Decay uncovered in nonverbal short-term memory

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Abstract

Decay theory posits that memory traces gradually fade away over the passage of time unless actively rehearsed. Much recent work exploring verbal short-term memory has challenged this theory, but there does appear to be evidence for trace decay in nonverbal auditory short-term memory. Numerous discrimination studies have reported a performance decline as the interval separating two tones is increased, consistent with a decay process. However, most of the tone comparison research can be explained in other ways, without reference to decay, and these alternative accounts were tested in the present study. In Experiment 1 signals were employed towards the end of extended retention intervals to ensure that listeners were alert to the presence and frequency content of the memoranda. In Experiment 2 a mask stimulus was employed in an attempt to distinguish between a highly detailed sensory trace and a longer-lasting short-term memory, and the distinctiveness of the stimuli was varied. Despite these precautions, slow-acting trace decay was observed. It therefore appears that the mere passage of time *can* lead to forgetting in some forms of short-term memory.

Keywords: Auditory memory, decay, forgetting, short-term memory.

Introduction

Trace decay theory, the proposal that representations of recent events gradually fade away with the passage of time, has emerged as perhaps the most contentious issue within contemporary forgetting research (e.g. Altmann, 2009; Barrouillet, De Paepe, & Langerock, 2012; Barrouillet, Portrat, & Camos, 2011; Cowan & AuBuchon, 2008; Lewandowsky, Duncan, & Brown, 2004; Lewandowsky & Oberauer, 2008; Lewandowsky, Oberauer, & Brown, 2009; Neath & Nairne, 1995; Oberauer & Lewandowsky, 2008, 2011). Barrouillet, Portrat, Vergauwe, Diependaele, and Camos (2011, p. 1315) have stated that “there is no direct evidence against the hypothesis of a time-related decay in the short-term”, but other researchers have been much more critical and favour interference as the cause of forgetting (e.g. Lewandowsky et al. 2009; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012).

However, there does appear to be evidence for time-based forgetting in nonverbal auditory memory. In the classic two-tone comparison paradigm, participants are asked to contrast standard and comparison tones over a silent retention interval (RI) of variable length. To discriminate the two tones, participants must memorize the standard, yet numerous studies have reported a strong decline in performance as the RI separating the standard from the comparison is lengthened (see McKeown & Mercer, 2012, for a review of this literature). This is exactly what decay theory expects and such degradation of auditory memory traces over the passage of time is predicted by the timbre memory model (TMM). This account states that memories of auditory events are used to build predictive models of the acoustical environment, and consequently TMM is primed to detect and respond to novel sounds (McKeown & Wellsted, 2009; Mercer & McKeown, 2010a, 2010b). This may occur through a rapid memory updating process driven by the occurrence of new auditory events, but slow-acting decay would also be advantageous in allowing the removal of memories which are no longer useful (Altmann, 2009, offers a similar argument about decay in episodic memory).

Nonetheless, given the very strong anti-decay arguments outlined in the wider short-term memory literature (e.g. Lewandowsky et al., 2009), it is important to revisit the two-tone comparison procedure. This is particularly pertinent since there are alternative explanations for the performance decline at long RIs which have never previously been tested. Notably, following a prolonged RI, listeners may have become inattentive at the time the comparison stimulus occurred. By this account, it is not decay of the standard tone memory trace that accounts for poorer performance when the RI is extended, but rather it reflects wandering attention or lack of preparedness. A related but separate possibility links to a form of drifting attention in audition which is thought to be frequency-specific. It is known that listeners can effectively monitor a particular frequency, and a pure tone cue can direct listeners to a particular frequency (e.g. Green & McKeown, 2001). Perhaps, then, attention wanders from the standard tone frequencies at longer RIs, leading to a decline in discriminatory accuracy.

Experiment 1

Listeners compared the timbre of two complex tones separated by an extended RI. In order to examine the lack of preparedness account, we introduced an alerting tone towards the end of the RI. It was expected that this alert cue would permit the directing of attention to the upcoming comparison tone. We also included a condition in which the alert cue stimulus had the same frequency components as our standard and comparison tones, better to direct attention to the relevant frequencies and assess the wandering attention explanation. Hence, if poorer performance at long RIs is due to a drifting of auditory attention from the frequency region(s) of the standard tone over time, the frequency specific alert should act to counter this. Decay theory would anticipate no beneficial effects of the alert stimuli. To prevent the alert stimuli from interfering with task performance, they were always presented in the opposite ear to the standard and comparison. This can minimize retroactive interference effects (Starr & Pitt, 1997). A control condition (silent 30) omitted the alert tone. Figure 1 illustrates the trial arrangement.

