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Trial-to-Trial Carryover in Auditory Short-Term Memory

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Using a short-term recognition memory task, the authors evaluated the carryover across trials of 2 types of auditory information: the characteristics of individual study sounds (item information) and the relationships between the study sounds (study set homogeneity). On each trial, subjects heard 2 successive broadband study sounds and then decided whether a subsequently presented probe sound had been in the study set. On some trials, the similarity of the probe item to stimuli presented on the preceding trial was manipulated. This item information interfered with recognition, and false alarms increased from 0.4% to 4.4%. Moreover, the interference was tuned so that only stimuli that were very similar to each other interfered. On other trials, the relationship among stimuli was manipulated to alter the criterion subjects used in making recognition judgments. The effect of this manipulation was confined to the trial on which the criterion change was generated and did not affect the subsequent trial. These results demonstrate the existence of a sharply tuned carryover of auditory item information but no carryover of the effects of study set homogeneity.

Keywords: auditory, carryover, short-term memory, proactive interference, criterion

In many different settings, previously acquired information interferes with memory for subsequently acquired information (Jacoby, Debner, & Hay, 2001; Postle, Brush, & Nick, 2004; Underwood, 1957). This inability to suppress irrelevant information from a previous trial can significantly limit key cognitive functions (Jonides & Nee, 2006; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). Our purpose in this study was to examine and compare two types of information that might carry over from trial to trial and disrupt auditory short-term memory.

One type of information that may carry over from trial to trial is item information, which arises from the characteristics of individual study stimuli. On each trial of a typical short-term recognition memory experiment, subjects are presented with a set of study items and then with a probe that either matches or does not match one of the study items (e.g., Sternberg, 1966). On a given trial, subjects are exposed to information arising from the values of the items presented on that trial, such as the identities of the words heard or the shapes of the objects seen. The carryover of such item information and subsequent interference with probe recognition is sometimes referred to as proactive interference (reviewed in Kahana, in press).

A second type of information that may carry over from trial to trial arises from the relationships among study stimuli. We refer to the similarity among items in the study set as study set homogeneity. Study set homogeneity does not represent information about individual items per se but nevertheless can influence subjects' recognition responses on a given trial (Kahana & Sekuler, 2002; Kahana, Zhou, Geller, & Sekuler, 2007; Nosofsky & Kantner, 2006; Wright, 1998). It has been suggested by Nosofsky and Kantner (2006) that study set homogeneity alters a subject's response criterion. Specifically, when the study set is more homogeneous, subjects adopt a stricter criterion to judge that a probe matches the stimuli. Whether and how a subject's response criterion is maintained across trials is a matter of debate (S. Brown, Steyvers, & Hemmer, 2007; Treisman & Williams, 1984). We hoped that examining whether the effect of study set similarity carries over across trials would help us better understand how a subject's criterion is created and maintained.

We asked whether the effect of study set homogeneity operated like item-specific proactive interference, carrying over from one trial to influence recognition performance on the next. Additionally, by using metric auditory stimuli tailored to individual subjects' discrimination thresholds, we were able to determine how similar an item had to be to a probe in order to interfere with recognition. This capacity allowed us to explore the sensitivity of interference from item information.

Auditory ripple stimuli, the auditory stimuli we used, are broadband sounds that vary in time. (See Method section and Shamma, 2001.) The decision to use these stimuli was based on several factors. As mentioned above, the use of continuously varying metric stimuli allowed precise control of similarity of items pre-

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sented within or between trials. The fact that these stimuli are not readily named allows examination of auditory memory in the absence of semantic information. The ripple sounds share characteristics with human speech (Shamma, 2001), and this similarity indicates that results found with these stimuli are likely to be valid for ecologically relevant stimuli, such as speech. In addition, previous work suggests that short-term memory processing for these auditory ripple stimuli has parallels with memory processing of visual gratings (Visscher, Kaplan, Kahana, & Sekuler, 2007). These parallels allow comparison across visual and auditory domains.

Item Information

Much research on carryover effects in recognition memory has focused on item information (reviewed in Jonides & Nee, 2006). Typically, these experiments have used verbal stimuli, such as lists of words (e.g., D'Esposito, Postle, Jonides, & Smith, 1999), or other readily named items, such as pictures of familiar objects (e.g., Smith, Leonard, Crane, & Milner, 1995). In such experiments, the strength of carryover often reflects the semantic connections among the verbal items presented on successive trials (Wickens, 1972), but fine-grained tests of the similarity between stimuli required for carryover have, to our knowledge, not been reported. Responses in tests of short-term memory can be affected by information retrieved from long-term memory, such as categories or names (Huttenlocher, Hedges, & Duncan, 1991; Olsson & Poom, 2005; Visscher, Viets, & Snyder, 2003). Thus, memory tasks that use easily categorized or nameable stimulus materials may promote semantic strategies and are likely to recruit different areas of the brain than do nonnameable materials (e.g., Ikeda & Osaka, 2007). To minimize semantic influences on our results, we examined carryover effects in human short-term memory for auditory stimuli that were difficult to categorize or name in a consistent fashion.

A few studies have observed proactive interference with single or multiple auditory stimuli, such as tones, that do not demand explicit verbal mediation (e.g., Ruusuvirta, 2000; Ruusuvirta, Wikgren, & Astikainen, 2006; Wright, 1999). We extended these results by using complex auditory stimuli that allowed us to quantify and manipulate the degree of similarity between any two stimuli and to measure how similar items must be before interference occurred.

Study Set Homogeneity

In addition, we examined carryover of the effect of study set homogeneity. By using the same data set to examine both effects, we contrasted the trial-to-trial influence of study set homogeneity with that of item information.

Homogeneity between items in a study set has been shown to exert a strong influence on subjects' recognition responses (Kahana & Sekuler, 2002; Kahana et al., 2007; Nosofsky & Kantner, 2006; Visscher et al., 2007; Yotsumoto, Kahana, Wilson, & Sekuler, 2007). Specifically, when study items are homogeneous, subjects are less likely to judge that a given probe matches a study stimulus (Kahana & Sekuler, 2002; Kahana et al., 2007; Nosofsky & Kantner, 2006; Yotsumoto et al., 2007). This effect has been made explicit by a computational model called the Noisy Exemplar Model (NEMo). Although the design of our experiment was guided by NEMo, analysis was carried out independently of the model.

