

Research Article

Auditory Change Detection

Simple Sounds Are Not Memorized Better Than Complex Sounds

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ABSTRACT—Previous research has shown that the detectability of a local change in a visual image is essentially independent of the complexity of the image when the interstimulus interval (ISI) is very short, but is limited by a low-capacity memory system when the ISI exceeds 100 ms. In the study reported here, listeners made same/different judgments on pairs of successive “chords” (sums of pure tones with random frequencies). The change to be detected was always a frequency shift in one of the tones, and which tone would change was unpredictable. Performance worsened as the number of tones increased, but this effect was not larger for 2-s ISIs than for 0-ms ISIs. Similar results were obtained when a chord was followed by a single tone that had to be judged as higher or lower than the closest component of the chord. Overall, our data suggest that change detection is based on different mechanisms in audition and vision.

Although audition and vision are very different perceptual modalities, they resemble each other in certain respects. For instance, similar Gestalt laws of perceptual organization operate in vision (Wertheimer, 1923) and in audition (Bregman, 1990). The temporal dynamics of perceptual organization also seem to be similar in the two modalities (Pressnitzer & Hupé, 2006). In the experiments reported here, we assessed whether people detect changes in visual and auditory stimuli in similar ways.

The detection of a change following an interruption requires some form of memory. In vision, two forms of memory may be used for change detection: *iconic memory* and *visual short-term memory* (VSTM). Iconic memory is retinotopic. Its capacity is essentially unlimited, but the duration of storage in iconic memory is brief. Thanks to iconic memory, as long as two

complex visual stimuli occur in the same position, a small local change between them can be detected easily even when this change is unpredictable; however, the interstimulus interval (ISI) must not exceed about 100 ms (Pashler, 1988; Phillips, 1974; Stelmach, Bourassa, & Di Lollo, 1984). VSTM, in contrast, is not retinotopic and stores information much more durably than iconic memory does (Phillips, 1974); however, its capacity is limited to at most four or five objects (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997). The low capacity of VSTM is one cause of the *change blindness* of human observers when they have to compare two complex images separated by more than a few 10s of milliseconds (Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997).

It is commonly believed that there is no major difference between auditory memory and visual memory: Iconic memory and VSTM are thought to have auditory counterparts with the same properties (Cowan, 1984; Massaro & Loftus, 1996; Vischer, Kaplan, Kahana, & Sekuler, 2007). It has also been claimed that change blindness has an auditory equivalent, “change deafness” (Eramudugolla, Irvine, McAnally, Martin, & Mattingley, 2005; Vitevitch, 2003). In contrast with such views, the experiments reported here suggest that the mechanisms of change detection are dissimilar in vision and audition. As mentioned earlier, the detection of a local change in a static image benefits from a high-capacity memory if the pre- and postchange images are separated by a very short ISI, but is limited by a low-capacity memory if the ISI exceeds 100 ms. As a consequence, the complexity of the prechange image (the number of its perceptual elements) has little effect on the detectability of a local change when the ISI is very short, but has a dramatic effect when the ISI exceeds 100 ms (Phillips, 1974). We show here that when the stimuli are sounds (random chords) rather than images, one does not observe a similar interaction. The effect of the spectral complexity of the prechange sound on the detectability of a spectrally local change does not depend on the ISI, for ISIs ranging from 0 ms to at least 2 s. It is more difficult to detect a change in one tone among many tones than to

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detect a change in one tone among few tones, and the difficulty of change detection increases with the ISI. However, the absence of an interaction between spectral complexity and ISI implies that it is not more difficult to *remember* many tones than to remember few tones. To that extent, auditory memory appears to make change detection easier in audition than in vision.

EXPERIMENTS 1 AND 2

Experiments 1 and 2 transposed one of the visual experiments reported by Phillips (1974) to the auditory domain. On each trial, the listener was presented with two successive “chords” (sums of pure tones) and had to indicate if they were identical or not. When the two chords were not identical, the difference resulted from a frequency shift in a single, randomly selected tone, as in the example given in Figure 1 (left). Performance, measured using the detectability index d' , was examined as a function of two variables: the number of tones in each chord (N) and the ISI.

