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Abstract

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Emotion typically enhances memory for emotional events relative to neutral events, a phenomenon often referred to as the emotional memory effect. Studies of this effect have used a variety of visual and verbal stimuli, but almost no studies have used emotional sounds (e.g., dogs snarling) and none have investigated recognition memory for emotional sounds. Thus, here we examined recognition memory for negative and neutral environmental sounds, predicting enhanced memory for negative stimuli. Based on the finding that emotional memory effects for visual stimuli are almost always reflected in the recollection component of recognition memory (remembering accompanied by contextual information) rather than the familiarity component (a sense of knowing without context), we further predicted that enhanced memory for emotional sounds would be reflected in recollection alone. To investigate these hypotheses, we conducted an online experiment in which participants first encoded 96 sounds (48 negative and 48 neutral). After a 15-minute delay, memory retrieval was assessed with a remember-familiar recognition memory task with semantically-matched target and distractor items to reduce the potential use of associated verbal descriptions. As predicted, recognition memory performance was enhanced for negative sounds relative to neutral sounds, and this enhancement was found for recollection, but not familiarity. Recognition performance was also higher for high- vs. low-arousal negative sounds. These results demonstrate that emotional enhancement effects observed for visual and verbal stimuli also extend to the auditory modality, and that, paralleling previous findings, this effect is reflected in recollection processes alone. These findings suggest that key properties of emotional memory are modality independent and help pave the way for future neuroimaging studies of memory for emotional sounds which can determine the extent to which the neural mechanisms of emotional memory are similar across stimulus modalities.

Keywords: Memory, emotion, auditory memory, emotional memory, recognition memory

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Introduction

Emotion typically enhances memory for emotional events relative to neutral events, a phenomenon often referred to as the *emotional memory effect*. Enhanced memory for emotional events is likely beneficial to evolutionary fitness, highlighting the potential impacts of salient information to long-term survival and reproduction (Hamann, 2001); for example, a brutal car accident is remembered better than a routine drive to the grocery store. Laboratory studies have typically used visual stimuli such as pictures to assess this phenomenon, and have demonstrated emotional enhancement effects in episodic memory (temporally and spatially specific memories for events) over a variety of retention intervals (e.g., Bradley et al., 1992). Emotional stimuli such as these are frequently described in terms of their component properties. According to dimensional theories of emotion, the two most important dimensions of emotion are valence (the extent to which an emotion is positive or negative) and arousal (the intensity or strength of an emotion). Although episodic memory is also enhanced for positive emotional stimuli, memory for negative stimuli is typically stronger than for positive stimuli (Bowen, Kark, and Kensinger, 2018).

Considerable evidence suggests that special neurobiological mechanisms enhance memory for emotional events. The amygdala, an almond-shaped subcortical brain structure located deep within the temporal lobe, plays a key role in facilitating this memory enhancement effect (Hamann, 2001). Through its highly elaborate connections with multiple brain regions – and in particular, the hippocampus – the amygdala facilitates the enhancement of memory for emotional events at all stages of memory processing: encoding (Cahill et al., 1996; Canli et al., 2000, Hamann et al., 1999a; Hamann and Mao, 2001) consolidation (Adolphs et al., 1997; Cahill et al., 1995), and retrieval (Dolan et al., 2000; Fink et al., 1996; Rauch et al., 1996) (Hamann, 2001). These studies have used diverse types of stimuli (e.g., pictures, films, words, and personal autobiographical memories) and have employed a range of methodologies (e.g., fMRI paradigms, PET imaging, and lesion studies) to investigate these enhancement effects.

In addition to enhancing overall memory accuracy, the effect of emotion on episodic memory appears to primarily be reflected in what has been termed the process of *recollection*. In dual process theories of memory (Yonelinas, 1994; Wixted, 2007), episodic memory is primarily mediated by two underlying processes: *recollection* and *familiarity*. *Recollection* is defined as episodic memory retrieval that is accompanied by contextual details of the original encoding event (e.g., a feeling of sadness, or thought about a scene in a recent television show one watched), while *familiarity* represents a feeling of 'knowing' that an event or stimulus has been previously experienced, but without the retrieval of these contextual details. Familiarity can vary in strength, reflecting varying degree of confidence that one has encountered an event or stimulus previously (Yonelinas 1994, 2002; Wixted, 2007). Although the two processes both contribute to the ability to recognize a previously encountered event or stimulus as old (previously encountered), considerable experimental evidence indicates that the processes of recollection and familiarity can be dissociated both behaviorally and neurally. For example, whereas familiarity is proposed to be a fast, relatively automatic process, recollection is a relatively slower process and is more effortful and strategic (Hintzman and Caulton, 1997; Hintzman, Caulton, and Levitin, 1998; Gronlund, Edwards, and Ohrt, 1997). Recollection and familiarity also differ in how they are affected by different experimental manipulations (e.g., divided attention affects recollection but not familiarity; Jacoby and Kelley, 1992), and lesion and neuroimaging evidence strongly suggests that these two processes are mediated by different networks of brain regions (e.g., Aggleton and Brown, 1999; Eichenbaum, Otto, and Cohen,

1993) (Yonelinas, 2002). For example, although some debate remains regarding the specific regions involved in recollection vs. familiarity, there is considerable support for the view that recollection but not familiarity is impaired by hippocampal lesions.

With very few exceptions, behavioral and neuroimaging studies have suggested that the emotional enhancement of memory is driven by emotional effects on recollection rather than familiarity. For instance, Ochsner (2000) found that the memory advantage for emotional pictures was primarily reflected by the enhancement of recollection rather than familiarity. In addition, Doerksen and Shimamura (2001) found that emotional arousal was associated with enhanced source memory (a process requiring recollection because it involves retrieval of encoding context for words; Kensinger and Corkin, 2003). The specific effects of emotion on recollection are consistent with studies that have reported that emotional events are remembered with greater detail and vividness (Baraly et al., 2016; e.g., Oschner, 2000). Additionally, several studies indicate that amygdala activity is heightened for – and perhaps even specific to – recollected emotional memories, as opposed to those that are merely familiar (Dolcos, LaBar, and Cabeza, 2005; LaBar and Cabeza, 2006; Sharot, Delgado, and Phelps, 2004). Together, these studies indicate that emotional enhancement effects are principally reflected in recollection processes of episodic memory.

There has been little emotional enhancement of memory beyond the visual modality (e.g., pictures or visually presented words). Of particular interest are auditory stimuli, which are crucial to physical and socioemotional function in daily life, as well as broader wellbeing and survival. Indeed, emotional sounds – such as the roar of a nearby bear – are arguably among the most biologically relevant stimuli. Examining memory for emotional sounds, in the context of a known enhancement effect for visual stimuli, would allow for a more complete picture of the influence of emotion on memory across modalities.

Remembering auditory information from our environments allows us to make inferences about the identity, location, structure, and function of surrounding organisms and objects, as well as the emotional states of others. Auditory stimuli often accompany visual stimuli; indeed, recognition memory for auditory and visual stimuli share a common neural substrate within the medial temporal lobe (Squire, Schmolck, and Stark, 2001). However, sounds can be present alone, without an associated visual stimulus (e.g., the sound of a fallen object in an unseen room). Memory for these isolated sounds can be equally significant, in this case enabling the listener to easily identify the fallen object as their new glass vase and a hazard to passersby that should be swiftly addressed. Understanding the nature of auditory memory, in both its durability for different classes of sounds and in comparison to other modalities, is foundational to characterizing how humans process information at the core of our lived experience.

In the laboratory, human memory for sounds is typically poorer than memory for visual stimuli such as pictures (Gloede and Gregg, 2019), scenes (Cohen, Horowitz, and Wolfe, 2009), and more dynamic stimuli such as videos (Bigelow and Poremba, 2014). This disparity is particularly evident at immediate test (Bigelow and Poremba, 2014; Cohen, Horowitz, and Wolfe, 2009) and at short delays (i.e., same day; Gloede and Gregg, 2019; Gloede, Paulauskas, and Gregg, 2017). Here, memory accuracy for visual stimuli is approximately 8-15% higher than for auditory stimuli (Bigelow and Poremba, 2014; Gloede and Gregg, 2019). Such disparities appear to be fairly robust, with one group finding that pairing sounds with relevant visual stimuli (i.e., a picture of the object that produces the sound) does not significantly benefit later memory for these sounds (Cohen, Horowitz, and Wolfe, 2009). The advantage of visual over auditory memory in humans also mirror that previously identified in nonhuman primates (Bigelow and Poremba, 2014; Cohen, Russ, and Gifford, 2005; Colombo and D'Amato, 1986; Kojima, 1985; Munoz-Lopez, Mohedano-Moriano, and Insausti, 2010; Wegener, 1964). Several potential explanations for an auditory memory deficit have been offered, including that auditory information initially has a more generalized memory representation (Bigelow and Poremba, 2014; Gleode and Gregg, 2019), enjoys a lower overall capacity than visual memory (Cohen, Horowitz and Wolfe, 2009), or is even supported differently by memory-relevant structures in the medial temporal lobe (i.e., the hippocampus-adjacent cortices; Bigelow and Poremba, 2014).