We were particularly interested in the trial-to-trial carryover of the effect of study set homogeneity because it has been argued (Nosofsky & Kantner, 2006) that study set homogeneity influences the subject's decision criterion and that stricter decision criteria are associated with higher levels of homogeneity between study items. This criterion shift may or may not persist from trial to trial.

The influence and mutability of response criterion have been focuses of research in the sensory and memory literatures (e.g., Ball & Sekuler, 1980; Cho et al., 2002; Gorea, Caetta, & Sagi, 2005; Gorea & Sagi, 2000; Jones, Cho, Nystrom, Cohen, & Braver, 2002). In both domains, theoretical accounts of performance typically assume that a subject adopts some criterion against which stimulus item information is compared. For example, in the case of memory, such a comparison can form the basis of a recognition response, such as a judgment of a test stimulus as "old" or "new." Regardless of how a criterion value is generated, that criterion could persist for some trials, either because the relevant conditions are unchanging or because there is inertia in the criterion-setting process; alternatively, the criterion might be reset anew on each trial and track trial-by-trial changes in task demands. The mutability of the subject's criterion is a matter of debate in the memory literature (Heit, Brockdorff, & Lamberts, 2003; Lages & Paul, 2006; Singer & Wixted, 2006; Stretch & Wixted, 1998), as well as the sensory psychophysics literature. Although some sensory studies suggest that a subject's criterion is highly mutable and adjusts to conditions from one trial to the next (Petzold & Haubensak, 2004; Treisman & Williams, 1984), other studies suggest that subjects adopt and hold a single, stable criterion across a group of trials (Gorea & Sagi, 2000). Additionally, at least one sensory study (Morgan, Watamaniuk, & McKee, 2000) has revealed a remarkable flexibility in criterion setting; subjects were able to develop and hold multiple, distinct criteria and to draw on any one as cued for a particular trial. Of course, evidence for or against the mutability of criteria in sensory tasks, such as detection or discrimination, does not constrain the mutability of criteria in memory tasks, which is the basis of the current study.

To control a subject's recognition criterion, we manipulated study set homogeneity, a variable linked to a subject's recognition criterion (Nosofsky & Kantner, 2006). The metric properties of our stimuli allowed us to manipulate the study set homogeneity on any given trial and thus to test whether its effect was maintained across trials. The requisite precise control over stimuli was made possible, in part, because our stimuli could be adapted for individual subjects in compensation for systematic differences in their powers of discrimination. Thus we were able to control the perceptual similarity between individual stimuli on each trial, as well as the relationships between stimuli on successive trials. We exploited this stimulus control to examine how item information and study set homogeneity on trial n affected performance on trial $n + 1$.

The Noisy Exemplar Model

The details of our experiment were guided by NEMo, which is described fully elsewhere (Kahana & Sekuler, 2002; Visscher et al., 2007). NEMo shares with several related models the idea that the similarity between the probe and all study items (summed

probe–item similarity) is a basis of recognition responses (e.g., Brockdorff & Lamberts, 2000; Clark & Gronlund, 1996; Humphreys, Pike, Bain, & Tehan, 1989; Lamberts, Brockdorff, & Heit, 2003; Nosofsky, 1991) but differs in its assertion that recognition responses are also influenced by the homogeneity of the study items. The ability of NEMo to predict subjects' performance for various classes of stimuli, such as complex sounds (Visscher et al., 2007), visual gratings (Kahana & Sekuler, 2002; Kahana et al., 2007), faces (Yotsumoto et al., 2007), and colors (Nosofsky & Kantner, 2006), is significantly improved because the model takes account of study set homogeneity.

On each trial in the experiments presented here, a pair of study items, s_1 and s_2, was presented, followed by a probe. The subject had to indicate whether the probe matched one of the items in the study set. As mentioned above, NEMo assumes that recognition judgments are based on the similarity between the probe and all the list items (termed "summed similarity") and the homogeneity of the items in the study set. Figure 1 illustrates the characteristics of a group of stimuli presented on a typical trial. The lengths of the solid lines represent the probe–item similarity. The length of the dashed line in Figure 1 represents the study set homogeneity on that trial.

Although the model predicts performance on a current trial, NEMo is mute as to whether the study set homogeneity on one trial affects performance on the next trial. The fact that study set homogeneity can be easily manipulated on a trial-to-trial basis suggests a way to examine the question. In addition, the model's tuning with probe–item similarity suggests the idea that the effect of a stimulus from a previous trial might also be tuned.

Overview

We asked two main questions: To what extent is item information maintained across trials and to what extent is the effect of study set homogeneity maintained across trials? To foreshadow, we found a distinction between the endurance of item information and study set homogeneity. Item information was maintained across trials and produced a modest but reliable change in response that was sensitive to the degree of similarity between stimuli on successive trials, whereas the effect of study set homogeneity seemed not to be maintained across trials but was modulated on a trial-to-trial basis. This distinction implies that the two effects stem from different mechanisms.

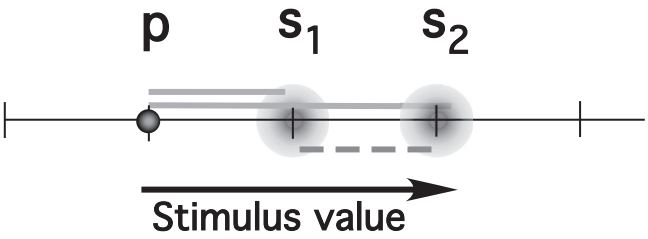

Figure 1. Schematic illustration of elements entering into a summed similarity computation. Perceptual representations for two study items, s_1 and s_2, are defined along a single stimulus dimension (labeled stimulus value). On any trial, the memory of some study item is a random sample from a distribution (the probability density function of possible memories for that item). The diameters of the schematic "clouds" signify the noise or variability associated with the memory of each stimulus item. The solid lines represent the similarity of each remembered stimulus to the probe (p). The dashed line represents the homogeneity of the set of two study items.