“Figure 1 about here”

Method

Participants. Six participants (four female) ranging in age from 21 to 31 volunteered to take part. All individuals self-reported normal hearing and received hourly payment for participation.

Stimuli. The sounds that listeners compared over a time interval were similar to musical chords of several simultaneous "notes", having distinct timbres. They were the same tones used in McKeown and Mercer's (2012) first experiment, and consisted of six periodic complex tones consisting of eight frequency components. Four of these components were incremented by 5.1 dB, creating a subtle change in the timbre of the sounds. The frequency specific alert was also a complex tone comprising eight equal amplitude components without any distinguishing timbre, although this always occurred at the same pitch as the standard and comparison. The pure tone alert sound was a single "note" or frequency.

All stimuli were approximately 80 dB, 200 ms in duration and varied in intensity both between (0-9 dB) and within (0-6 dB) trials. The timbre complexes could be presented at any of seven pitches between trials (D at 146.8 Hz through Fs, A, C#1, E1, G1 and Bb1 at 466.2

Hz). The pure tone alerts were presented at six distinct pitches, each of which was associated with one of the timbres. Stimuli were created via TDT RP2.1 hardware, MathWorks MATLAB and TDT RPvdsEx software. Tones were attenuated (PA5), filtered (Kemo VBF21M filter: 100 Hz to 10 kHz), and output to STAX SR-303 Classic headphones. Participants completed the experiment whilst seated within an Industrial Acoustics Company double-walled sound-attenuating booth.

Design and procedure. Each trial commenced with a pure tone alert in the right ear. The to-be-memorized standard tone was then presented in the left ear 1 s after the offset of the alert cue. This alternation occurred with the same stimuli two more times, establishing a simple acoustical context. After the offset of the third standard, the comparison tone was presented in the left ear following an interval of either 1.2 or 30 s. Participants were required to determine whether the standard and comparison were the same or different, indicating their decision using a response box. When the RI was just 1.2 s, the next trial commenced 10 s after a response. The inter-trial interval (ITI) was increased to 35 s when the RI was 30 s, which helped to reduce confusion between tones on the current and previous trial.

A key manipulation was whether a tone occurred during the RI separating the standard and comparison. The intervals in the 1.2 s and silent 30 s conditions were always unfilled. In the experimental conditions, the 30 s interval also incorporated an alert tone in the right ear, occurring 1.2 s prior to the onset of the comparison. This was either a repetition of the pure tone alert encountered at the beginning of the trial or the frequency specific alert. Participants were told to ignore the alert tones in their right ear during standard tone presentation. In the 30 s condition a single alert tone prepared the participant for the presentation of the comparison tone. To eliminate proactive interference from previous trials, the pitch of the tones was varied between trials (see Mercer & McKeown, 2010b). The intensity of the stimuli was also varied between and within trials, to reduce the likelihood that listeners were using intensity information to perform the discrimination (Lentz, 2007). The abstract sounding timbres made it very difficult for participants to verbally encode the stimuli in a reliable fashion.

All participants began the study with a single training session, contrasting the standard and comparison tones over a silent 1.2 s interval. This was completed in a single session. Participants then proceeded to the testing stage. Every stimulus block was pre-programmed prior to the start of the experiment and was always original (i.e. participants never completed the same stimulus block twice and each trial was unique in some way). Conditions with 1.2 and 30 s retention intervals were completed in distinct blocks. Additionally, the silent 30 s condition was completed separately to conditions that incorporated the alert tone. Each of the four major conditions contained 84 trials and participants completed the experiment in individual 30 minute sessions over a period of several weeks.