In order to assess the nature of emotional auditory memory in the laboratory, two of the developers of IAPS created a smaller database of 111 emotional sounds (Stevenson and James, 2008) known as the International Affective Digitized Sounds (IADS; Bradley and Lang, 1999). After an expansion of this repository nearly a decade later (IADS-2 and -E; Bradley and Lang, 2007; Yang et al., 2018), the complete set consists of over 900 six-second clips encompassing a wide variety of naturalistic and artificial sounds, from waves crashing to ambient conversation and mechanical sirens. Included with each sound clip are normative ratings of valence (i.e., degree of positivity or negativity), arousal (i.e., intensity), and other qualities. To compare the emotional distribution of these stimuli to the pictorial IAPS database, Bradley and Lang (2000) obtained additional valence and arousal ratings for a subset of IADS sounds and found a similar pattern: low-arousal sounds are typically neutral in valence, while high-arousal sounds are either positively- or negatively-valenced. This similarity demonstrates that any divergence in emotional enhancement effects of memory for sounds and images is likely not due to differences in the overall affective properties of these two types of stimuli.

A recall memory test in the same study revealed that high-arousal (i.e., emotional) sounds were remembered significantly better than neutral sounds, with 5-10% more emotional sounds accurately recalled. This effect mirrors the emotional enhancement of memory for visual stimuli. In addition, the authors also verified psychophysiological responses to emotional sounds by using facial electromyography, electrocardiography, and skin conductance electrodes (Bradley and Lang, 2000). However – although this study was instrumental in better characterizing the initial IADS database – to our knowledge, it is the only investigation of emotional auditory memory in adults (see Burrell, Johnson, and Melinder, 2016 for a limited study in children). Indeed, much remains to be known about memory for emotional sounds that this study did not fully address.

Bradley and Lang (2000) assessed memory for auditory stimuli with a free recall test, in which participants are asked to verbally describe all of the items they can recall from a previously-presented list. Because the stimuli Bradley and Lang (2000) used could be labeled easily with distinctive verbal descriptions (e.g., 'dog barking'), an important limitation of their study is that it is unclear to what extent participants' free recall performance may reflect memory for the auditory stimuli themselves (i.e., the perceptual features of the sounds) versus memory for verbal labels that participants may spontaneously generate during the encoding phase. Indeed, previous studies have shown that participants spontaneously label sounds and that this can enhance later free recall (e.g., Crutcher and Beer, 2011, as in pictures, Paivio and Csapo, 1973); thus, free recall for sounds likely reflects a combination of memory for a sound's auditory perceptual details and verbal descriptions. Also, in contrast to auditory stimuli, verbal labels can be potentially rehearsed during encoding, further increasing the contribution of verbal memory processes to free recall for sounds.

Because our primary interest in the current study was to examine the effect of emotion on memory for auditory stimuli, we took steps to reduce the possible contribution of verbal memory. By using a recognition paradigm with targets (i.e., items presented during encoding) and distractors (i.e., new items presented only during the recognition test) that were closely matched on semantic category, we greatly decreased the potential effectiveness of verbal labels in contributing to recognition memory. For example, for a target sound consisting of a dog barking presented during encoding, during the recognition task the same target sound would be presented intermixed with other sounds, including *another* sound of a different dog barking. With the most recent expansion of IADS (Yang et al., 2018), as well as access to numerous online auditory repositories (e.g., Epidemic Sound; https://www.epidemicsound.com/) we were able to capitalize on an extensive pool of stimuli to draw on for semantic matching for both negative and neutral sounds and to ensure that the degree of similarity between matched sounds (i.e., the two dog barking sounds) were balanced across valence. This balance is essential to make certain that the likelihood of being able to generate a verbal description is the same (i.e., minimized) for both negative and neutral sounds.

As previously mentioned, the emotional enhancement of memory for pictures and words has been reported to be primarily reflected in recollection and not in familiarity (e.g., Oschner, 2000; Doerksen and Shimamura, 2001; Kensinger and Corkin, 2003). However, given that performance on free recall tests is generally considered to be mediated by recollection and not by familiarity (Baraly et al., 2016), we cannot fully assess predictions about this process dissociation for auditory stimuli using free recall. In contrast, performance on recognition memory tests is mediated by a combination of recollection and familiarity processes. Recognition tests of auditory memory therefore provide the opportunity to assess potential emotional enhancement effects across both recollection and familiarity. Indeed, recollection and familiarity for auditory stimuli have been successfully assessed using recognition tests in previous human studies, finding distinct levels of performance for each memory component in certain groups (Drakeford et al., 2006; Libby et al., 2012).

Thus, in the current study we had the following two aims: 1) to determine whether recognition memory performance for emotionally negative auditory stimuli is enhanced relative to neutral auditory stimuli, paralleling emotional enhancement effects for words and pictures, and 2) to determine whether the process of recollection for auditory stimuli is specifically enhanced for negative relative to neutral auditory stimuli. We also predicted that the emotional enhancement of memory would not be present in familiarity, based on the prior findings for pictures and words. Investigating these aims will extend prior emotional memory work in other modalities to a new stimulus domain, and will determine whether key findings obtained with in the visual modality also extend to nonverbal auditory stimuli (Bradley and Lang, 2000), setting the stage for future investigations into the extent to which the mechanisms of emotional memory enhancement are modality-independent.

To address these aims, we conducted a within-subjects online experiment that examined recognition memory performance for novel negative and neutral environmental sounds. In the encoding phase, participants incidentally encoded a series of 6-second negative and neutral sound clips, making emotional arousal ratings for each stimulus. Next, during the retention phase, participants engaged in a distractor task for 15 minutes. In the retrieval phase, memory for the target sounds was assessed using a 6-point remember-familiar recognition task in which target (old) sounds were intermixed with an equal number of distractor (newly presented) sounds. Estimates of recollection and familiarity processes were calculated from performance on the remember-familiar recognition task. At the end of the experimental session, participants made emotional valence ratings for each target sound. We predicted that, paralleling prior results in other modalities, recognition memory accuracy would be enhanced for negative sounds than neutral sounds (demonstrating emotional enhancement of memory), and that this enhancement would be observed for the estimate of recollection but not for the estimate of familiarity.

Materials and Methods

Participants

43 total Emory undergraduate students completed this study in partial fulfillment of an introductory psychology requirement. Students were given the option to complete an alternative assignment if they opted not to participate. All participants gave informed consent for study procedures approved by the Emory University Institutional Review Board. We excluded seven participants for insufficient (i.e., >20% missing) rating responses and one participant for anomalous rating responses (i.e., providing only two out of seven of the possible responses), which demonstrated inattentiveness to the sound stimuli and/or low engagement with the task. 35 participants (26 female; *M* age = 18.80 $\pm$ 0.96) were included in the final analysis.

Stimuli

108 sounds were selected from a combination of the IADS-2 (Bradley and Lang, 2007) and IADS-E (Yang et al., 2018) databases. This set of 108 sounds was divided into two subsets of 54 sounds each, with each set used as either target items ('old' items presented during encoding and again during retrieval) or distractor items ('new' items presented only at retrieval). To decrease the effectiveness of verbal labeling strategies during encoding and to increase the difficulty of the recognition test by increasing similarity between targets and distractors, each target-distractor pair was matched on semantic category and normative valence (i.e., such that

the sounds were either both negative or both neutral). This matching procedure was further validated by obtaining similarity ratings from five research assistants, who listened to each target-distractor pair and rated the pairs on a scale from not perceptually similar at all (1) to very perceptually similar (5). The 24 negative and 24 neutral pairs with the lowest similarity ratings were retained. This produced a final set of 96 sounds, with 48 targets and 48 semantically similar distractors. The following statistics were calculated prior to piloting. Negative items (e.g., a belch) and neutral items (e.g., footsteps) had significantly different normative valence (M_{neg} = 2.92; M_{neu} = 4.73), $t(94) = -13.21$; $p < .001$, and arousal ratings (M_{neg} = 6.27; M_{neu} = 5.38), $t(94) = 4.78$; $p < .001$. Normative valence and arousal ratings were measured out of 10. Similarity ratings from the previously-described group of research assistants for negative (M = 2.94) and neutral (M = 3.18) target-distractor pairs were not significantly different, $t(46) = -1.48$; $p = .15$. Negative (M = -2.54) and neutral (M = -2.86) items also did not significantly differ in peak amplitude, $t(90) = .0.54$; $p = .59$. Two rounds of piloting (total $n = 32$) were conducted prior to the final experiment. These two pilot studies had very similar designs, with the major differences being 1) 6s or 3s sound presentation, respectively and 2) a 10 min or 24 hr delay period, respectively. After piloting, 14 negative and neutral items were removed due to high average false alarm rate and replaced with 10 items from the IADS databases, as well as four items from an additional online source (Epidemic Sound; https://www.epidemicsound.com/) edited for length. All sounds were 6s in length. Stimuli and instructions were presented using the behavioral experiment software program PsychoPy (Peirce et al. 2019), and the experiment was hosted on the online platform Pavlovia (https://pavlovia.org/).

Online Sound Presentation

Auditory stimuli should ideally be presented in a highly controlled laboratory environment in which experimenters can control sound volume, the acoustic properties of participants' surroundings, and other factors (Seow and Hauser, 2021). However, because this study was conducted online due to risks associated with the COVID-19 pandemic, best-practice procedures for administering online studies using online studies with auditory stimuli were employed. The current study utilized an adapted version of the calibration procedures described by Seow and Hauser (2021), which were administered prior to stimuli presentation. These procedures included the following: 1) Ensuring the use of earbuds or headphones by participants 2) Verifying that participants set their computer system volume to a loud, but not uncomfortable level which was to remain the same throughout the experiment, and 3) Presenting three test trials to participants, who in each trial indicated which of three sounds of different volumes was the quietest. One of these trials was difficult to complete without earbuds or headphones. In addition to these calibration steps, participants were asked if all of the sounds presented for encoding were audible, either directly after encoding or later in the experiment. These measures helped to ensure that each participant could hear all of the sounds in the experiment clearly.