Method

Moving Ripple Stimuli

To examine how similarity relationships among stimuli affect subjects' responses, we used moving ripple sounds as stimuli. They could be continuously varied and their study set similarities could be measured. Moving ripple sounds are broadband sounds that vary sinusoidally both in time (with a period of w cycles per second) and in frequency content (with a period of Ω cycles per octave). In Figure 2, the horizontal axis represents time and the vertical axis represents the frequency content of two sample stimuli. These stimuli were generated by superimposing sounds at many frequencies whose loudness at any time (t) and for any frequency (f) is defined by

$$s(t, x) = D_0 + D\cos[2\pi(wt + \Omega x) + \psi]. \quad (1)$$

Here, $x = \log_2(f/f_0)$ and f_0 is the lowest allowed frequency. ψ is the phase of the ripple, and D is modulation depth. D_0 is the base loudness, which was set to 1.0. The stimulus space was simplified by having only one parameter (w) vary among the stimuli. Other parameters took fixed values: $\Omega = 1$, $\psi = 0$, $D = 0.9$, and $f_0 = 200$ Hz. Frequencies ranged over three octaves above f_0 (i.e., from 200 to 1600 Hz). Each stimulus contained 20 logarithmically spaced frequencies per octave. Each stimulus has a spectral profile that drifts in time, so that different frequencies are at their peaks at different times. For each stimulus, duration was set to 1 s. Example stimuli can be found at http://people.brandeis.edu/~sekuler/rippleSoundFiles/movingRippleSounds.html.

The advantages of this particular kind of stimulus for the study of memory were described by Visscher et al. (2007), who also showed that short-term memory for these stimuli exhibits strong parallels to short-term memory for visual stimuli, such as oriented sinusoidal gratings. An additional benefit of studying ripple sounds is that they share similarities to speech sounds (see Shamma, 2001). For example, their frequency bands modulate in time. Thus, findings pertaining to these ripple sounds are likely to generalize to speech sounds. The ripple sounds are difficult to verbalize but allow examination of memory for language-like sounds independent of verbal labels.

Subjects

Subjects were between 18 and 30 years of age and came from the student population of Brandeis University. At the outset, each potential subject underwent audiometric screening. We used a MAICO MA39 audiometer to measure thresholds at 250, 500, 750, 1000, 2000, 3000, 4000, and 6000 Hz. Each subject had normal or above-normal hearing (i.e., had thresholds at or below 20 dB_{HL} at each frequency).

Twelve subjects participated in eight sessions each, following an initial session in which just noticeable difference (JND) thresholds for the w parameter (cycles per second) were measured (see below) and 200 practice trials were performed. Experimental sessions, lasting about 1 hr each, comprised 586 trials. At the beginning of every session, each subject completed at least 30 practice trials that

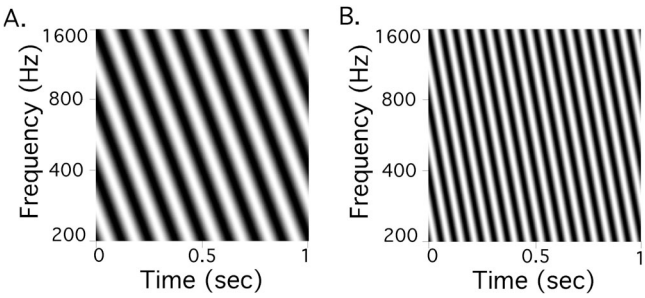

Figure 2. Spectrotemporal plots of ripple sounds. The horizontal axis shows time in seconds, and the vertical axis shows frequency content in hertz. Darker colors represent sounds of greater amplitude. Modulations over time are referred to as the ripple's velocity and have units of sinusoidal frequency w; modulations over frequency are referred to as spectral density and have units of sinusoidal frequency Ω. Panel A represents a stimulus with $w = 8$ Hz; Panel B represents a stimulus with $w = 16$ Hz. In our experiment, other stimulus parameters were held constant (e.g., $\Omega =$ 1 cycle per octave).

were excluded from data analysis. Successive sessions were separated by at least 6 hr, and all subjects completed all of the sessions within 3 weeks. Subjects participated for payment of $72, plus a performance-based bonus of up to $16. The methods used in the study were approved by the institutional review board of Brandeis University.

Apparatus and Sound Levels

Subjects listened to stimuli through Sennheiser Pro HD 280 headphones. Stimuli were generated by an Apple iMac computer and Matlab, including its PsychToolbox add-on (Brainard, 1997). To characterize the stimulus intensity at the subject's eardrum, we verified sound levels for this system using a Knowles electronic mannequin (Knowles Electronics, Itasca, IL) for acoustic research. All stimuli were 79 dB_{SPL} and were well above our subjects' hearing thresholds.

Stimulus Presentation

On each trial, either one or two study items were presented, followed by a probe. The analyses detailed here focus on the two-item lists. We included one-item trials to quantify pairwise perceived similarity, a parameter needed for the NEMo model fits presented in Visscher et al. (2007). We restricted study lists to no more than two items to provide control of the variables required for the questions of experimental interest. The subject's task was to judge whether the probe (p) matched any of the study items (s_1 or s_2). The response was indicated by a button press. During the presentation of study items, subjects fixated on a + sign in the center of a computer screen. Trials with one study item were intermixed among trials with two items.

Each stimulus was 1 s in duration. When two study items were presented, they were separated by 0.25 s. The probe was presented 0.75 s after the final study item and was accompanied by the presentation of a *?* on the computer screen. Subjects responded with a button press to indicate whether the probe matched ("Yes") or did not match ("No") a study item. Immediately after the subject's response, a distinctive tone provided feedback about response correctness. After each trial, to increase motivation, we showed subjects their percentage correct thus far in the session and the difference between that value and their goal of at least 70% correct. Subjects were rewarded at the end of a session with a candy bar if their percentage correct exceeded 70%. For every percentage point above that value, subjects received a $0.25 increment to their base payment.