Results and Discussion

To examine task performance, P_{ss} (number of times correctly responding "same" on same trials) and P_{sd} (number of times incorrectly responding "same" on different trials) were calculated and used to generate *d'*, a bias-free index of sensitivity (Bi, 2002). Two cases of perfect performance were identified in the 1.2 s condition (participants DG and LR) and these were corrected using the log-linear rule (see Snodgrass & Corwin, 1988). Performance in the 1.2 s condition was contrasted with silent 30 s using Gourevitch and Galanter's (1967) statistic. There was a significant drop in performance as the interval was extended, and this effect was reported for the group, $Z = 3.21$, $p = 0.001$, and all individual participants: CE, $Z = 2.28$, $p = 0.023$, DG, $Z = 2.20$, $p = 0.028$, EP, $Z = 4.00$, $p = 0.0001$, LR, $Z = 2.91$, $p = 0.004$, NS, $Z = 2.83$, $p = 0.005$, and RT, $Z = 4.32$, $p < 0.0001$. Accuracy on the task therefore strongly declined as the interval separating the standard and comparison tones increased, highlighting time-based forgetting.

"Figure 2 about here"

Crucially, Figure 2 (displaying group data) and 3 (displaying individual participant results) suggest that the pure tone and frequency specific alert cues had little effect. Indeed, performance in all conditions with a 30 s interval was worse than 1.2 s. Marascuilo's (1970) *K*-signal significance test, a statistic similar to the one-way within-subjects ANOVA, was used to contrast the four conditions. Significant main effects were found for the group, $\chi^2(3) = 14.85$, $p = 0.002$, and all individual participants, CE, $\chi^2(3) = 11.23$, $p = 0.012$, DG, $\chi^2(3) = 8.06$, $p = 0.045$, EP, $\chi^2(3) = 22.94$, $p < 0.0001$, LR, $\chi^2(3) = 17.40$, $p = 0.0006$, NS, $\chi^2(3) = 9.16$, $p = 0.027$, and RT, $\chi^2(3) = 28.21$, $p < 0.0001$. Gourevitch and Galanter's (1967) post-hoc comparisons revealed that discriminatory accuracy for both alert tones was significantly lower than 1.2 s for the group and participants CE, EP, LR, and RT. However, the pure tone alert and 1.2 s condition did not differ for participants DG ($Z = -0.58$, $p = 0.562$) or NS ($Z = -1.7$, $p = 0.089$), implying some equivalence in performance (although the pure tone alert *d'* did not differ from silent 30 either). None of the 30 s conditions significantly differed from each other. Overall, performance on this task was strongly affected by the duration of the RI, and the alert tones were quite ineffective in mitigating time-based forgetting. The decline in performance observed between 1.2 and 30 s was similar to the steady decline in performance observed in McKeown and Mercer (2012), which charted a gradual decline at intervals of 1, 2, 4, 8, 16, and 32 s. These data are therefore consistent with steady trace decay.

"Figure 3 about here"

Experiment 2

We now consider whether the time-based performance decline shown in previous two-tone comparison studies reflected decay in *short-term* as opposed to *sensory* memory. In visual discrimination tasks (e.g. Vogel, Woodman, & Luck, 2006) post-perceptual masks may be presented in the same modality as the to-be-memorized stimuli in an attempt to dissociate a highly detailed but fleeting sensory afterimage from a much less detailed but more enduring memory trace. Therefore in Experiment 2 an auditory pattern mask was introduced to explore decay in short-term acoustical memory. Participants compared standard and comparison complex tones over intervals of 2 or 32 s. The 200 ms masking noise, of a level and bandwidth sufficient to mask the standard tones were they to occur simultaneously, was presented 100 ms following the offset of the 200 ms standard. The intention was for the mask to eradicate any persisting sensory memory trace, but not interfere with *encoding* of the stimulus (known to be complete by 250 ms; Kallman & Massaro, 1979). Thus, if previously reported temporal forgetting was solely due to the involvement of a highly vivid *sensory* memory, there should be no differences between the 2 and 32 s conditions. Conversely, if *short-term* auditory memories do decay then a performance decline over the RI should still be evident. Importantly, this explanation has not previously been considered.