Procedure

The experimental design consisted of one online session conducted on Zoom (Zoom Video Communications Inc., 2021), which was approximately one hour in duration. At the start of the experiment, participants were asked to share their screen and computer audio, and were encouraged to leave their camera on for the entire procedure (one participant did not) in order help ensure that the participant was engaged with the task. After informed consent was obtained and participant audio was calibrated, the encoding phase occurred. In the encoding phase, 48 target sounds (24 negative, 24 neutral) were presented in a pseudorandom order (with no more than two consecutive sounds of the same valence). Two additional neutral sounds, which did not appear elsewhere in the experiment, acted as buffers at the start and end of the encoding task. Each encoding trial (10s total duration) consisted of a 1s orienting cross (ISI), a 6s sound presentation, and a 2s arousal rating (1-7; 1 = low level of emotion; 7 = high level of emotion); see Figure 1. The arousal rating task was used to assess the participant's emotional response to each sound and also served to promote active semantic engagement with the sound stimuli. A brief practice phase preceded the encoding phase in which participants rated their arousal level for one negative and one neutral sound.

The encoding phase was followed by a delay interval consisting of 15 minutes of an online puzzle game (Tetris; https://tetris.com/play-tetris; audio included) in which the objective was to eliminate rows of game pieces by manipulating these pieces in space. Participants were instructed to start the game over if they lost before 15 minutes had passed, and were led to believe that the experimenter recorded their score for evaluation. This task simply served as a distractor task to maintain cognitive engagement and discourage memory rehearsal during this time.

Next, in the retrieval phase, participants completed an unexpected remember-familiar recognition memory test for the sound stimuli from the encoding phase. Here, all of the 24 negative and 24 neutral target sounds from the encoding phase were presented intermixed with an equal number of negative (24) and neutral (24) sounds from the corresponding set of distractor items that had been closely matched on semantic and other properties. Thus, a total of 96 sounds (48 old and 48 new sounds) were presented in the recognition memory task. Items were presented in a pseudorandom order, such that no more than two sounds of the same valence and no more than two targets or distractors were presented consecutively. Each retrieval trial consisted of a 1s orienting cross, a 6s sound presentation, and a self-paced recognition memory judgment. For this recognition judgment, participants indicated whether they recollected the presented sound (6 = remember) or alternately, judged the sound be more or less familiar, using a 1-5 scale (1 = definitely new, 2 = probably new, 3 = not sure, 4 = probably old, 5 = definitely old); see Figure 2. A brief practice phase preceded the retrieval phase in which participants encoded one negative and one neutral sound and then provided their recognition judgment for these two 'target' sounds intermixed with two similar 'distractor' sounds. Participants were encouraged to explain their choices to ensure adequate understanding; these were verified or corrected by the experimenter, with additional clarification as necessary. The qualitative distinction between strong familiarity (5) and recollection (6) was emphasized, with recollection necessitating the memory of a particular association, thought, or feeling (i.e., contextual detail) from the time of original sound presentation; see test instructions in Appendix A. A final task consisted of valence ratings (1-7; 1 = negative; 7 = positive) for all target sounds in order to further assess the participant's emotional response to each sound; see Figure 3. Sounds were arranged in four lists each for encoding and retrieval to ensure that the stimuli appeared equally often as targets and distractors and in four different orders during both encoding and retrieval. In this way, four versions of the experiment were used for stimulus counterbalancing. 20s breaks were given throughout the session following every 24 sounds.

Statistical Analysis

The memory and ratings data for each participant were processed and examined for abnormalities as previously described. Overall recognition memory was evaluated by calculating hit rates ($\frac{\#\ of\ hits}{\#\ of\ targets}$), false alarm rates ($\frac{\#\ of\ false\ alarms}{\#\ of\ lures}$), corrected recognition scores (hit rate –

false alarm rate) and *d*' discriminability measures (Gaetano, 2017) for each valence, within each participant. The *d*' measure assesses memory accuracy separately from a participant's bias to respond that a certain item is 'old' or 'new' (Verde, MacMillan, and Rotello, 2006).

For overall recognition memory scoring, 'new' and 'not sure' responses (1-3) were collapsed into the response category 'new', and 'old' and 'remember' responses (4-6) were collapsed into the response category 'old', following a similar analysis method used in Ritchey et al. (2015) to collapse a 6-point scale into binary old/new response categories. Paired *t*-tests (two-tailed, α = .05) were used to compare participants' mean corrected recognition scores and *d*' scores for negative and neutral sounds. A two-way repeated measures ANOVA with Memory Component and Valence as within-subject factors assessed recollection- and familiarity-specific effects. To calculate the recollection estimate (RE = recollection hit rate – recollection false alarm rate), the 'remember' response (6) alone was designated as old. To calculate the familiarity estimate (FE = $\frac{familiarity\ hit\ rate}{1-recollection\ hit\ rate} - \frac{familiarity\ false\ alarm\ rate}{1-recollection\ false\ alarm\ rate}$), 'old' responses (4-5) were designated as old. Recollection and familiarity estimates were combined on one scale for the 'memory estimate' outcome variable in this ANOVA (a process endorsed by Ozubko, Gopie, and MacLeod, 2012). In addition, response times were compared for recollection and familiarity responses (given that recollection is typically recognized as a slower phenomenon; e.g., Hintzman and Caulton, 1997; Hintzman, Caulton, and Levitin, 1998; Gronlund, Edwards, and Ohrt, 1997), as well as to examine the general distribution of response times across all responses. Effect sizes were also calculated for each statistical test, and an alpha value of α = .05 was used. All analyses were performed using R (R Core Team, 2020).

Results

Participants' valence ratings for negative sounds (*M* = 2.68) were significantly lower (i.e., rated more unpleasant) than for neutral sounds (*M* = 3.93), $t(93.95) = -9.95$, $p < .001$, $r = .72$; see Figure 4. The sound with the lowest valence rating was a female scream (*M* = 1.50); the sound with the highest valence rating was applause (*M* = 5.42). Negative sounds (*M* = 4.56) also received significantly higher arousal ratings than neutral sounds (*M* = 3.14), $t(90.59) = 8.96$; $p < .001$, $r = .69$; see Figure 5. The sound with the highest arousal rating was the same female scream (*M* = 6.25), and the sound with the lowest arousal rating was a babbling brook (*M* = 2.00). The two neutral sounds used as buffers were excluded from these analyses. Visual inspection of the distribution of arousal ratings from our sample and that of the normative arousal ratings from IADS (Bradley and Lang, 1999; 2007; Yang et al., 2018) shows that they were relatively similar. As expected, there was a strong negative correlation between arousal and valence ratings, $\rho = -.79$, $p < .001$; as arousal ratings increased, valence ratings decreased (see Figure 7). Here, a Spearman correlation test was used after a Shapiro-Wilk normality test found that the distribution of arousal ratings significantly deviated from a normal distribution ($W = 0.97$, $p = .039$).

Figure 8 shows that, after a 15-minute delay, memory for negative sounds as assessed by the *d*' discriminability measure was better for negative sounds (*M* = 1.63) than for neutral sounds (*M* = 1.44) $t(32) = 2.33$, $p = .026$, $r = .38$. Because *d*' values become substantially biased when hit rates approach maximal, near-ceiling values (Verde, MacMillan, and Rotello, 2006), potentially introducing outliers, the *d*' scores of participants with outlier *d*' values for either of the two valence conditions (defined as greater than 2 standard deviations above the respective condition mean), and that were also associated with hit rates greater than .95, were excluded (two participants were excluded).

Corrected recognition scores showed the same pattern of results as was found with the *d*' scores. Negative sounds ($M = .57$) were remembered significantly better than neutral sounds ($M = .51$), $t(34) = 2.43$, $p = .020$, $r = .39$; see Figure 9. This corrected recognition effect was associated with higher hit rates for negative sounds than neutral sounds. As shown in Figure 10, on average, negative sounds had a higher hit rate ($M = .76$) than neutral sounds ($M = .68$), $t(34) = 4.26$, $p < .001$, $r = .59$. The corrected recognition effect was *not* associated with higher false alarm rates for neutral sounds than negative sounds. As shown in Figure 12, on average, the false alarm rates for neutral sounds ($M = .17$) and negative sounds ($M = .19$) did not significantly differ, $t(34) = 1.47$, $p = .15$.

We further examined the effect of arousal on memory for sounds by comparing memory for negative sounds that had been rated higher versus lower in arousal by our participants, predicting that memory as assessed by hit rate would be better for higher versus lower arousal negative sounds. In order to perform this comparison, we divided negative sounds into high-arousal and low-arousal groups based on the group mean arousal rating for negative sounds ($M = 4.56$). Therefore, sounds rated 1-4 on arousal were labeled as 'high-arousal' and sounds rated 5-7 were labeled as 'low-arousal.' Missed arousal responses ($n = 13$ across 35 participants) for negative sounds were replaced with a close approximation of the group average arousal rating for that sound in order to categorize them as high- or low-arousal. We found that, on average, high-arousal negative sounds had a higher hit rate ($M = .81$) than low-arousal negative sounds ($M = .67$), $t(34) = -3.61$, $p < .001$, $r = .53$; see Figure 11.

To examine recollection- and/or familiarity-specific effects, we conducted a two-way repeated measures ANOVA with Valence (negative and neutral) and Memory Component (recollection and familiarity) as within-subject factors and memory estimates derived from the remember-familiar recognition task as the outcome variable. As expected, there was a significant main effect of Valence on memory estimates, $F(1,34) = 8.82$, $p = .0054$, $\eta^2_p=.027$. There was also a significant main effect of Memory Component on memory estimate, $F(1,34) = 27.46$, $p < .001$, $\eta^2_p=.17$; see Figure 13. There was no significant interaction effect between Valence and Memory Component, $F(1,34) = 0.49$, $p = .49$. However, to evaluate our specific prediction of emotional enhancement for recollection alone, we conducted two paired *t*-tests that directly compared memory estimates for negative and neutral sounds within recollection and familiarity, respectively. We used a Bonferroni-corrected alpha value of $\alpha = .025$. As predicted, recollection for negative sounds ($M = .31$) was greater than for neutral sounds ($M = .24$), $t(34) = 3.07$, $p = .004$, $r = .47$. Also as predicted, familiarity estimates for negative sounds ($M = .46$) did not differ from those for neutral sounds ($M = .42$), $t(34) = 1.47$, $p = .15$.