Adjustment for Discrimination Threshold

Stimuli were adjusted to each subject's auditory discrimination threshold to eliminate one source of potential individual differences and make the memory task comparably difficult for all subjects (Zhou, Kahana, & Sekuler, 2004). In addition, the similarity among stimuli made it difficult for subjects to use naming or categorizing strategies in a consistent, reliable fashion. In a subject's first experimental session, pairs of stimuli were presented in succession on each trial, and the subject identified which stimulus had the faster rate of modulation. Watson and Pelli (1983)'s QUEST algorithm found the difference in modulation rate ($\Delta w/w$) that just permitted correct identification of the more rapidly modulated stimulus on 70% of trials. This value was taken as the just noticeable difference (JND).

We used this JND value to generate the stimuli that would be used in subsequent sessions to test that subject's recognition memory. The lowest value of w was $w_0 = 7$ Hz, and successive values were given by $w_0(1 + JND)^n$, with n varying from 0 to 9. This equation generates stimuli that increment in steps of one JND. To reduce the possibility that subjects could memorize the stimuli and assign verbal labels to them, we increased the number of stimuli to which subjects would be exposed by creating a second set of 10 stimuli whose values lay midway between successive stimuli in the first set. This set took on values $(w_0 + w_1)/2\ (1 + JND)^n$, with n again varying from 0 to 9. Trials whose test items were drawn from the first series were randomly intermixed with trials whose test items came from the second series. Thus, the complete collection of possible stimuli comprised 20 sounds. Items in the stimulus pool were tightly packed along the dimension w and were separated by just 0.5 JND. This tight packing was meant to make absolute identification of individual stimuli difficult. On a particular trial, stimuli were drawn from only one series or the other, meaning that a trial's stimuli (s_1, s_2, p) were always an integral number of JNDs from each other.

Trials were self-paced and were initiated by the press of a key on a computer keyboard. On equal numbers of trials, the probe matched one of the study stimuli or did not match either of the study stimuli. We designated matching trials as target trials and nonmatching trials as lure trials. Target and lure trials were randomly intermixed during memory testing.

Experimental Design

To assess the carryover of information from trial to trial, we manipulated the stimulus materials that were presented on successive trials. For each trial pair, the first trial (Trial A) constituted the setup trial, which was intended either to establish some particular item information or to produce some particular value of study set homogeneity. Following each setup trial, the response on the next,

test trial (Trial B) provided an index of the influence that had been established on the preceding trial. The details of the various conditions represented in the design are described below and in Table 1.

To minimize subjects' awareness of the complex regularities in the stimulus presentation schedule, we randomly interleaved trial pairs with trials of other types (a total of 320 carefully controlled pairs of trials within the 4,680 trials presented to each subject). Trials listed as "Model testing" in Table 1 were analyzed in addressing a separate issue (Visscher et al., 2007). Trials on which just one study item was followed by a probe were randomly interleaved among all trials and were used to gauge stimulus similarity.

Item similarity and study set homogeneity were manipulated by controlling the relationships among stimulus values from one trial to the next, as described below. Table 1 summarizes the effects that were targeted by each condition in our experiment. Note that the column headed "Condition" signifies the relationship among presented stimuli (s_1, s_2, p) rather than specific choices of stimuli, which varied from trial to trial. Many sets of stimuli consistent with the rules defining each condition were generated; examples were generated for both target trials (on which the probe replicated a study item) and lure trials (on which the probe did not replicate a study item). For example, the last row in the table refers to trials on which there was one study item (s_1) and it did not match the probe (p). As each trial's stimuli were chosen from a set of 10 stimuli, there are 90 possible pairings of s_1 and p. For the conditions represented in the bottom two rows of the table, all possible pairings were used; other conditions used only a random subset of all possible pairings.

Carryover of item information. To gauge carryover of item information from one trial to the next, we constructed pairs of successive trials so that the stimuli from the first trial in the sequence (Trial A; $A = [s_1^A, s_2^A, p^A]$) were similar to the probe, p^B, on the second trial (Trial B). This condition, represented in the top panel of Figure 3, is labeled hiSim after the relatively high similarity of the probe from Trial B to the stimuli from Trial A. On these trials, s_1^A, s_2^A, p^A, and p^B were all within three JND of each other (as seen in Figure 3). If item information were carried over from trial to trial, memory of the study items on Trial A might influence recognition and induce subjects to judge erroneously that p^B matched a study item on Trial B (s_1^B or s_2^B). In other words, carryover of item information from Trial A to Trial B would be characterized by the proportion of false positive recognitions.

This hiSim condition was contrasted with the loSim condition, in which pairs of trials were arranged so that p^B had a low similarity to Trial A's stimuli. Trials A and B in the loSim condition were the same as in the hiSim condition, except that trials were paired such that Trial A's stimuli (s_1^A, s_2^A, p^A) differed from p^B by at least five JND. Such low similarity between stimuli on subsequent trials should give rise to very little proactive interference of item information and few false positive recognitions.

In Trial A of both the hiSim and loSim conditions, the probe (p^A) and both study items (s_1^A, s_2^A) were all very similar to each other (that is, within three JND of each other). On this subset of trials, the probe and both study items all took values among the three highest allowed stimulus values or the three lowest allowed stimulus values. The following trial, Trial B, always contained study items (s_1^B, s_2^B) that were only one or two JND from each other. The probe (p^B) differed from the closest study item by five JND. In all conditions, only the similarity among s_1, s_2, and p was constrained; their ordering in stimulus space along the w-axis was not. Thus, s_1 was equally likely to take a value greater than or less than s_2. For simplicity, Figure 3 illustrates only the case in which $s_1 < s_2$. In addition, the probe's value was equally likely to be greater than or less than that of the study items. On Trial A (but not Trial B), the probe could also fall at a stimulus value between two study items or hold an identical stimulus value to one of the items.