Method

Participants

Four audiometrically normal listeners, including authors L.D. and W.T., participated in both experiments. Each listener was initially trained in the task for at least 4 hr. This training period was used to adjust the magnitude of the frequency shifts to listener-specific values, so as to prevent floor or ceiling effects.

Stimuli

The pure tones forming each chord had a duration of 600 ms and a nominal sound pressure level (SPL) of 65 dB; they were gated

on and off with 20-ms raised-cosine amplitude ramps. In the first chord of each trial, adjacent tones were separated by frequency intervals varying randomly (and uniformly, on a logarithmic frequency scale) between 3 and 6 semitones (1 semitone = 1/12 octave). The first chord was randomly positioned in a 5-octave frequency range (125–4000 Hz) and was followed by the second chord after a silent ISI of 0, 250, 750, or 2,000 ms. From the first chord to the second chord, the probability of a frequency shift in one tone was .5; when such a shift occurred, it was equiprobably positive or negative. The tones forming the two chords had random initial phases, but any tone appearing in both chords had the same initial phase in these two chords.

In Experiment 1, the value of N was 4, 7, or 12. The probability of a shift was equal for all tones, and the magnitude of the shifts, Δ_s , was fixed for a given listener. As Figure 2a indicates, Δ_s was equal to 0.50 semitone for 3 listeners and 0.70 semitone for the 4th listener.

In Experiment 2, the value of N was either 4 or 12, and only “inner” tones could shift (so that only 2 tones could shift when N was 4, whereas 10 tones could shift when N was 12). In this experiment, moreover, we used larger Δ_s values for 12-tone chords than for 4-tone chords, as indicated in Figure 2b, in order to obtain similar overall levels of performance for these two conditions.

The stimuli were digitally generated with a sampling rate of 44.1 kHz and a 24-bit amplitude quantization. They were presented binaurally via headphones (Sennheiser HD265).

Procedure

Trials were arranged in blocks of 40, with N and the ISI fixed within each block. The listener, seated in a sound-attenuating

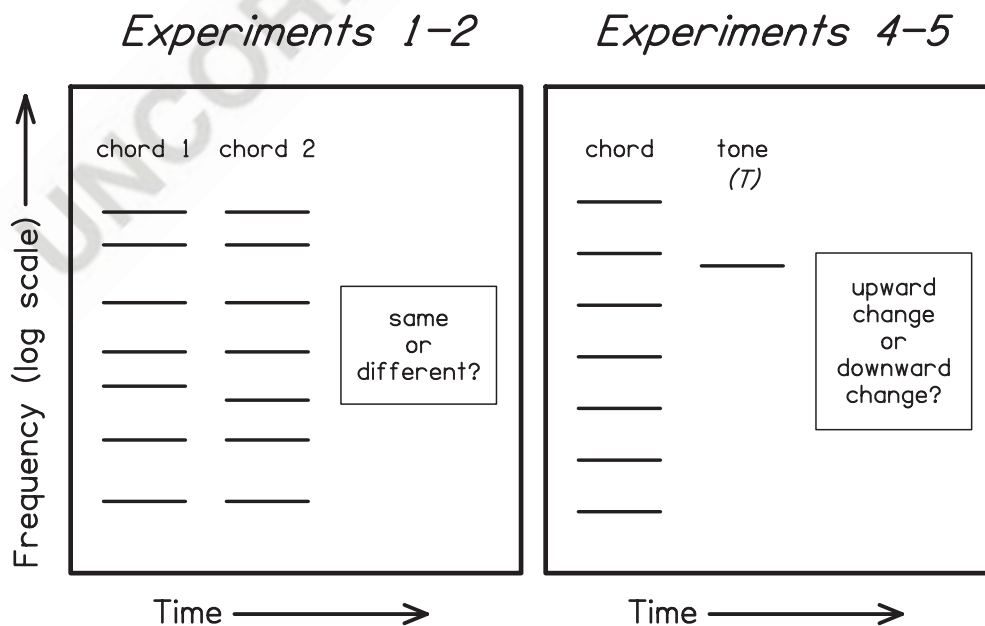


Fig. 1. Illustration of the task used in Experiments 1 and 2 (left) and in Experiments 4 and 5 (right). Dashes represent pure tones. The correct responses on these two trials are “different” (left) and “downward” (right).