As an exploratory analysis of the effects of stimulus features on memory for negative and neutral sounds, we investigated the potential role of a stimulus feature we will refer to as *perceptual repetitiveness* (or *repetitiveness*). The motivation for this analysis was that several of the sounds in the IADS databases are perceptually repetitive, in the sense that they are composed of a series of short repeating auditory clips (e.g., a short dog bark repeated several times), presumably to allow the duration of each sound file in the set to be matched. Accordingly, we defined a perceptually repetitive stimulus as having the same auditory perceptual information repeated multiple times within the 6s sound clip. Sounds were labeled as repetitive or non-repetitive by two research assistants and any disagreements were adjudicated. Although perceptually repetitive sounds can be emotionally arousing, they are less perceptually complex and distinctive than non-repetitive sounds, and thus memory for repetitive sounds may be worse than for non-repetitive sounds.

To explore these relationships, we conducted a two-way repeated measures ANOVA with Valence (negative and neutral) and Repetitiveness (repetitive and non-repetitive) as within-subject factors and *d*' scores as the outcome variable. This ANOVA revealed a significant interaction effect between Valence and Repetitiveness, $F(1,34) = 15.00$, $p < .001$, η^2_p=.062; see Figure 10. This interaction effect indicates that the valence of the sound had different effects on memory performance depending on the repetitiveness of the sound; see Figure 14. Six Bonferroni-corrected *post hoc* tests ($\alpha = .008$; all *p*-values adjusted) revealed that for non-repetitive sounds, there were significant differences between negative and neutral sounds ($p < .001$), but not for repetitive sounds ($p = 0.74$). Negative non-repetitive sounds were also remembered better than negative ($p < .001$) repetitive sounds, but not neutral repetitive sounds ($p = .078$). There were no significant differences between neutral non-repetitive sounds and negative ($p = 1.00$) or neutral repetitive sounds ($p = 0.36$). Follow-up analyses indicated that non-repetitive negative sounds were rated by our participants as more arousing ($M = 4.14$) than repetitive negative sounds ($M = 4.04$), $t(45.99) = 0.47$, $p = .64$, and more negative ($M = 2.40$) than repetitive negative sounds ($M = 2.55$), $t(45.32) = -0.79$, $p = .43$, but these differences were not significant. There was also a significant main effect of Valence on *d*' memory performance, $F(1,34) = 5.01$, $p = .032$, η^2_p=.015. However, there was no significant main effect of Repetitiveness on *d*' memory performance, $F(1,34) = 2.12$, $p = .15$.

Discussion

The current study demonstrated that negative sounds were recognized more often than neutral sounds; that is, there was overall emotional enhancement of memory for auditory stimuli at a 15-minute delay. This enhancement effect was in line with our predictions and reflected in two measures of recognition memory performance: corrected recognition scores and *d*' statistics, both at a moderate effect size. These results are consistent with the initial findings of Bradley and Lang (2000) that emotional sounds are freely recalled more often than non-emotional sounds. Crucially, however, such an effect was unlikely to be driven by the enhancement of memory for associated verbal labels, given that semantically-matched distractors were used to deter the effective use of these labels as retrieval cues.

Additionally, in our study, the emotional enhancement effect was driven by differences in hit rates rather than false alarm rates, indicating that participants *correctly recognized* more negative sounds than neutral sounds (and did not simply confuse more neutral sounds as old). Further, high-arousal negative sounds were correctly recognized more often than low-arousal negative sounds. This effect is consistent with other arousal effects identified both for emotional sounds (Bradley and Lang, 2000) and emotional pictures (Bradley et al., 1992).

Further, the current study demonstrated that negative sounds were *recollected* more often than neutral sounds, but were not familiar more often than neutral sounds. In other words, emotional enhancement effects were present for *recollection*-based – but not familiarity-based – recognition memory processes. These findings are also in line with our predictions and are consistent with the more elaborative, context-rich experience of memory retrieval for emotional events over neutral events, resembling recollection (Baraly et al., 2016; e.g., Oschner, 2000). Unexpectedly, response times for recollection were shorter than those for familiarity; see Figure

15. Indeed, average response times were qualitatively greatest for 'not sure' and 'probably old' responses; see Figure 16. These findings were in contrast to dual-process literature suggesting that recollection occurs more slowly (e.g., Hintzman and Caulton, 1997; Hintzman, Caulton, and Levitin, 1998; Gronlund, Edwards, and Ohrt, 1997; Yonelinas, 2002). However, many of these studies require decisions of recollection and familiarity within a limited timeframe. In the current study, participants were given 6 seconds to listen to the sound clip before they could provide any memory response. It is conceivable that participants spent these 6 seconds searching for any contextual details that might 'clear the threshold' of a recollection response. If this threshold was cleared, it is possible that participants could make a recollection response immediately when prompted, leading to a very short response time. Alternatively, participants could be using the recollection response as a proxy for a very-high confidence familiarity response, also producing a short response time. However, participants received a nuanced explanation of the difference between recollection and familiarity – including examples – and were told to explain their practice responses aloud to the experimenter to discourage this misunderstanding from taking place.

Validating these findings, our valence and arousal ratings data indicated that participants generally differentiated between negative and neutral sounds as expected. That is, participants experienced negative sounds as more arousing and more negative than neutral sounds, on average. This relationship is reflected in the strong negative correlation between arousal and valence ratings. In addition, the rank order of arousal ratings for each sound broadly matched the normative rank order from IADS (Bradley and Lang, 1999; 2007; Yang et al., 2018; except for the online-sourced sounds, which did not have normative ratings). The two distributions are quite similar in general shape, with normative ratings consistently 1-2 points larger (likely due to the upper rating limit of 9 rather than 7). These similarities demonstrate that our participants interpreted negative and neutral sounds similarly to the large group of individuals with which this database was created. It is possible that our (or even both groups of) participants were influenced by demand characteristics; that is, they provided ratings consistent with the emotion they believed they 'should' have experienced (perhaps even more so for artificial-sounding stimuli). Although it is difficult to determine if this is true from ratings alone, it appears that, in general, these stimuli evoked the expected affective response. It should also be noted that this sample consisted mostly of females, and the small number of male participants ($n = 9$) prevented the reasonable interpretation of sex differences in memory performance or affective ratings. However, Bradley and Lang (2000) found general similarities in the latter for a subset of IADS sounds.

An additional exploratory analysis examined the relationship between sound valence, sound repetitiveness, and memory performance. We uncovered an interaction in which negative sounds were remembered better than neutral sounds when they were *non-repetitive*, but not repetitive. That is, memory for non-repetitive sounds alone were enhanced by emotion. Given that non-repetitive sounds have greater perceptual distinctiveness, which has been shown to benefit episodic memory in some cases (e.g., Rajaram, 1998), it is possible that this distinctiveness enhanced emotional salience. Follow-up analyses indicated that non-repetitive negative sounds were rated by our participants as more arousing and negative than repetitive negative sounds, but this difference was not significant. It is unclear what additional characteristics of non-repetitive sounds might drive this interactive effect and thus facilitate the emotional enhancement of memory. Additional studies could clarify this phenomenon further.

Future research could also extend the findings of the current study by determining whether emotional enhancement effects exist at longer delay intervals, e.g., 24 hours or 1 week. This is of particular interest given that emotional pictures have been remembered better than neutral pictures over extended periods of time (e.g., Shepardson, 2021), even as long as 1 year later (Bradley et al., 1992). It is unclear whether such advantages would generalize to auditory stimuli, given that there is some disagreement in the literature whether rates of forgetting differ in general for visual and auditory stimuli. Some experiments indicate that visual stimuli continue to be remembered better than auditory stimuli in the long-term (Bigelow and Poremba, 2014; Gloede, Paulauskas, and Gregg, 2017), whereas others show similar memory levels for visual and auditory stimuli over time (Bigelow and Preomba, 2014; Gloede and Gregg, 2019). Broadening the current investigation to examine memory performance over time would deepen our understanding of both the long-term emotional enhancement of auditory memory, as well as its differences with that of visual memory.

Additional studies could also probe emotional enhancement effects of memory for even more naturalistic auditory events, such as those found in movies or real-life episodes. While updates to IADS aimed to provide more natural sounds with which to design experiments, many sounds remain artificial and/or obviously performed by actors (Yang et al., 2018). Real-life auditory events are often more dynamic and complex than 6-second sound clips of a single entity, making them more ecologically relevant while also more difficult to control in the laboratory. Emotional auditory memory experiments with more relevant classes of stimuli would improve the external validity of the current findings.