Related procedures using a "recent negative probe" condition have been shown to provide a sensitive assay of the degree of carryover of item information (D'Esposito et al., 1999; Monsell, 1978). If information in memory did not carry over between trials, recognition performance on instances of Trial B in the hiSim condition should be no different from instances of Trial B in the loSim condition. One difference between the recent negative probe design and our own is that our design controlled the similarity of the probe from Trial B (p^B) to the stimuli in Trial A. Thus in the hiSim condition, p^B could either exactly match a stimulus from Trial A ($p^B \in A$) or be highly similar though not identical to a stimulus from Trial A ($p^B \notin A$). In the loSim condition, p^B was highly dissimilar to stimuli on Trial A (loSim condition). The similarity among stimuli could be quantified, and this capacity allowed evaluation of the specificity of item information maintained from previous trials. Note that Trial B consistently had a low value of homogeneity. Trial B was the same in both hiSim and loSim conditions and was likely, on the basis on previous experiments (Kahana & Sekuler, 2002; Kahana et al., 2007; Nosofsky & Kantner, 2006; Visscher et al., 2007; Yotsumoto et al., 2007), to

Table 1
Trial Types in Experimental Design

Effect examined	Condition	Lure	Target	Repetitions
Item information	hiSim	4	4	10
Item information	loSim	4	4	10
Study set homogeneity	hiHom	4	4	10
Study set homogeneity	loHom	4	4	10
Model testing	Other two-item lists	64	64	20
Define perceptual similarity	One study item (targets)		10	90
Define perceptual similarity	One study item (lures)	90		10

Note. Lure = number of types of lure trials (combinations of two list items and a probe); target = number of types of target trials; hiSim = high similarity; loSim = low similarity; hiHom = high homogeneity; loHom = low homogeneity.

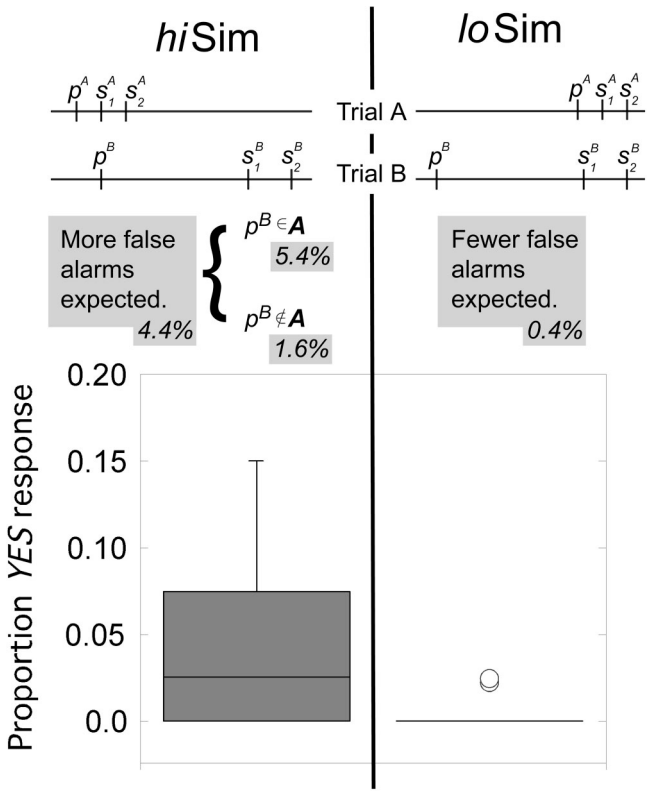

Figure 3. Upper panel: Schematic diagram of design examining maintenance of item information across trials. Trial A immediately precedes Trial B. In the hiSim condition, the probe for Trial B (with value p^B) is very similar in perceptual space to the stimuli from Trial A (study stimuli, s_1^A and s_2^A, and probe, p^A). The horizontal axis represents the stimulus space; items closer to each other are more similar. In the loSim condition, p^B is different from s_1^A, s_2^A, and p^A. If item information were maintained from trial to trial, more false alarms (on Trial B) would be expected for the hiSim condition, as interference between the probe and stimuli from a previous trial should be greater in that condition than in the loSim condition. Note that Trial B is the same in each case. p indicates the probe frequency, s_1 and s_2 indicate the frequencies of the first and second study stimuli (for simplicity, only the case in which $s_1 < s_2$ is shown; equally often, $s_1 > s_2$). Within the hiSim condition, on some trials p^B matched a stimulus from Trial A ($p^B \in A$), whereas on other trials, p^B did not match any stimulus from Trial A ($p^B \notin A$). The percentages of false alarm trials observed for each condition are shown in filled boxes. Lower panel: Box plot shows median (thick bar); middle 50% of data are encompassed by boxes. The whiskers include all data points that are not outliers. Circles represent outliers, defined as points $> 1.5 \times$ the interquartile range from the median. Note that more false alarms to Trial B were made in the hiSim condition.

give rise to a relatively low false alarm rate on those trials due to the low value of homogeneity.

Carryover of effect of study set homogeneity. The relationships among study stimuli robustly affected subjects' responses on Trial B (Kahana & Sekuler, 2002; Kahana et al., 2007; Nosofsky & Kantner, 2006; Visscher et al., 2007). To evaluate the possibility that such information was maintained from one trial to the next (Gorea & Sagi, 2000), we used a design parallel to that described above. Again, pairs of successive trials were generated, and the setup trial (first in the pair) varied in study item homogeneity. Guided by NEMo, we generated two kinds of setup trials, which we labeled hiHom and loHom. These are represented in the top of Figure 4. On hiHom trials, s_1 and s_2 were highly homogeneous, differing from one another by just one JND. These trials were expected to promote a high, stricter criterion and fewer false alarms. On loHom trials, s_1 and s_2 differed from one another by at least four JND and thus had relatively low homogeneity. These trials were expected to promote a lower, more liberal criterion and more false alarms.

Presentation of either a hiHom trial or a loHom trial was followed by the presentation of a neutral test trial. These test trials were drawn from a pool of four different lure stimulus sets (four sets of values for s_1^B, s_2^B, and p^B). Study stimuli and probes were chosen randomly for each set in the pool of neutral test trials, and each of these random trials followed hiHom and loHom trials with equal frequency (20 times each). Any systematic difference in performance on neutral test trials after loHom trials versus hiHom trials would indicate that the effect of study set homogeneity had been maintained and carried over to the neutral test trial. For simplicity, Figure 4 illustrates only the case in which $s_1 < s_2$, but it was equally likely that $s_1 > s_2$.