We also examined the role of temporal distinctiveness. According to Brown, Neath, and Chater's (2007) SIMPLE, memories are (partly) represented by a temporal dimension encoding representations along a continuum from the immediate present to the past. Retrieval is determined by whether an individual is able to discriminate the target memory from its temporal neighbors, and this becomes more difficult as time passes due to temporal crowding. Within the two-tone comparison paradigm, a trial consists of a sequence of standard and comparison stimuli separated by the RI. As such, the memory trace of the standard stimulus on trial *N* is distinct to the extent that it is well separated from surrounding stimuli, most importantly the comparison stimulus on trial *N*-1, but also the comparison stimulus on trial *N*. Therefore, according to distinctiveness accounts, performance should be determined not by the *absolute* RI duration, but by the *ratio* of this interval to the interval separating the standard from the previous comparison tone (the ITI). The ITI was then varied (either 2 or 34 s). Distinctiveness models would expect performance to improve as the ITI was lengthened, and this should occur for both 2 and 32 s RIs. Conversely, theories which rely on decay would still expect ITI duration to have relatively little effect. We do already have evidence against distinctiveness (McKeown & Mercer, 2012, Experiment 2), but the stimuli on successive trials were very dissimilar in that experiment, thereby limiting the chances of distinctiveness expressing itself. Therefore in the present experiment the frequencies of our stimuli varied within quite a narrow range from trial to trial, ensuring a high degree of stimulus overlap. This served to maximize the possibility of proactive interference from previous trials, creating a better setting through which to examine distinctiveness.

Method

Participants. Four female participants with self-reported normal hearing (aged 21-22) volunteered for the study.

Stimuli. Two complex tones comprising four components served as the standard and comparison tones. Two of the components within these tones were incremented by 7 dB to create a change to the spectral profile, and the frequencies of the components were adapted from those used by Moore, Glasberg, Low, Cope, and Cope (2006). See Table 1. Tone stimuli were approximately 78 dB, 200 ms in duration (including a 10 ms cosine onset and offset ramp) and roved in intensity (0-6 dB) within trials. The 200 ms noise mask was approximately 80 dB, a level that we established was sufficient to make the timbre of the standard tone unrecognizable when standard tone and mask were presented simultaneously. The hardware arrangement was the same as Experiment 1.

Design and procedure. The two-tone comparison procedure was used and there were four combinations of RI (2 vs. 32 s) and ITI (2 vs. 34 s). Each RI:ITI condition was run in a separate trial block. To equate participants' attending levels across sessions, there were 30 trials within a 2:2 block, 20 trials in the 2:34 and 32:2 blocks, and 12 trials in the 32:34 blocks. Participants completed 60 trials in each condition.

All individuals began the study with a number of training sessions, contrasting the standard and comparison tones over a silent 2 s interval until they could reliably perform the discrimination. Participants then proceeded to the testing stage. Every block was pre-programmed prior to the start of the experiment and the participants completed four different orders of the blocks over a period of several weeks; orders were fully counterbalanced across participants.

Results and Discussion

Time-based forgetting. As before, cases of perfect performance were corrected with the log-linear rule (here for participants AC, BE and CF). Figure 4 displays performance for the group (panel 1) and each individual participant (panels 2-5). The ability to discriminate the standard and comparison tones declined as the RI increased, although ITI did not appear to have a consistent beneficial effect. Specifically, whilst participants EK and AC appeared to show a small improvement as the ITI was extended for the 2 s RI, BE and CF showed the opposite effect. The *K*-signal test was used to examine differences between the four temporal conditions (2:2 vs. 2:34 vs. 32:2 vs. 32:34). A significant main effect of condition was reported for the group, $\chi^2(3) = 20.96$, $p = 0.0001$, and all individual participants: AC, $\chi^2(3) = 24.81$, $p < 0.0001$, BE, $\chi^2(3) = 18.86$, $p = 0.0003$, CF, $\chi^2(3) = 11.27$, $p = 0.01$, and EK, $\chi^2(3) = 22.4$, $p < 0.0001$. Post-hoc tests revealed that performance at 2 s was always significantly better than 32 s, regardless of ITI duration (the only exception was participant CF – she showed a marginally significant difference between 2:34 and 32:2, $Z = 1.95$, $p = 0.052$). There was no reliable difference between ITIs (i.e. 2:2 = 2:34; 32:2 = 32:34).

"Figure 4 about here"

These data demonstrate a strong effect of time, with participants' discriminatory ability being severely impaired as the RI was lengthened from 2 to 32 s. This time-based decline was found despite the presence of a mask, therefore supporting the belief that *short-term* auditory memories decay over the passage of time. Experiment 2 also challenged distinctiveness models, since discriminatory performance only seemed to be influenced by the absolute length of the RI, not the ITI.