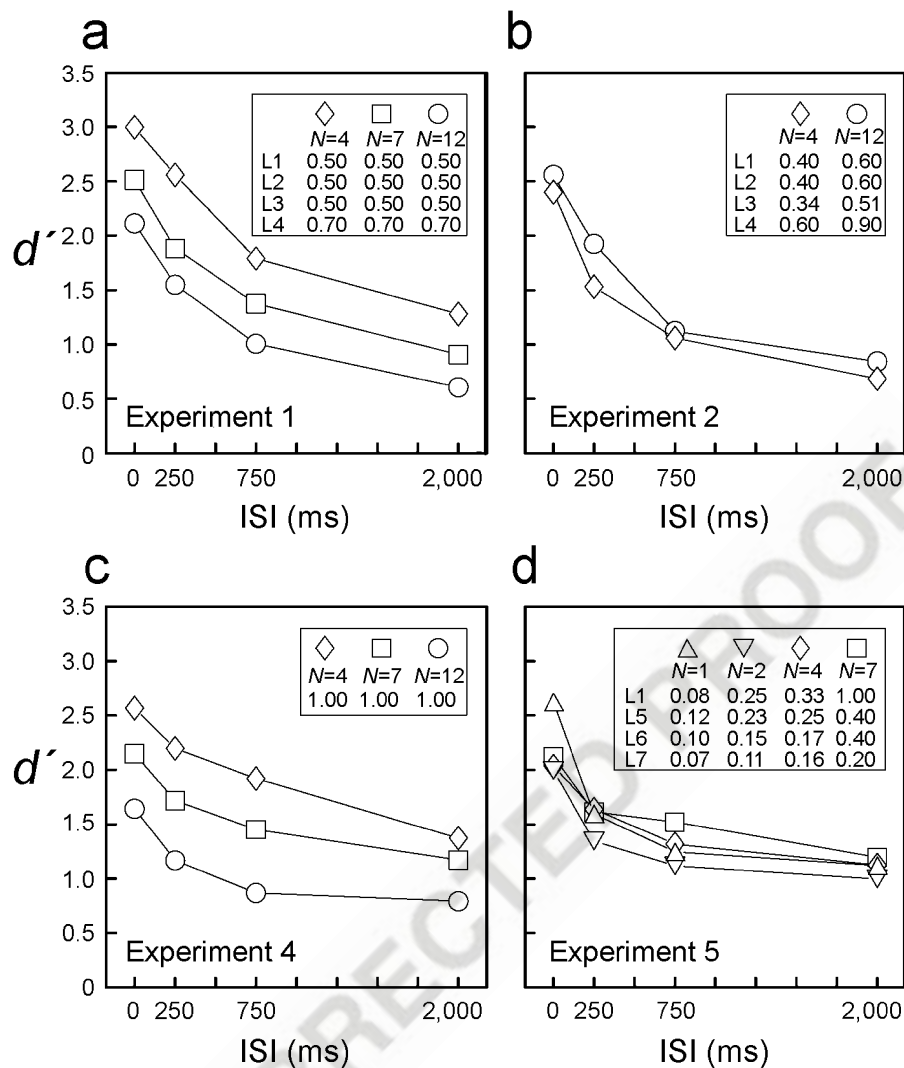


Fig. 2. Results of Experiments 1, 2, 4, and 5: mean values of d' as a function of the interstimulus interval (ISI) and the number of tones in the chords (N). For each experiment, a table displays the magnitude of the frequency shifts, Δs (in semitones), as a function of N for each tested listener (L1, L2, . . . L7; in Experiment 4, Δs did not vary across listeners).

booth, gave his or her responses (“same” or “different”) by clicking a computer mouse on two virtual buttons. When the ISI was 0 or 250 ms, the delay separating a response from the first chord of the next trial was 600 ms; otherwise, this delay was equal to the ISI. Every session included one block of trials in each of the 12 (Experiment 1) or 8 (Experiment 2) possible conditions, which were randomly ordered. Each experiment consisted of 12 sessions.

