive advantage.

Further theoretical advances are likely needed. Simple elemental representations of perceptual information without combinatorial properties that can be changed by experience may not fully capture the changes that training with complex stimuli generates. At the same time, theories that rely upon quick all-or-none top-down learning whether from within perception or at a decision level (Ahissar & Hochstein, 1997; Casale & Pashler, 2011) may also be inadequate. We believe it is time to consider models that allow for incremental change (see Saksida, 1999) to the representation of perceptual information at multiple levels (not just input and output). It will likely be important for future models to test different multilevel architectures to fully account for how perception and perceptual representations change with experience.

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Figure 1.

Spectrograms of the original and the 20% faster stimulus (critical contrast). Other stimuli had similar spectral structure, but were time stretched to be 10%, 30%, 40%, 50%, and 70% faster than the original.

Mean Percent Correct (%) and Discriminability Index (d') of the Critical Contrast and Novel Contrasts by Learning Presentation and Sequencing Type in Experiment 1.

Table 1

Learning Contrasts	Training			
	Progressive	Constant	Random	Anti-progressive
Critical				
Training				
20%	%	86	79	74
20%	d'	2.170	1.536	1.086
Exposure				
20%	%	87	75	70
20%	d'	1.899	1.344	0.852
Novel				
Training				
40%	%	92	86	84
40%	d'	2.562	2.139	2.101
10%	%	73	61	57
10%	d'	1.113	0.449	0.215
Exposure				
40%	%	97	86	89
40%	d'	2.315	1.447	1.738
10%	%	62	60	57
10%	d'	0.459	0.426	0.186

Table 2

Mean Percent Correct (%) and Discriminability Index (d') of the Critical Contrast and Novel Contrasts by Sequencing Type in Experiment 2.

	Training	Progressive	Random	Anti-progressive
<u>Contrast Type</u>				
Critical 20%				
%	87		79	73
d'	1.976		1.395	1.240
Novel 40%				
%	94		91	83
d'	2.656		2.517	1.920
Novel 10%				
%	67		60	59
d'	0.716		0.335	0.343