General Discussion

Understanding how the passage of time affects memory and forgetting is of central theoretical importance to experimental psychology, but it is also one of the most controversial topics and trace decay has been heavily criticised, at least for verbal memory (e.g. Lewandowsky et al., 2009). For non-verbal stimuli, the present study has uncovered that time-based forgetting in short-term memory is 1) not explicable by a wandering attention account, 2) not due to a lingering contribution from sensory memory, and 3) not caused by proactive interference from stimuli on previous trials, even when there is a high level of similarity between tones on successive trials. The decline in performance at extended retention intervals therefore seems to be most consistent with memory trace decay, yet this time-based forgetting also appears to be very slow, unfolding over periods of half a minute, even in the presence of a mask. Yet a recent study, not dissimilar to our Experiment 2, has provided evidence against temporal decay. Horoufchin, Phillipp, and Koch (2011) examined performance in a perceptual judgment task in which a cue (a dollar sign or yellow squares) indicated the response type for one of two concurrent tasks. What was varied over four experiments was control over successive durations of the interval from the response on one trial to the cue on the next (the response-cue interval or RCI), with the presumed “decay” being the prior activation of the task "set" or preparedness from the previous trial. On the basis of their data they concluded that “task-set activation does not decay as a mere function of time during the RCI” (p. 469). Of course, there are many differences between our tasks and stimuli. But perhaps the major difference is the time-scales involved. Whilst we used intervals varying between 1 s and 32 s, their intervals were varied over a range of 100 ms to 2 s (Experiment 1) or a range of 100 ms and 1 s (Experiments 2, 3 and 4). These intervals may be insufficient to uncover slow-acting trace decay, and we would argue that the “short” in short-term memory should be extended greatly if we are to understand the decay of memory traces.

It is an exciting time to be investigating human immediate or short-term memory, with the functional role of memory decay being uncovered and its biological bases identified (e.g.

Hardt, Nader, and Nadel, 2013). We have earlier presented a theoretical conception of immediate memory which acts as a predictor and updater of the auditory environment, and proposed that a slow decay process is adaptive: when an acoustical event has not re-occurred after a certain period of time, there may be little value in continuously maintaining it within the memory buffer (McKeown & Wellsted, 2009; Mercer & McKeown, 2010b). But by maintaining auditory information for tens of seconds, it is possible to build predictive models of the acoustical environment that can be updated when necessary, so that the time-course of minutes may be ideal for a gradually changing auditory environment, charting changes but maintaining old patterns. For nonverbal visual patterns, Ricker and Cowan (2010) have shown quite marked decline in discriminative performance over a relatively short time period of 6 s. And Zhang and Luck (2009) charted "sudden death" in visual memory for colours between 4 and 10 s, on the basis of little change in variance of performance between these time intervals (taken as an index of memory precision) but an increase in the proportion of "chance" errors (taken as an index of complete loss of memory). And, consistent with our conception of a predictive auditory memory, the updated contents of immediate visual memory may drive what is prioritised by attention (e.g. Hollingworth, Matsukura, & Luck, in press). We therefore conclude by speculating that the time-course of visual immediate forgetting (and updating of the memory buffer) may follow a much more rapid time course than auditory forgetting. The case for verbal memory remains open (Barrouillet et al., 2012; Campoy, 2012; Oberauer & Lewandowsky, in press).

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Figure captions

Figure 1. Design of Experiment 1. P = pure tone alert; S = standard tone; C = comparison tone; A = alert tone. Each trial began with the alternating presentation of a pure tone alert stimulus and the standard tone, separated by a 1 s gap. The retention interval (RI) between the third standard tone and the comparison stimulus was 1.2 or 30 s, and listeners had to determine whether the two sounds were the same or different. In two additional conditions another alert tone was presented in the right ear 1.2 s prior to the onset of the comparison. This was either a repetition of the pure tone alert (P) or a flat spectrum complex tone presented at the same pitch as the standard and comparison (frequency specific alert). Conditions featuring the alert tone always had a 30 s RI.

Figure 2. Task performance (*d'*) for the group data of Experiment 1. Error bars reflect +/- 1 standard error of *d'* (see Macmillan & Creelman, 2005).