Results

For each listener and experimental condition, we computed d' from the responses given on the 480 trials. The mean values of d' across listeners are displayed in Figures 2a and 2b.

In Experiment 1, d' decreased significantly as the ISI increased, $F(3, 9) = 35.6$, $p < .001$, $p_{\text{rep}} > .998$ (see Killeen, 2005), $\eta^2 = .92$, and as N increased, $F(2, 6) = 123.0$, $p < .001$,

$p_{\text{rep}} > .998$, $\eta^2 = .98$, but these two factors did not interact significantly, $F(6, 18) < 1$. The three curves displayed in Figure 2a are indeed nearly parallel.

In Experiment 2, we found, again, a strong main effect of ISI, $F(3, 9) = 151.1$, $p < .001$, $p_{\text{rep}} > .999$, $\eta^2 = .98$. However, because of the covariation of Δs and N , the overall level of performance was not better when N was 4 than when N was 12, unlike in Experiment 1. Nevertheless, there was again no significant interaction of N and ISI, $F(3, 9) < 1$. Figure 2b shows that nearly identical results were obtained for the two values of N .

EXPERIMENT 3

When a pure tone is gated on or off abruptly rather than smoothly, the resulting discontinuity produces spectral splatter and is audible as a salient click. In Experiments 1 and 2, we

gated each chord with 20-ms amplitude ramps in order to avoid such effects. Because of the ramps, however, the two chords presented on a given trial were separated by an audible gap even when the nominal ISI was 0 ms. In addition, the ramps still produced, inevitably, some spectral splatter. Previous studies have shown that the trace of a visual stimulus in iconic memory is easily masked by a subsequent visual stimulus that is different (Averbach & Coriell, 1961; Becker, Pashler, & Anstis, 2000; Phillips, 1974). It is conceivable that in Experiments 1 and 2, an echoic, iconlike trace of the first chord was masked by the ramp placed at the end of this chord, as well as by the initial ramp of the next chord when the ISI was short. Masking might have been produced by the ramps themselves, as well as by the associated spectral splatter. If the echoic trace of the first chord was masked, performance would have been limited by the low capacity of short-term memory whatever the ISI. This hypothesis accounts for the fact that d' depended on N even when the nominal ISI was 0 ms.

We carried out Experiment 3 to determine if the ramps used in Experiments 1 and 2 indeed had a deleterious effect on change detection, especially when the nominal ISI was 0 ms.

Method

Participants

Two of the authors (L.D. and M.S.) and 2 audiometrically normal students participated in the experiment. They were initially trained in the task for at least 4 hr.

Stimuli and Procedure

As in Experiment 2, participants were asked to make same/different judgments on pairs of 600-ms chords consisting of 4 or 12 pure tones presented at 65 dB SPL. The frequencies of the tones forming the first chord were selected exactly as before, and the changes to be detected resulted again from a positive or negative frequency shift in a randomly chosen component of the first chord. The direction of the shifts was again randomly varied, but each shift now had a magnitude of 0.40 semitone. As in Experiment 1, the possibility of shifting was not restricted to inner components of the chord.

For each value of N (4 or 12), there were two experimental conditions: *ramped* and *nonramped*. In the ramped condition, the two chords presented on each trial were temporally contiguous (so that the nominal ISI was 0 ms), but they were gated on and off with the same amplitude ramps used in Experiments 1 and 2. The initial phases of the tones were also manipulated as before. The upper part of Figure 3 illustrates a ramped transition for a single tone shifted in frequency.