For each subject, 40 hiHom and 40 loHom trial pairs were randomly intermixed among all trials. Note that these condition labels refer to the characteristics of the first trial in a pair, whereas the results plotted refer to responses on the second trial in a pair.

Results

Individual Thresholds and Perceptual Similarity

Individual subject thresholds for discrimination between ripple sounds differed. Table 2 shows the JND for each subject. The mean JND was 0.17, with a standard deviation of 0.053. Two stimuli differing by this proportion would be discriminated correctly 70% of the time. As mentioned earlier, the stimuli we used to assess memory were created according to individual subjects' JND thresholds.

Carryover of Item Information Across Trials

Stimulus information from Trial A carried over to Trial B. The proportion of false alarms was greater when a previous trial's stimuli could be confused with the current trial's probe: proportion "Yes" for hiSim $>$ for loSim, paired t test, $t(11) = 2.55$, $p < .03$. In fact, only 2 subjects made any "Yes" responses in the loSim condition, and the other 10 subjects made none. Because of the low variance in the loSim condition, we double-checked the statistics using nonparametric analyses. A two-sided Wilcoxon rank sum test also showed the effect to be strong and significant ($p < .03$). This result indicates maintenance of stimulus memory from one trial to the next (see Method section and Figure 3). False alarm rates were low, as shown in Figure 3 (mean of 4.4% in the hiSim vs. 0.4% in the loSim condition). This modest rate was expected, as the probe is relatively dissimilar to either study item (the probe is five JND from the closest study item).

Further, we examined the selectivity of this carryover effect. On 72% of hiSim trials, p^B exactly matched s_1, s_2, or p from Trial A ($p^B \in A$), whereas, due to stimulus constraints, on the remaining trials p^B was one JND away from the closest stimulus on Trial A

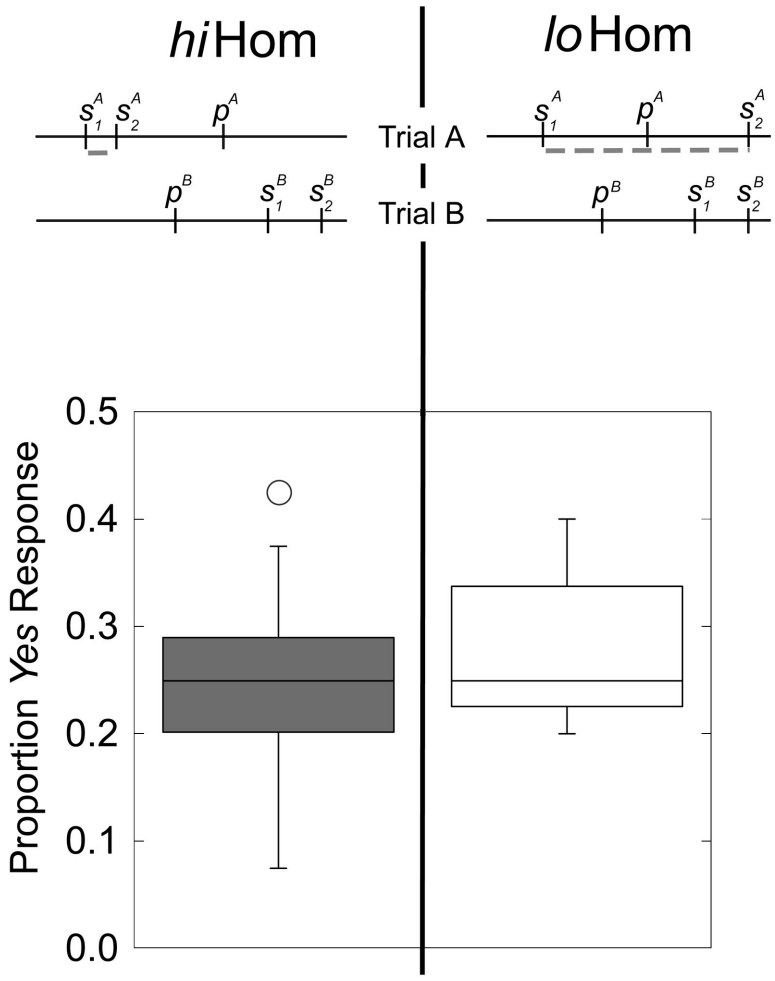

Figure 4. Upper panel: Schematic diagram of design examining maintenance of the effect of study set homogeneity across trials. Trial A immediately preceded Trial B. In the hiHom condition, the study stimuli in Trial A were homogeneous (dashed line between s_1^A and s_2^A is short), whereas in the loHom condition, the two stimuli were different (dashed line is longer). The horizontal axis represents the stimulus space; items closer to each other are more similar. If the effect of study set homogeneity were maintained from trial to trial, more false alarms (on Trial B) would be expected for the loHom condition, as the false alarm rate on Trial A is greater in that condition. Note that Trial B is the same in each case. p indicates the probe frequency, and s_1 and s_2 indicate the frequencies of the first and second study stimuli. (For simplicity, only the case in which $s_1 < s_2$ is shown; equally often, $s_1 > s_2$.) Lower panel: Identical trials following trials of high study set homogeneity (hiHom) or low study set homogeneity (loHom) showed no difference in proportion correct. The effect of study set homogeneity is not carried over from trial to trial. Box plot shows median (thick bar); middle 50% of data are encompassed by boxes. The whiskers include all data points that are not outliers. Circles represent outliers, defined as points $> 1.5 \times$ the interquartile range from the median.

($p^B \notin A$). Subjects were significantly more likely to make a false recognition judgment when $p^B \in A$ than on trials in which $p^B \notin A$: $M = 5.4\%$ versus 1.6%, paired t test, $t(11) = 2.57$, $p < .03$. In fact, the false recognition rate when $p^B \notin A$ was not significantly different from zero, $t(11) = 1.48$, $p = .16$. This rate indicates that carryover from item information on previous trials was very selective and affected exact matches much more than it did similar but not identical item information.