Figure 3. Task performance, highlighted by *d',* for each individual participant in Experiment 1. Error bars reflect +/- standard error of *d'*.

Figure 4. Results from Experiment 2 displaying *d'* for group data (panel 1) and individual participants (panels 2-5). The retention interval (2 or 32 s) is shown on the *x*-axis. The black line shows conditions with a 2 s inter-trial interval and the gray line shows conditions with the longer 34 s ITI. Error bars reflect +/- 1 standard error of *d'.* Participants AC and EK were 100% correct on trials in the 2:2 and 2:34 conditions, respectively.

Figures

Figure 1

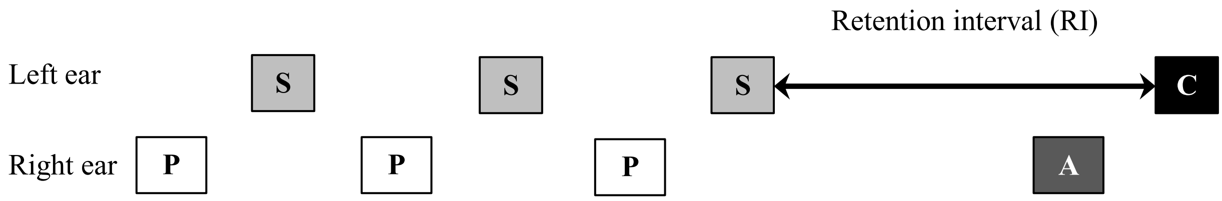


Figure 2

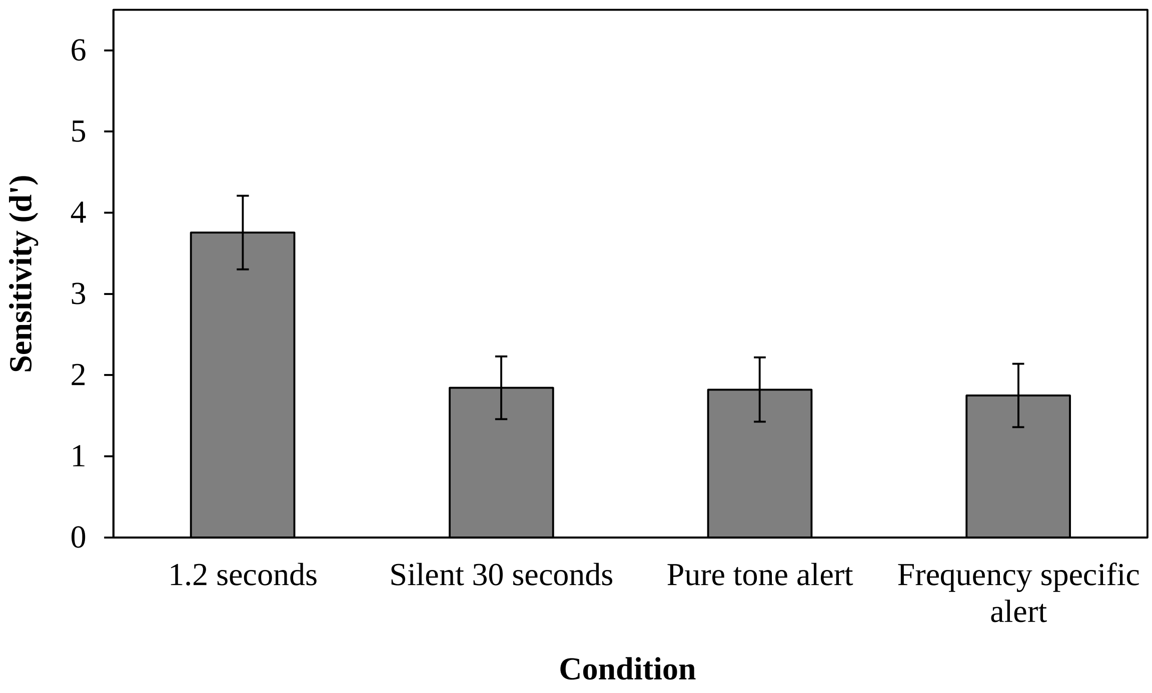

6
5
4
3
2
1
0
Sensitivity (d')
1.2 seconds
Silent 30 seconds
Pure tone alert
Frequency specific alert
Condition