In the nonramped condition, the two chords were also temporally contiguous, but there were no amplitude ramps around the transition point. When no frequency shift occurred, the listener was actually presented with a single, continuous chord 1,200 ms in duration. When the frequency of one tone was

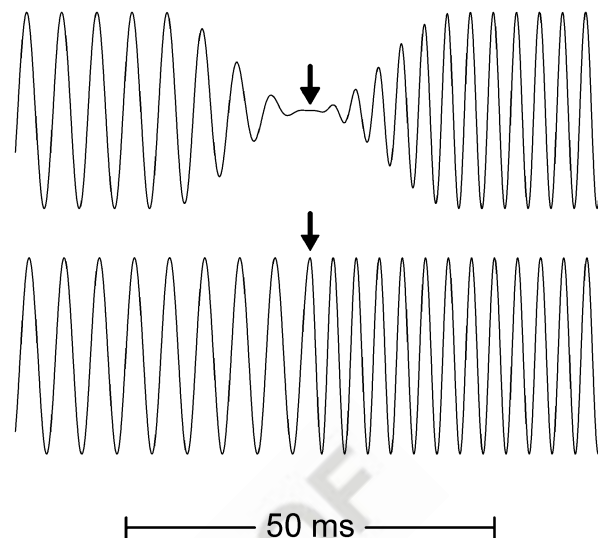


Fig. 3. Transitions between a 210-Hz tone and a 320-Hz tone. The illustration at the top is an example of a ramped transition, and the illustration at the bottom is an example of a nonramped transition. The arrows indicate the instant at which the frequency shift occurs.

shifted, the shift occurred instantaneously, after exactly 600 ms, but always at an amplitude peak, as in the example given in Figure 3 (lower illustration). The frequency shift produced no discontinuity in the waveform, nor in its first derivative. However, a discontinuity was produced in the waveform's second derivative, and this discontinuity generated some spectral splatter.

Trials were arranged in blocks of 40, with N and the transition type (ramped vs. nonramped) fixed within each block. The four possible types of blocks were run in counterbalanced order, 10 times for each listener.

Results and Discussion

We processed the data in the same manner as in Experiments 1 and 2. As Table 1 indicates, performance was better when the value of N was 4 than when it was 12, and transition type affected performance appreciably when N was equal to 4, but not when N was equal to 12. The main effect of transition type was not statistically significant, $F(1, 3) = 4.3, p = .13, p_{\text{rep}} = .78, \eta^2 = .59$, but the main effect of N was significant, $F(1, 3) = 12.3, p = .04, p_{\text{rep}} = .89, \eta^2 = .80$, as was the interaction of the two factors, $F(1, 3) = 15.7, p = .03, p_{\text{rep}} = .91, \eta^2 = .84$.

The most important finding is that when N was large (12), performance was not markedly poorer in the ramped condition

TABLE 1
Mean Values of d' in Experiment 3

Number of tones in each chord (N)	Condition	
	Ramped	Nonramped
4	1.74	2.19
12	1.34	1.47

than in the nonramped condition. This is remarkable because the nonramped condition clearly minimized the negative effects of memory limitations on change detection (although it is conceivable that, in this condition, the small transient spectral splatter produced by a frequency shift affected the internal representation of the first chord). The fact that performance was nearly the same in the ramped condition strongly suggests that the negative effects of memory limitations were also minimized in the ramped condition. Therefore, the results of this experiment do not support the hypothesis that in Experiments 1 and 2, the observed effect of N when the nominal ISI was 0 ms was due to a deleterious influence of the ramps on memory.

When N was equal to 4, however, we found an advantage of the nonramped condition over the ramped condition. This advantage presumably originated from the transient spectral splatter produced by a frequency shift in the nonramped condition. Detecting this transient spectral splatter was sufficient for the listener to know that the correct response was “different,” whereas in the ramped condition, the transition between the two chords provided no cue. The spectral splatter was apparently less detectable for 12-tone chords than for 4-tone chords, probably because the 12-tone chords had much larger bandwidths.

EXPERIMENTS 4 AND 5

A successful same/different judgment on two successive (and noncontiguous) chords may not require separate memory storage of each of the first chord’s component tones. The detection of a frequency shift in one tone might instead be based on a global cue (e.g., the average pitch of all the tones that make up a chord). This is not implausible, because a sum of synchronous tones is normally perceived as a single sound, within which individual tones are difficult to discern. Therefore, one might think that in Experiments 1 and 2, increasing N did not really increase the memory load of the task.