While acknowledging that the current study is purely behavioral, it is reasonable to speculate that the amygdala may underlie a modality-independent mechanism to enhance memory for emotional events over non-emotional events, including for auditory events. Although less is known regarding the role of the amygdala in the emotional enhancement of memory for items of less-traditional modalities – including sounds – the auditory cortex shares connections with the amygdala (Amaral et al., 1992; Kolb and Tees, 1990; Paxinos, 2004; Romanski and LeDoux, 1993). A lesion study conducted by Frühholz and colleagues (2015) identified an amygdala-mediated response to emotional voices in the auditory cortex, demonstrating that the amygdala contributes to the processing of emotional auditory stimuli. Further, functional interplay between the auditory cortex and amygdala has been demonstrated in fear conditioning paradigms, suggesting a mutual role in emotional memory (Chavez, McGaugh, and Weinberger, 2009, 2013) (Grosso et al., 2015). The parahippocampal cortex may also play a unique role in processing memory for auditory items within the medial temporal lobe (MTL). This cortex may serve as a 'gateway' from auditory cortex into MTL structures such as the hippocampus, which is highly interconnected with the amygdala (Engelien et al., 2000). Together, this evidence suggests that some aspects of emotional enhancement effects may be modality-independent.

Given that it is possible that memory for emotional events is enhanced over neutral events in such a manner via modulatory pathways involving the amygdala (see Hamann et al., 1999a; Hamann, 2001), future fMRI studies could assess the neurobiological underpinnings of enhancement effects for auditory memory. For instance, participants could encode emotional and neutral auditory events while in the scanner, and assess whether related amygdala activity is associated with differences in memory performance (mirroring the design of Hamann et al., 1999a). Memory retrieval paradigms could also be conducted in a similar way. To evaluate a more causal relationship between the amygdala and the emotional enhancement of auditory memory, additional studies could examine whether patients with amygdala lesions remember emotional sounds better than neutral sounds (as shown with words, Markowitsch et al., 1994; stories, Cahill et al., 1995; Adolphs et al., 1997; and pictures, Hamann et al., 1999b; but not verbal stimuli, Phelps et al., 1997, 1998) (Hamann, 2001).

In sum, the current study demonstrated that there is an emotional enhancement of memory for auditory events, and that this enhancement occurs for recollection processes, but not familiarity processes of recognition memory. These findings extend the emotional memory literature, which has long focused on enhancement effects for visual and verbal stimuli but has largely not examined auditory stimuli. Research efforts further exploring emotional auditory memory are thus merited, particularly those that investigate longer delay intervals and more naturalistic stimuli. Neuropsychological and neuroimaging investigations might also contextualize the potential role of MTL brain structures in enhancing memory for emotional sounds over neutral sounds, similarly to other modalities – particularly in the case of recollection. Indeed, by demonstrating that emotion enhances memory for sounds, this study provides evidence that dimensions of affect may influence what we remember, regardless of the modality of that information (Bradley and Lang, 2000).

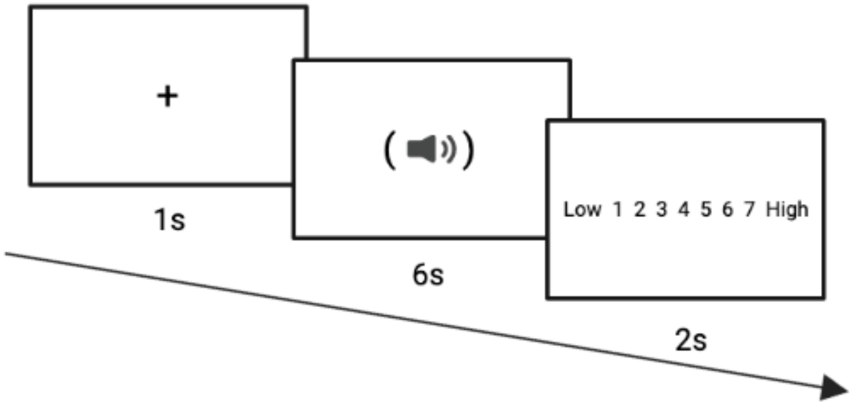

Figure 1. Encoding trial procedure. Each trial began with presentation of a fixation cross for 1s, followed by a 6s sound and an arousal rating scale. The speaker icon represents the sound presentation; no speaker icon was presented and the screen was blank during sound presentation.

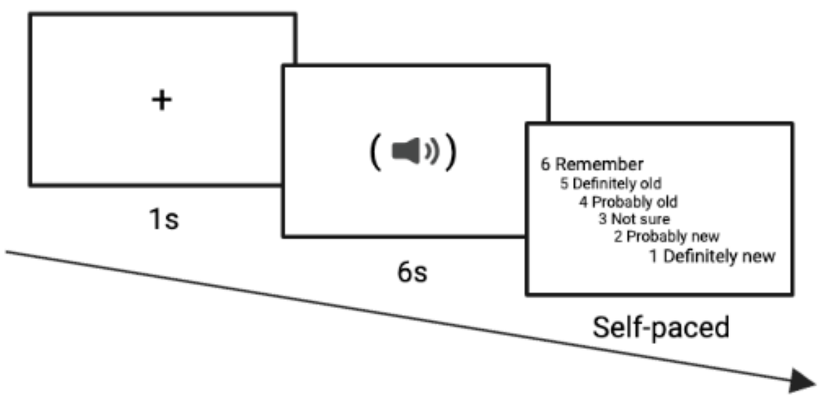

Figure 2. Retrieval trial procedure**.** Each trial began with presentation of a fixation cross for 1s, followed by a 6s sound and a remember-familiar recognition memory scale. Memory response was self-paced. The speaker icon represents the sound presentation; no speaker icon was presented and the screen was blank during sound presentation.

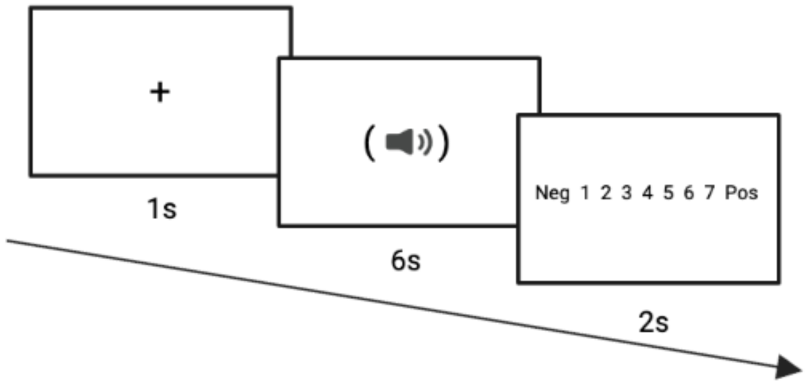

Figure 3. Valence rating trial procedure for sounds**.** Each trial began with presentation of a fixation cross for 1s, followed by a 6s sound and a valence rating scale. The speaker icon represents the sound presentation; no speaker icon was presented and the screen was blank during sound presentation.

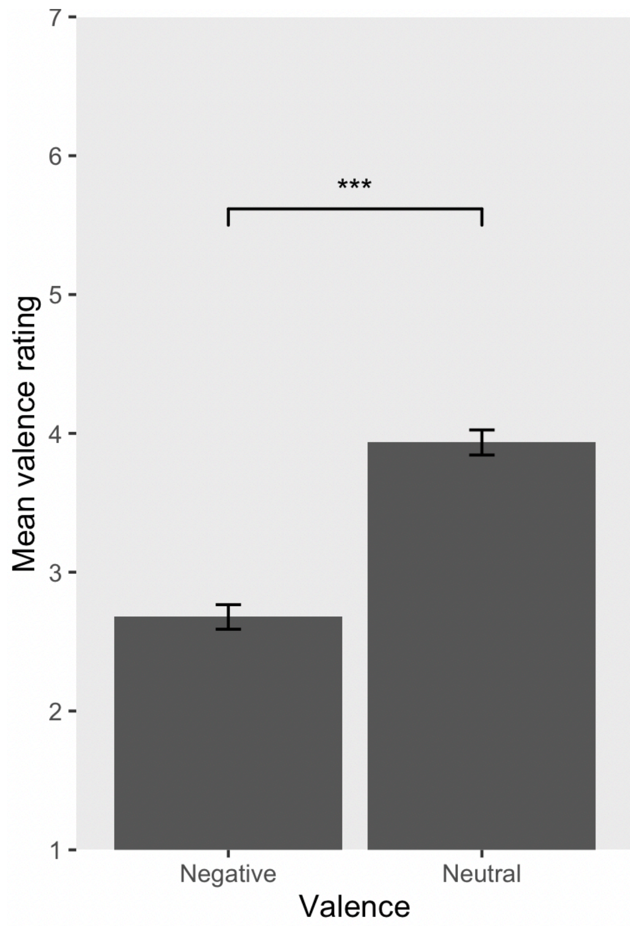

Figure 4. Mean valence ratings from study participants for negative and neutral sounds**.** Possible ratings range from 1 (negative) to 7 (positive). Error bars display standard error of the mean. *** $p < .001$

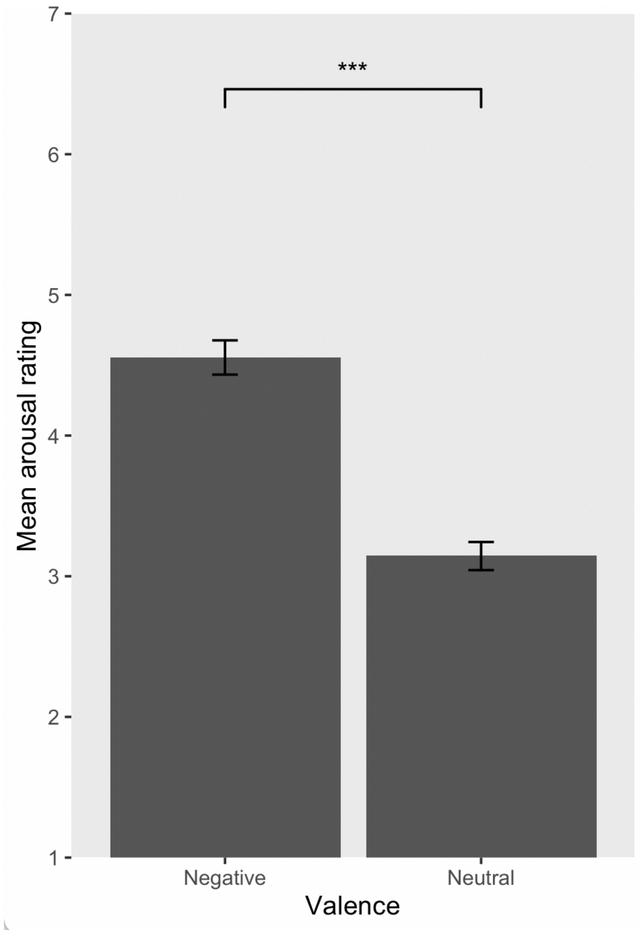

Figure 5. Mean arousal ratings from study participants for negative and neutral sounds. Possible ratings range from 1 to 7. Error bars display standard error. *** $p < .001$