Because all stimuli from Trial A as well as p^B were constrained to fall within three JND of each other, trials of $p^B \notin A$ could follow a Trial A only if it were a target trial. This constraint meant that a difference between the $p^B \in A$ and $p^B \notin A$ conditions could have arisen from a difference in target versus lure trials. On average, 80% of the Trial A cases were target trials (due simply to the constraint that both stimuli and probe from Trial A were within three JND). There was no overall difference between the false alarm rates for target and lure trials in either the hiSim or loSim conditions, paired t test, $t(11) = 0.64$ and 0.74, $p = .53$ and 0.47, respectively. The absence of a difference between target and lure trials in the hiSim condition indicates that the increase in false alarm rate in cases when $p^B \in A$ likely is a reflection of increased similarity rather than an artifact of following lure trials more often.

Table 2
Thresholds for 70% Correct Recognition Performance

Subject	JND	Subject	JND
1	0.22	7	0.08
2	0.11	8	0.17
3	0.26	9	0.22
4	0.23	10	0.13
5	0.17	11	0.14
6	0.16	12	0.15

Note. JND = just noticeable difference.

Overall, the data demonstrate carryover of item information across trials. This interference lessened when p^B was less similar to the interfering stimuli.

Carryover of Study Set Homogeneity Across Trials

Figure 4 shows the mean proportion of "Yes" responses on trial $n + 1$, when trial n was hiHom (left box and whiskers) or loHom (right box and whiskers). These two proportions were nearly identical, paired t test, $t(11) = 1.0$, $p = .33$; this suggests that whatever effect might have been generated on trial n did not carry over to trial $n + 1$. The absence of an effect is confirmed by the lack of difference for mean reaction times between the groups of trials whose data are shown in Figure 4, paired t test, $t(11) = 0.56$, $p = .59$.

Figure 4 suggests that manipulation of study set homogeneity on trial n has no detectable effect on trial $n + 1$. Before concluding that this result represents an absence of carryover from one trial to the next, we needed to verify that the manipulation of study set homogeneity did indeed affect performance on the current trial. To this end, we examined trials that simultaneously met three criteria. For inclusion in the analysis, a trial had to (a) qualify as Trial A in the hiHom or loHom condition, (b) be a lure trial, and (c) have a summed probe–item similarity of five JND (i.e., $|p - s_1| + |p - s_2| = 5$ JND). These constraints make it possible to examine the effect of study set homogeneity without confounds from other parameters that are known to affect performance. Because summed probe–item similarity affects performance, one must hold this value constant between conditions to compare them. A summed probe–item similarity of five JND was chosen for our third constraint because this value gave the largest proportion of trials. Of course, only a fraction of the trials survived the imposition of the three constraints: Of the 40 total trials per condition, only an average of 12.5 hiHom and 20 loHom trials per subject survived. The effect of study set homogeneity was robust and statistically significant despite the relatively small number of trials. The select hiHom trials (in which $|s_1 - s_2| = 1$ JND) produced a mean false alarm rate of 15.9%; the select loHom trials (in which $|s_1 - s_2| = 5$ JND) produced almost twice as many false alarms (30.6%). This was a statistically significant difference, paired t test, $t(11) = 2.5$, $p < .05$. These false alarm rates were expected to be higher than those in Figure 3 because the probe on these trials was more similar to the study items. (Compare Trial B between Figures 3 and 4. The probe is more similar to s_1 and s_2 in Figure 4.)

We should note that this robust 14% difference between hiHom and loHom trials was in line with the effect observed in the entire data set and was not some artifact of the strict selection process we used to determine the subset of trials analyzed. The overall difference between hiHom and loHom trials (with no selection criteria) was 12%, paired t test, $t(11) = -2.7$, $p < .05$. Thus, the absence of a difference between conditions in Figure 4 did not mean that the manipulation of study set homogeneity was ineffectual; rather, it showed that the robust effect generated by the manipulation failed to survive from one trial to the next.

Discussion

Item Information Interferes Across Trials, but the Effect of Study Set Homogeneity Does Not

Our results show that interference from item information can operate over successive trials and can allow what was heard on trial n to influence recognition on trial $n + 1$. In particular, as Figure 3 shows, carryover from item information produced more false alarms in the hiSim than the loSim condition; this effect depended strongly on the degree of similarity between stimuli on successive trials. In contrast to this strong trial-to-trial influence, the effect generated by the homogeneity of one trial's study stimuli failed to influence performance on the next trial: No difference was found between trials following loHom and hiHom conditions (see Figure 4). The data presented here suggest that the mechanisms giving rise to carryover of item information are distinct from those responsible for the effect of study set homogeneity.

Item Information Carries Over Trial to Trial

Our results confirm that stimuli encountered on trial n can affect responses on trial $n + 1$. This finding had been demonstrated for verbal and visual stimuli (Bennett, 1975; D'Esposito et al., 1999; Feredoes, Tononi, & Postle, 2006; Monsell, 1978; Postle et al., 2004; Wickens, 1972; Wright, 1999) but not, to our knowledge, until now for abstract auditory stimuli in humans. Previous studies of item information carryover showed small but significant reaction time effects and small effects on accuracy (so long as accuracy was below its upper limiting value). This pattern of results is consistent with the modest but significant differences in performance shown in Figure 3. Finally, it is worth noting that even under conditions that generate the greatest carryover, relatively few false recognitions result (only 4.4%). This effect is not attributable to some dissipation of memory over the interval between trials; in fact, we have shown that in the absence of interference, memory for the stimuli used here is very well preserved for many seconds (Visscher et al., 2007). So, despite the highly significant carryover of item information, subjects are usually able to gate out item memory from the previous trial.

Memory trace for interfering item information is sharply tuned. The carryover of item information depends on how closely the previous trial's stimuli match the current trial's probe. Previous experiments showed that subjects use summed similarity to judge whether the probe matches a stimulus in the current study list (Brockdorff & Lamberts, 2000; Clark & Gronlund, 1996; Humphreys et al., 1989; Kahana & Sekuler, 2002; Kahana et al., 2007; Lamberts et al., 2003; Nosofsky, 1986, 1991; Nosofsky & Kantner, 2006; Yotsumoto et al., 2007). Our data extend this point by suggesting that a full computational model of short-term recogni-

tion memory must take account of a probe's similarity to stimuli not only on the current trial but on a previous trial or trials. Several existing computational models can be readily modified to take previous trial information into account. For example, Brown et al.'s SIMPLE model can treat carryover effects as extensions of errors in serial order (G. D. A. Brown, Neath, & Chater, 2007).