An alternative experimental paradigm, however, makes it possible to study, without any ambiguity, the memory storage of individual components of chords. In a previous study, Demany and Ramos (2005) produced sound sequences consisting of a chord followed by a single tone that was slightly higher or lower in frequency than a randomly selected component of the chord. Listeners were asked to identify the direction of this frequency shift. Even though the components of the chords were difficult to discern individually, it appeared that many listeners could perform the task rather easily. This paradoxical finding inspired our design of Experiments 4 and 5, in which we used Demany and Ramos’s task and manipulated the number of tones making up the chord (N), as well as the ISI. Because the listeners had to make comparisons between tones rather than between chords, it was certain that increasing N increased the memory load of the task.

Method

Participants

Experiment 4 was performed with 3 listeners, including 2 of the authors (W.T. and M.S.). Experiment 5 was performed with 4 listeners, also including 2 of the authors (L.D. and M.S.). Each listener was initially trained on the task for at least 4 hr.

Stimuli and Procedure

On each trial, a chord of N pure tones was followed by a single pure tone (T), and the task was to indicate if T was higher or lower than the closest component of the chord (see Fig. 1, right side). All components of the chord were, a priori, equally likely to be the closest to T , and the correct response was equiprobably “higher” or “lower.” The ISI separating T from the chord was 0, 250, 750, or 2,000 ms. We constructed the chords in the same manner as in Experiments 1 and 2, except that adjacent components were now separated by a fixed frequency interval, namely, 5 semitones in Experiment 4 and 8.5 semitones in Experiment 5. As before, each chord was randomly positioned in a 5-octave frequency range, from 125 to 4000 Hz. In Experiment 4, N was equal to 12, 7, or 4, and T was at a fixed frequency distance ($\Delta s = 1$ semitone) from the closest component of the chord. In Experiment 5, N was equal to 7, 4, 2, or 1 (in the latter case, the “chords” were in fact pure tones), and Δs depended on both N and the listener, as indicated in Figure 2; the goal of this manipulation of Δs was to obtain a similar overall level of performance for the various values of N , as in Experiment 2.

The procedure was identical to that used in Experiments 1 and 2. Thus, we ran 480 trials for each listener and condition.

Results

The results of Experiment 4 (see Fig. 2c) were similar to those of Experiment 1. That is, d' decreased significantly as the ISI increased, $F(3, 6) = 11.3, p = .007, p_{\text{rep}} = .96, \eta^2 = .85$, and as N increased, $F(2, 4) = 78.5, p < .001, p_{\text{rep}} = .99, \eta^2 = .98$, but these two factors did not interact significantly, $F(6, 12) = 1.2, p = .35, p_{\text{rep}} = .60, \eta^2 = .38$.

In Experiment 5 (see Fig. 2d), ISI again had a significant main effect, $F(3, 9) = 8.5, p = .005, p_{\text{rep}} = .97, \eta^2 = .74$. Because of the covariation of N and Δs , N had no significant main effect, $F(3, 9) < 1$. The interaction of N and ISI was significant, $F(9, 27) = 2.6, p = .03, p_{\text{rep}} = .92, \eta^2 = .46$. However, Figure 2 shows that this small interaction effect is due to the fact that d' was unexpectedly high when N was equal to 1 and the ISI was 0 ms. Paradoxically, therefore, the deleterious effect of longer ISIs on performance was somewhat stronger when N was equal to 1 than when N was larger.

GENERAL DISCUSSION

We found that the ability to detect a frequency change in one component of a chord of N tones depends on N and also on the

ISI. In themselves, these two observations are not surprising. Our main—and more surprising—finding is that an increase in the ISI does not have a more deleterious effect on performance when N is large (e.g., 12) than when N is small (4, or even 1). The effect of N is not smaller when the ISI is 0 ms than when the ISI is as long as 2 s. This finding implies that the effect of N on change-detection performance is unrelated to memory and is instead entirely due to sensory or attentional factors. Given that an increase in N nonetheless increases the memory load of the task when the ISI is not 0 ms (an obvious fact for Experiments 4 and 5), we conclude that the memory system involved in the auditory detection of frequency changes apparently has no capacity limit. This appears to be true for retention delays of at least 2 s.