Figure 3

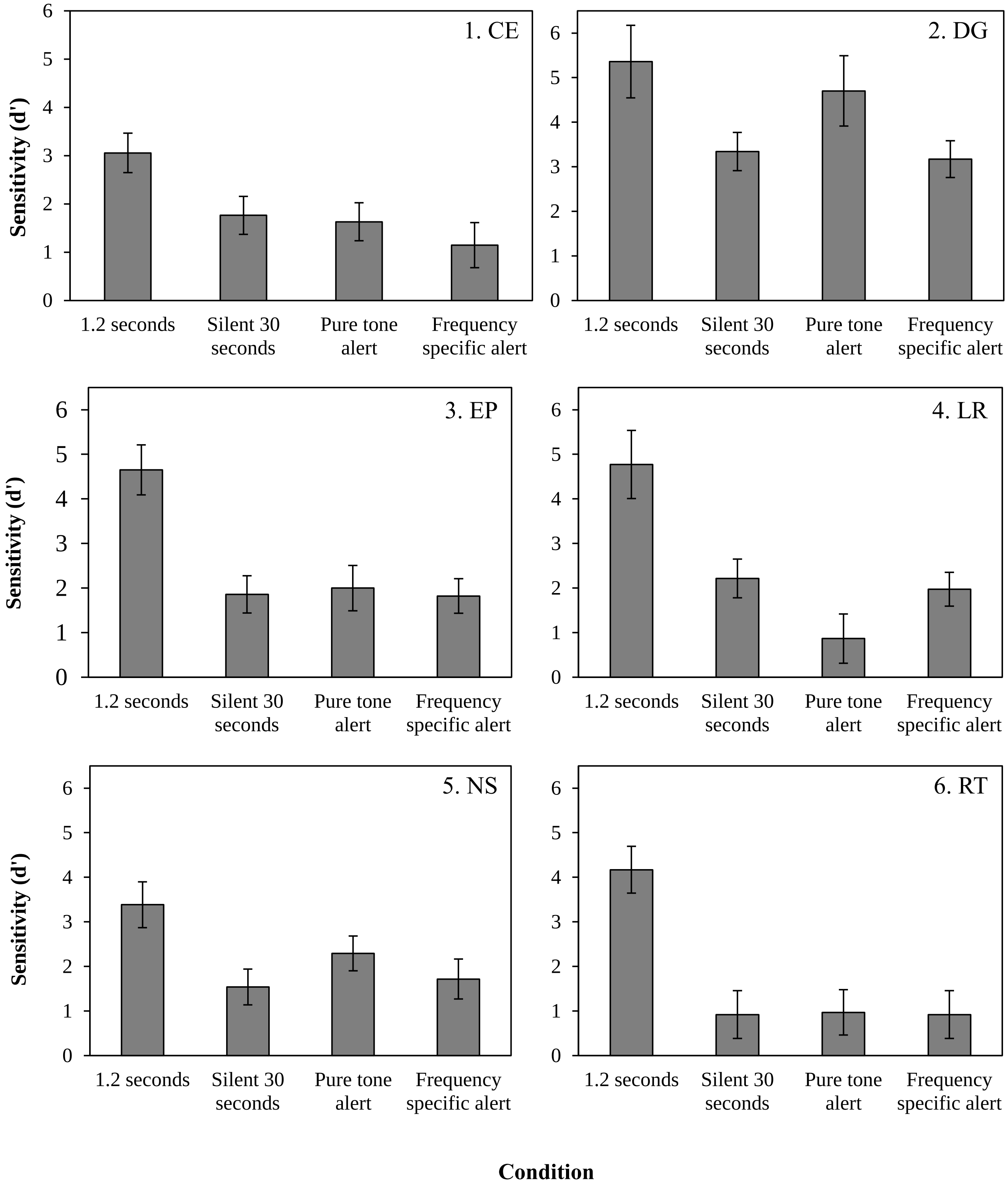
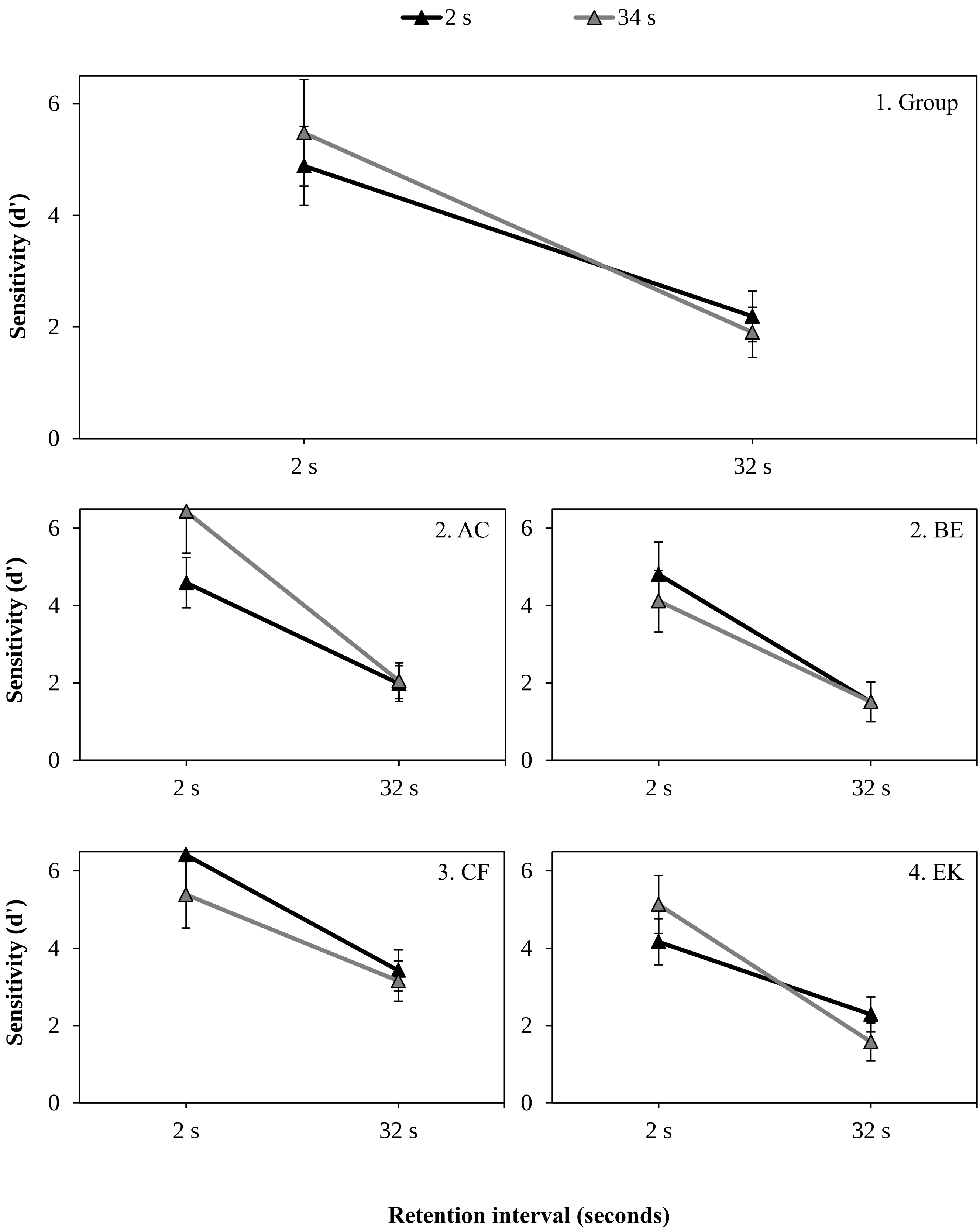

1. CE
2. DG
3. EP
4. LR
5. NS
6. RT
Sensitivity (d')
1.2 seconds
Silent 30 seconds
Pure tone alert
Frequency specific alert
Condition

Figure 4


2 s
34 s
1. Group
2. AC
2. BE
3. CF
4. EK
Sensitivity (d')
0
2
4
6
2 s
32 s
Retention interval (seconds)

Tables

Table 1.

Frequencies of each component of the complex tones used in Experiment 2. Stimuli are adapted from those used by Moore et al. (2006).

Tone	**Frequency (Hz)**			
1	652	806	988	1201
2	806	924	1055	1201
3	893	988	1090	1201
4	2094	2501	2980	3544
5	2501	2812	3158	3544