The data indicate that trial-to-trial interference from item information is highly selective, as moving p^B only one JND away from the closest stimulus on the previous trial caused a relatively large and reliable decrease in false recognitions (from 5.4% to 1.6%). This decrease shows that the memory trace for the interfering item information is sharply tuned for perceptual similarity.

Further studies that used metric stimuli less than one JND apart could more finely examine the tuning curve. Related further studies could compare the tuning of interfering memory to the tuning for memories of stimuli on the current trial. Additionally, such experiments could determine how closely the recent negative effects observed in other paradigms depend on exact identity between a probe and a recent stimulus or whether rough similarity to the probe is sufficient.

Our results demonstrate that proactive interference is strongest when the probe precisely matches a study item from the preceding trial (see Figure 3). This relation suggests that stimulus values are maintained in memory with considerable fidelity even across trials. Some researchers have suggested that carryover of item-specific information reflects a residual item-memory trace generated on a previous trial (Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998). Other researchers have suggested that such proactive interference reflects a reliance on general familiarity information that is available when explicit recollection has failed (Jacoby et al., 2001; Tulving, 1985). The current data add to this debate by showing that stimulus information is precisely maintained by the memory mechanism responsible for proactive interference.

Extensions of proactive interference effects. The reliance of our experimental design on pairs of trials limits assessment of interference effects to just one previous trial. Of course, it is certainly possible that some interference effects persist beyond one trial. For example, Cho et al. (2002) made the case that interference can persist from individual stimuli several trials removed from the current trial. Further research might explore the number of trials over which carryover effects for complex auditory stimuli can act (Petzold & Haubensak, 2001). Another possible source of proactive interference is the accumulation of interfering information across many items from many previous trials, which is often called item-non-specific interference (Postle et al., 2004; Postman & Keppel, 1977). Item-specific and item-non-specific forms of interference are thought to be mediated by the same regions of the brain (Postle et al., 2004). Studies in monkeys demonstrated item-non-specific interference for auditory stimuli (nonconfusable environmental sounds; Wright, 1999). Such nonspecific effects may be relevant for the present experiments as well, as stimuli were chosen to be somewhat confusable and to resist perfect, consistent categorization. Thus, the item-specific proactive interference effects we observed may have been operating against a background of item-nonspecific effects.

Proactive interference from stimulus information is but one of many ways in which stimulus information on one trial might affect a subject's response on a subsequent trial. For example, repeated presentation of a stimulus affects a subject's judgment of subsequent stimuli, so that later stimuli are recalled differently depending on their relationship to the well-studied stimulus (Huttenlocher et al., 1991; Visscher et al., 2003). In addition, the much-studied phenomenon of priming (Henson, 2003), in which perception of a stimulus is enhanced on the basis of input from a previous trial, depends on the maintenance of stimulus information from one trial to the next. Most salient for the issues we address are demonstrations that various forms of stimulus information can be maintained across trials for priming (e.g., nonverbal information such as spatial frequency and color; Huang, Holcombe, & Pashler, 2004; Maljkovic & Nakayama, 1994).

All of these effects (proactive interference, effects of a well-studied stimulus, and priming) reflect the preservation of stimulus representations over trials. In each case, remembered stimulus information affects later recognition responses. The relationship among study stimuli constitutes a different type of information that does not come directly from the individual stimulus values. It is notable that information about study set homogeneity is treated differently from many other types of trial-related information and is not maintained across trials.

Effect of Study Set Homogeneity Does Not Carry Over

Although the homogeneity of a given study set robustly affected the response on that trial, this effect was not maintained across trials. This finding implies that the study set homogeneity affects only the current trial. As described in the Introduction, the homogeneity of study items is thought to influence a subject's response criterion for recognition memory (Nosofsky & Kantner, 2006). The current findings show that if study set homogeneity does impact a response criterion, it does so by resetting the criterion on each trial. Such a quick criterion modulation is similar to the cue-driven modulations of sensory criterion shown by Morgan et al. (2000).

Item Information Is Encoded Separately From Relationships Among Study Items

The data show that stimulus information generated on one trial carries over to interfere with recognition judgments on the succeeding trial but that the effect of study set homogeneity does not. This result indicates that item-specific information, not information about relationships between study items, carries over between trials.

The recognition task used here imposes artificial temporal, episodic boundaries that define which remembered stimuli are relevant for the current trial. Specifically, only the two stimuli seen most recently are relevant. The implicit reward structure of the experiment punishes subjects for allowing information acquired on trial n to affect responses on trial $n + 1$. However, in normal, everyday application of short-term memory, temporal boundaries are less distinct and maintenance of stimulus information can be advantageous. Therefore it makes sense that despite the expected reward structure, subjects will not show a perfect ability to exclude recent but no longer relevant information from memory. Without maintaining item information across episodes, we would not be able to convert episode information into more general knowledge. For example, without the ability to generalize, one may not be able to infer from a previous episode that the roar of a river indicates

the presence of water nearby. This inability might degrade one's ability to find water. On the other hand, rapid adjustments based on information regarding the homogeneity of a current study set would be useful in real-world situations. For example, orienting toward the river on a still day would require a relatively lax criterion for identifying water sounds among few distractors, but moments later, if the wind picked up, discriminating the water sounds from the rustling of leaves would require a much more stringent criterion. Thus, rapid reactions to study set homogeneity would be advantageous in a way that complete inhibition of previous trial item information would not.

Summary

We found that remembered information about stimulus properties (item information about auditory stimuli) carries over from one trial to the next, as indexed by the recognition judgment on the next trial. This form of proactive interference appears to be relatively narrowly tuned. In contrast, we have demonstrated that the effect of study set homogeneity is temporally restricted and does not carry over into the successive episode.

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