(a) (b)

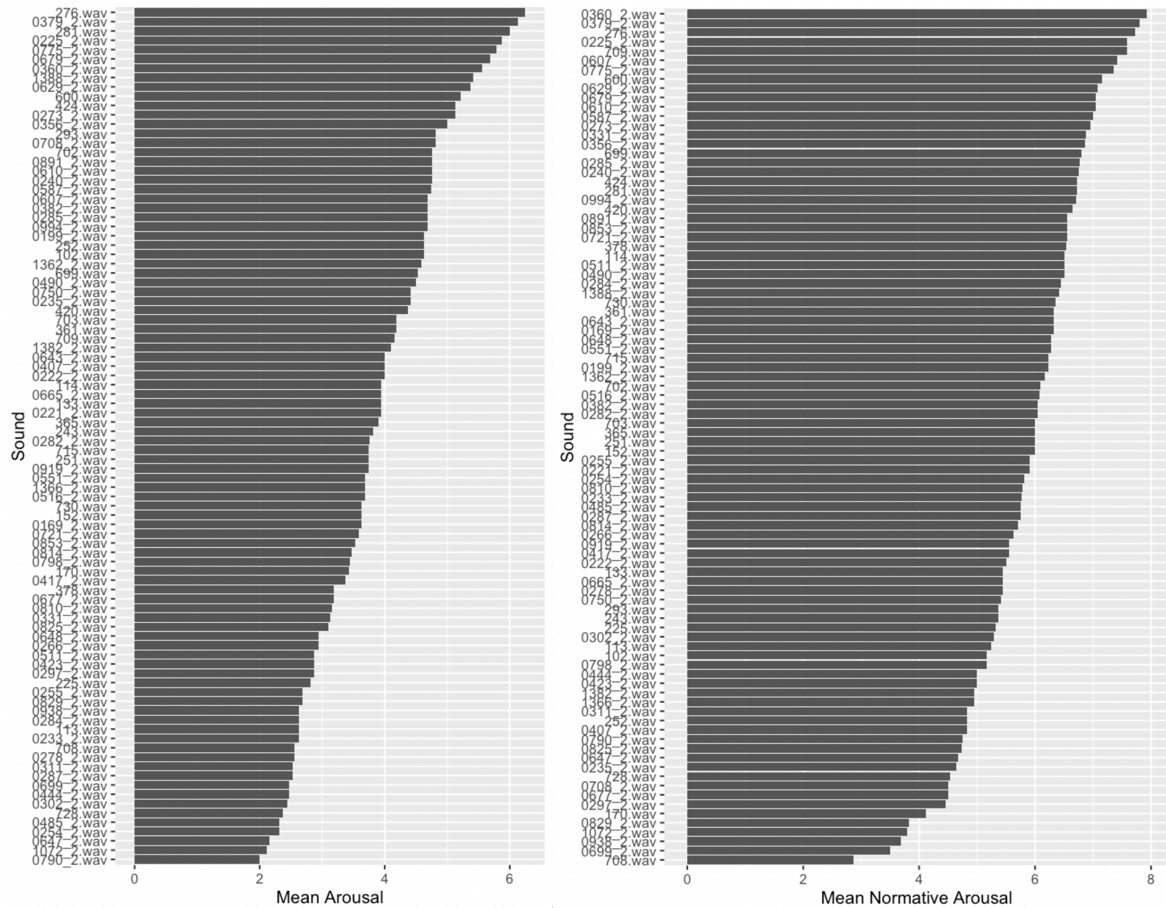

Figure 6. Distribution of sound stimuli ranked by mean arousal ratings. (a) Ranked mean arousal ratings from study participants. Sounds used as buffers excluded and sounds sourced from online sources excluded. (b) Ranked mean normative arousal ratings from IADS databases (Bradley and Lang, 1999, 2007; Yang et al., 2018). Sounds used as buffers excluded.

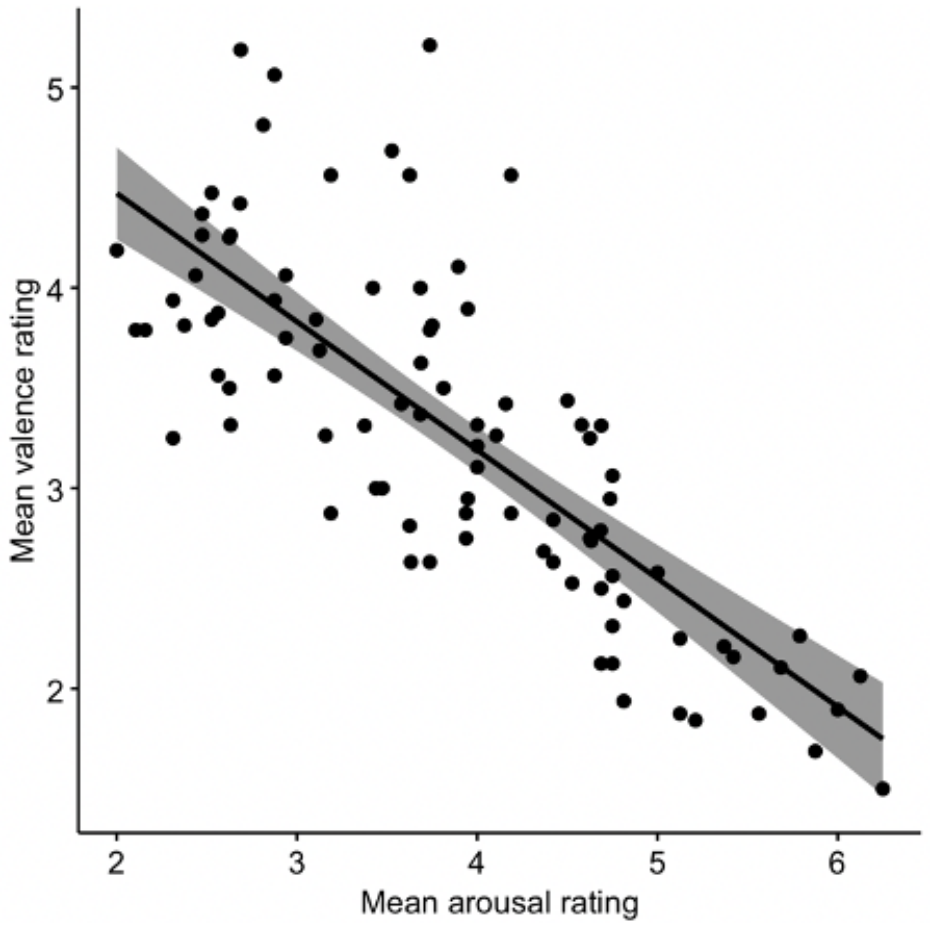

Figure 7. Relationship between mean arousal and valence ratings from study participants. Possible ratings for both arousal and valence range from 1 to 7. Regression line and 95% confidence interval included.

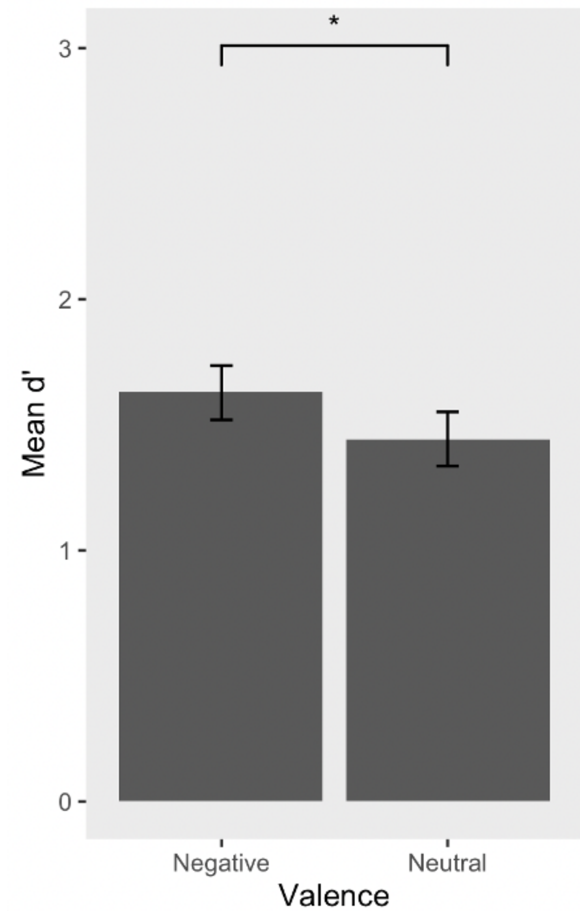

Figure 8. Mean *d*' discriminability scores for negative and neutral sounds. Error bars display standard error. * $p < .05$