Visual change detection is quite different. As mentioned in our introductory section, humans do possess a high-capacity visual memory. However, the duration of storage in this iconic memory system does not exceed about 100 ms. Phillips and Singer (1974; see also Stelmach et al., 1984) proposed a plausible neural model for the detection of visual changes based on iconic memory. In this model, change detection depends on transient neural responses to a sudden increase (“on” responses) or decrease (“off” responses) of luminance at a given location on the retina. The model holds that locally, off-activity inhibits on-activity, and vice versa, an idea that is consistent with physiological data. Iconic memory is accounted for by the time course of the transient off responses and the time course of the inhibition of on responses by off responses. This mechanism allows an observer to detect local changes in a complex image automatically (i.e., without an active search) if, and only if, the ISI is shorter than about 100 ms.

In contrast, our data suggest that local changes in a sound spectrum are detected in the same manner when the ISI is close to 0 ms as when it is as long as 2 s. Thus, it seems unlikely that a change-detection device similar to the model proposed by Phillips and Singer (1974) exists in the auditory system. Nevertheless, spectral changes can be detected automatically. Demany and Ramos (2005; see also Demany & Semal, in press) demonstrated that a sequence of two tones differing in frequency can elicit a percept of pitch shift when the first tone is included in a chord and not consciously perceived. This finding provides strong evidence for the presence of automatic frequency-shift detectors. The participants in the study reported here probably made use of such detectors, because all participants reported informally that the components of the chord initially presented within a trial were not audible individually when N was larger than 3.

Overall, our results indicate that auditory change detection is only weakly limited by memory factors. This finding, along with the fact that a difference between two tones can be consciously perceived even when the first tone has not been consciously perceived (Demany & Ramos, 2005), is at odds with the idea that humans exhibit change deafness (Eramudugolla et al., 2005; Vitevitch, 2003). The alleged evidence for change deafness

comes from experiments in which the changes to be detected were much more complex than those presented in our study. A crucial difference is that the prechange and postchange stimuli were not static sounds, as in our study, but sound sequences—or mixtures of sound sequences—within which spectral changes were already present. The static stimuli we used are more similar to the static images typically used in demonstrations of change blindness (e.g., O’Regan, Rensink, & Clark, 1999; Rensink et al., 1997). Let us emphasize that the detection of small frequency changes, such as those presented in our study, undoubtedly involves a *sensory* memory system. A change between sequential stimuli, such as those used by Eramudugolla et al. (2005), is more likely to be detected by means of a categorical (verbal) form of memory. We suspect that the “deafness” of the listeners tested by Eramudugolla et al. had, in fact, little to do with audition per se, but rather reflected limitations of short-term verbal memory (Cowan, 2001).

In summary, the present findings indicate that, as regards change detection, the auditory counterpart of iconic memory has a storage duration that is at least 20 times the storage duration of iconic memory. One can make sense of this important difference between audition and vision. As mentioned earlier, iconic memory is retinotopic. That is, the iconic trace of a visual stimulus is tied to the position of its retinal projection, so that a mere displacement of the retinal projection modifies the content of iconic memory, exactly as if the distal stimulus had changed (Phillips, 1974). Thus, an eye movement is sufficient to change the iconic representation of a given stimulus. Because visual saccades are frequent, a difference between two retinal images separated by a substantial time interval is likely to stem from the observer’s own activity, rather than from a change in the visual scene itself. Consequently, it would be superfluous, or even disadvantageous, to possess an iconic memory system permitting detection of changes across long ISIs. By contrast, the motor activity of a human listener has no major effect on the cochlear representation of an auditory scene, so a change in the excitation of the cochlea is typically due to a change in the distal stimulus. Therefore, it is clearly advantageous to possess a high-capacity auditory memory by means of which local spectral changes can be detected across long ISIs.

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