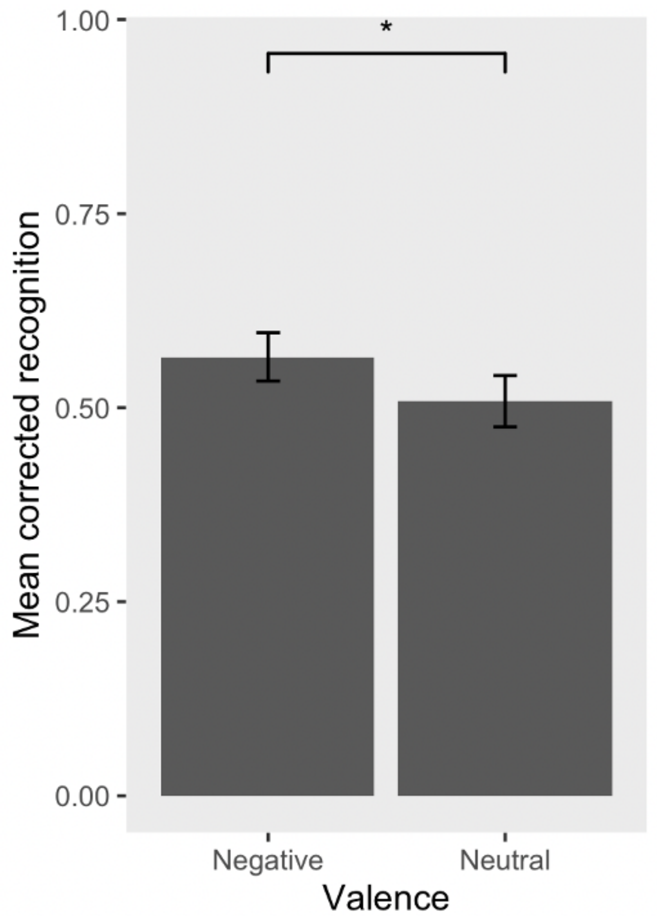

Figure 9. Mean corrected recognition for negative and neutral sounds. Error bars display standard error. * $p < .05$

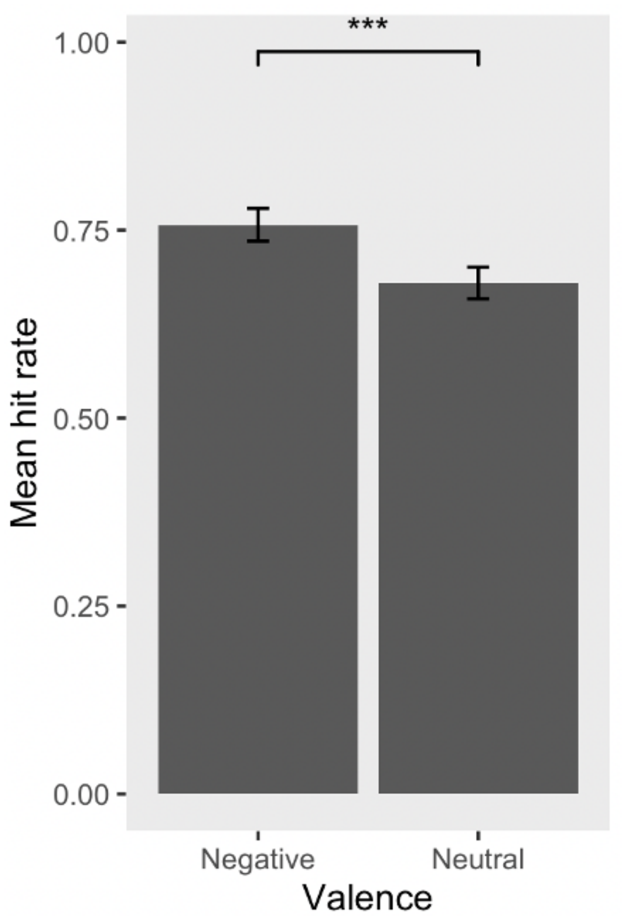

Figure 10. Mean hit rate for negative and neutral sounds. Error bars display standard error. *** $p < .001$

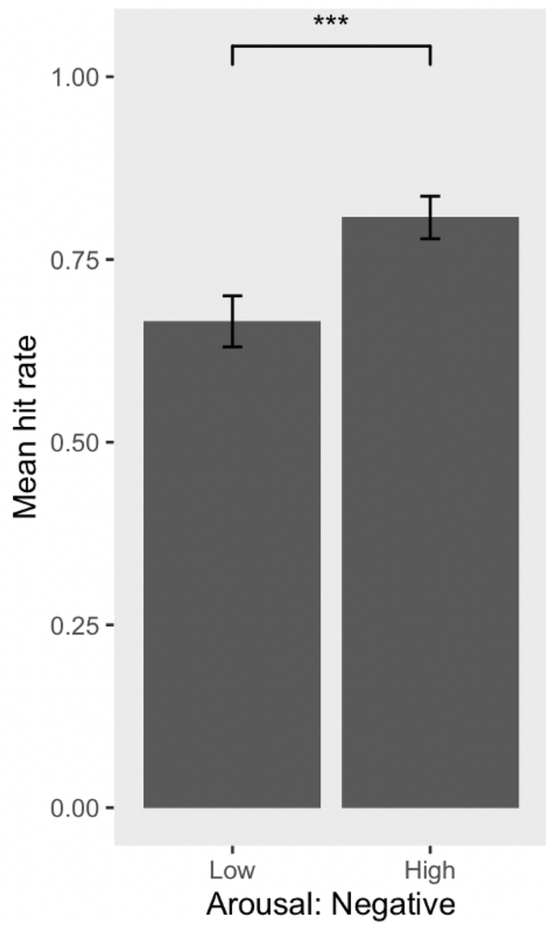

Figure 11. Mean hit rate for high-arousal and low-arousal negative sounds. Error bars display standard error. *** $p < .001$

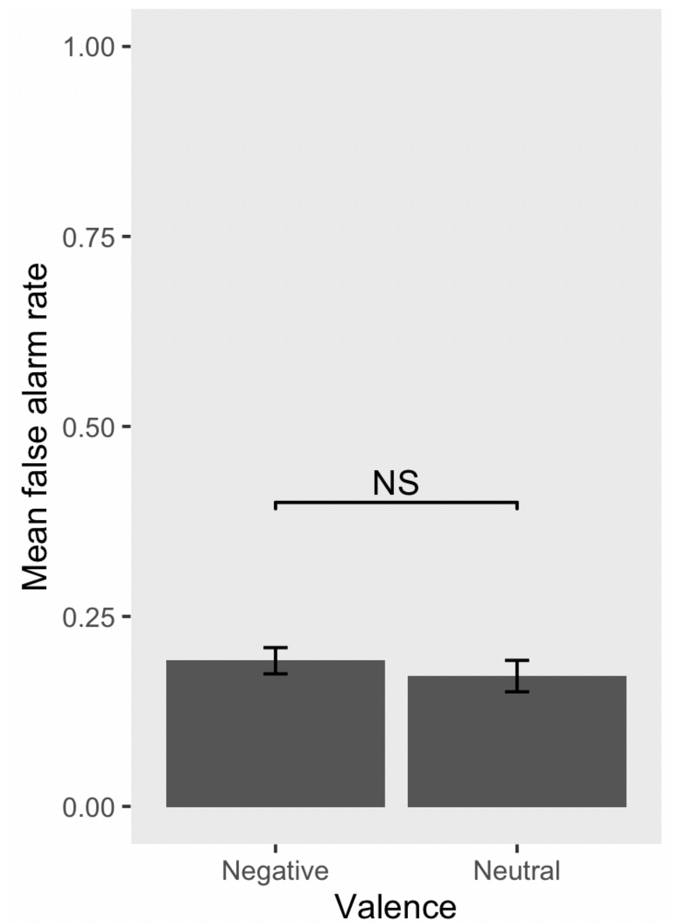

Figure 12. Mean false alarm rate for negative and neutral sounds. Error bars display standard error. NS = Not significant.

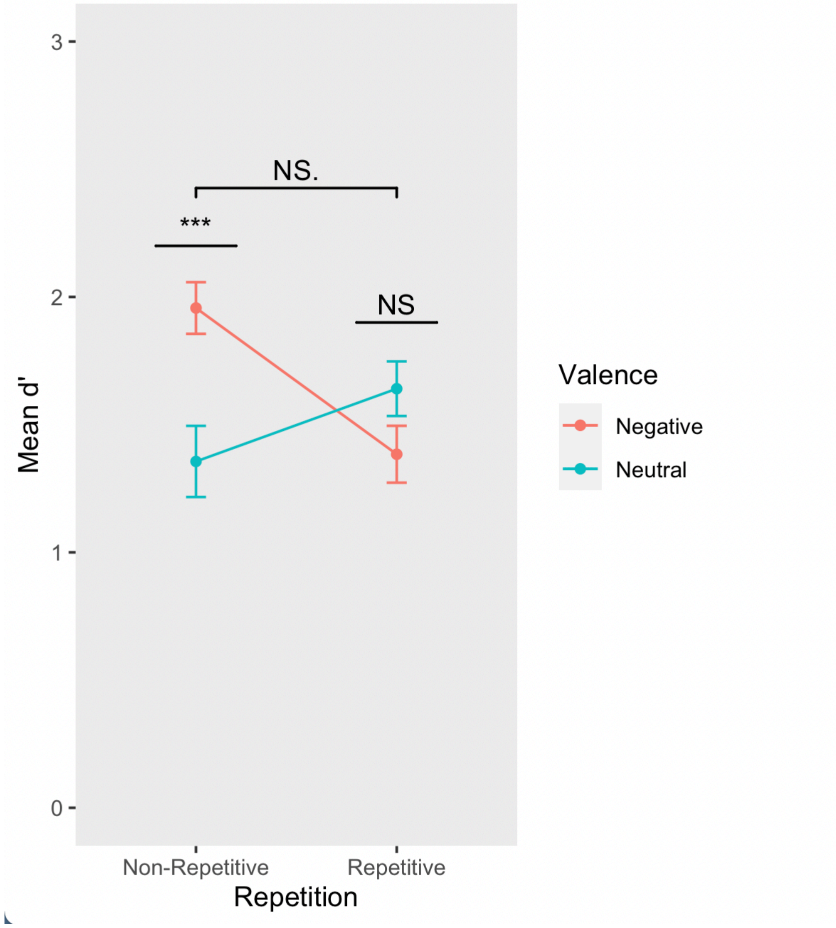

Figure 13. Mean *d*' discriminability measures by valence and perceptual repetitiveness. Negative in red, neutral in blue. Error bars display standard error. *** $p < .001$ NS = Not significant. Interaction between valence and perceptual repetitiveness was also significant at $p < .001$.

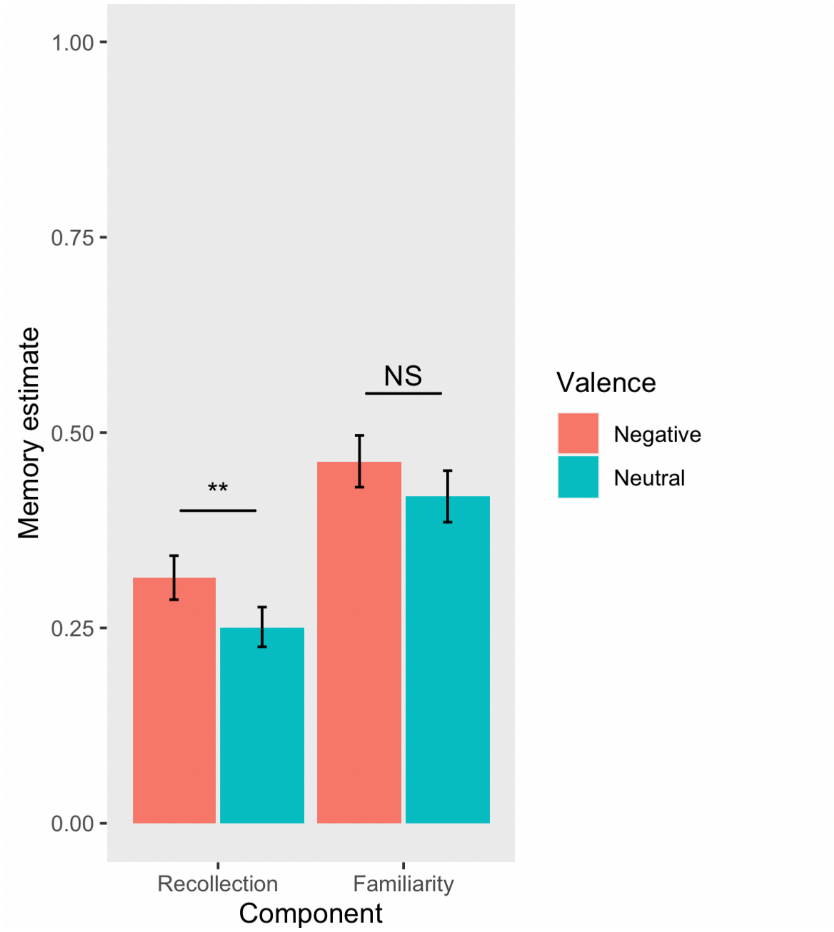

Figure 14. Mean memory estimates by recollection/familiarity and valence. Error bars display standard error. Negative in red, neutral in blue. ** $p < .005$ (Bonferroni-adjusted $\alpha = .025$) NS = Not significant.

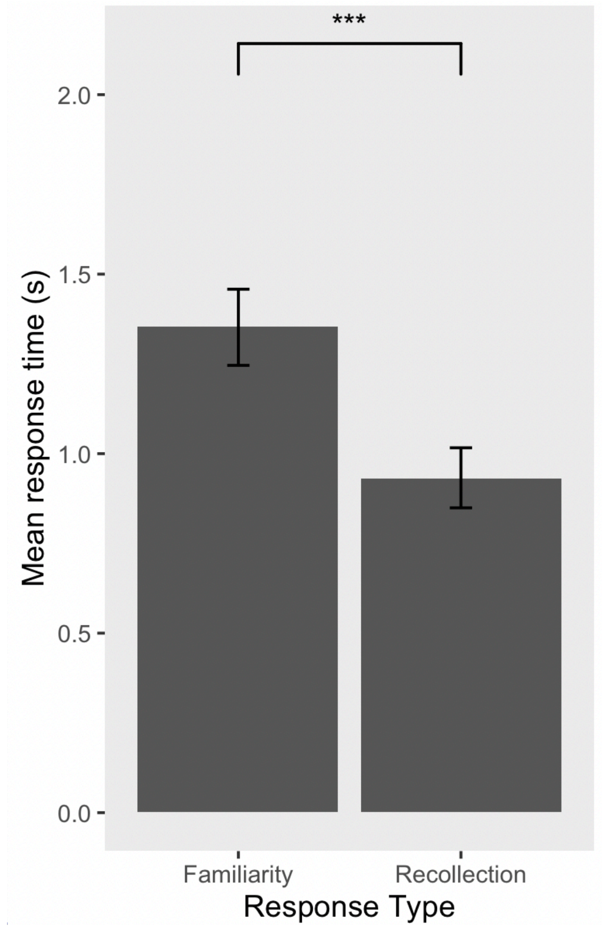

Figure 15. Mean response times for familiarity (4 or 5) and recollection (6) responses. Error bars display standard error. *** $p < .001$

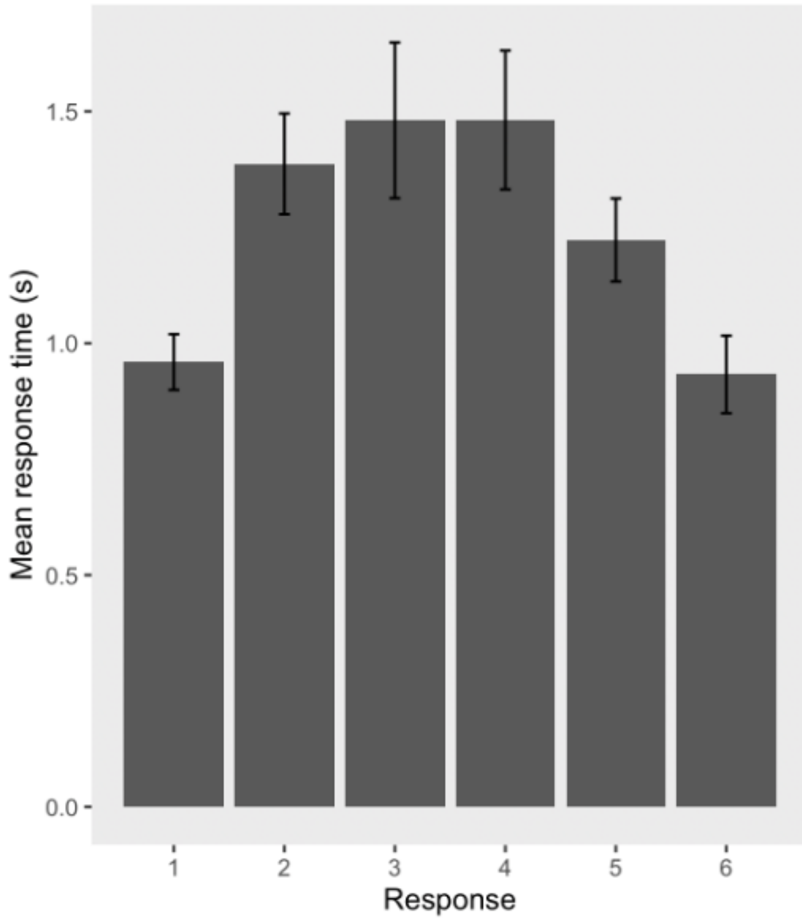

Figure 16. Mean response times for all remember-familiar test responses. Error bars display standard error.

Appendix A: Remember-familiar recognition memory test instructions.

Now we have a third task. Sounds will be presented from before and you will indicate whether or not you recognize them from earlier.

For this task you'll choose between 6 options: for Definitely new, press 1. Probably new, press 2. Not sure, press 3. Probably old, press 4. Definitely old, press 5. Remember, press 6.

You should respond "Remember," or 6, if you think the sound is one you heard before in the study, AND you can recollect any information about what happened at the time you heard the sound. A "Remember" response means you can recollect at least one thing from when the sound was presented before. For example, maybe you can recollect how it made you feel, what you were thinking about at that time, or something that happened in the room. In other words, you should respond "Remember" if the sound brings back to mind any particular association, feeling, thought, or detail from when you heard the sound before. For example, if you hear a song on the radio, you may think, "What is this song? Oh yes, it is the song that was playing when I was at the grocery store." That would be a "Remember" response.

You should respond with the other 5 options depending on how confident you are that you have heard the sound before. You would select one of the "new" options if you think you have not heard it before, and you would select one of the "old" options if you think you have heard it before. So the difference between "Definitely old" and "Remember" is that "Definitely old" would mean that you are highly confident that you have heard the sound before, while "Remember" would mean that you can also recollect any particular association, feeling, thought, or detail from when you heard the sound before.

Please be sure to try to use all of the response options at some point during the study.

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