Detailed Long-Term Memory for Unattended, Irrelevant, and Incidentally Encoded Auditory Information

Fabian Hutmacher and Christof Kuhbandner

University of Regensburg

This manuscript was accepted for publication in *Journal of Experimental Psychology: General*.

This is a preprint. Please refer to the publisher's website for the version of record.

Author Note

Fabian Hutmacher and Christof Kuhbandner, Department of Psychology, University of Regensburg, Regensburg, Germany.

Correspondence concerning this article should be addressed to Fabian Hutmacher, Department of Psychology, University of Regensburg, 93040 Regensburg, Germany. E-mail: fabian.hutmacher@ur.de.

Word Count: 4,917 words; *Display Items:* 2 Figures; *Reference List:* 55 Items.

Abstract

At any moment, a myriad of information reaches our senses, of which only a small fraction is attentively processed. A long held believe is that unattended information is only weakly processed if attentional demands are high and the unattended information is irrelevant, leaving no recognizable trace in long-term memory. The present study challenges this assumption. Participants (N = 51) were simultaneously presented with a rapid visual stream of words and an auditory stream of everyday sounds, with the instruction to attend to the visual stream and detect word repetitions, and to avoid distraction by the irrelevant sounds. No mention was made that their memory would be tested later. Memory for the sounds was tested in a surprise two-alternative forced choice recognition test with similar foil sounds. Half of the sounds were tested immediately after encoding, the other half after a delay of 24 hours. Memory performance was substantially above chance in both the immediate and the 24-hours delayed test, without significant forgetting across time. These results demonstrate that detailed and durable long-term memory representations are formed for unattended and irrelevant information that is incidentally encoded in a different sensory modality than the attended information.

Keywords: perceptual long-term memory, auditory long-term memory, long-term memory capacity, attention, attentional load

Detailed Long-Term Memory for Unattended, Irrelevant, and Incidentally Encoded Auditory Information

Imagine you are sitting in a café, engaged in a conversation with a friend that fully captures your attention. At the table behind you, somebody fills a glass with water from a bottle, producing a sound that reaches your auditory senses but is not noticed by you. One day later, somebody unexpectedly asks you about your memory for the perceptual details of the sound. Would you be able to recognize the perceptual details despite not having noticed the sound the day before? The aim of the present study was to examine this question.

At any moment, a vast amount of information reaches our senses, of which only a small fraction is relevant for our current goals. In order to behave in a functional way, our cognitive system needs to attend to the relevant fraction of the incoming information. Furthermore, since capacity is limited at several stages of the processing hierarchy (e.g., Cowan, 2001; Luck & Vogel, 1997), processing at these limited-capacity stages should be focused on the attended information as well. Thus, it seems to be a natural necessity of functional behavior that only a part of the incoming information is attended and processed in an enhanced way, an assumption that is supported by an abundance of empirical findings (for a review, see Serences & Kastner, 2014).

However, while the enhanced processing of attended information seems to be a settled fact, the fate of the unattended information is still debated, although this has received considerable research attention for several decades (for reviews, see, e.g., Driver, 2001; Lavie, 2006). Initially, at the heart of the debate was the question at which stage of the processing hierarchy unattended information is filtered out. According to early selection accounts (Broadbent, 1958), unattended information is initially represented in the form of low-level feature representations but does not reach subsequent processing stages where feature representations are integrated into coherent objects and represented in semantically meaningful ways. In contrast, according to late selection accounts (Deutsch & Deutsch, 1963), both attended and unattended information is processed in parallel up to the levels of object perception and semantic description. Attention operates after completion of these processing stages, selecting a subset of the processed items that is further processed in working memory and consciously perceived, filtering out processed items that are not selected.

As empirical findings did not reveal a clear picture in favor for either early or late selection, more flexible models have been suggested. For instance, according to attentional-load accounts (Lavie, 1995; 2010), the stage at which unattended information is filtered out varies as a function of the demands that are imposed by a task on perceptual capacity. If a task imposes high demands that exceed capacity limits, only task-relevant items are processed so that early selection occurs. If a task imposes only low demands, the remaining capacity spills over to task-irrelevant items that are then processed at higher levels as well. Taken together, the existing findings are best interpreted in terms of a flexible multi-level account, suggesting that unattended stimuli are filtered out at different stages in the processing hierarchy, depending on the specific demands of a task (e.g., Serences & Kastner, 2014).

One common assumption that is shared by all of the mentioned accounts is that unattended information is filtered out somewhere during the processing hierarchy, at least if the attentional demands of a task are high enough, suggesting that unattended information does not reach the stage of long-term memory storage. In fact, such an assumption was initially supported by numerous empirical studies showing that unattended information is not consciously remembered (e.g., Glucksberg & Cowen, 1970; Norman, 1969; Peterson, 1964). However, in the course of the discovery of the phenomenon of the existence of unconscious implicit memory, this view has been challenged. Using tasks such as word-fragment completion or perceptual identification, it has been shown that past experiences can affect current thoughts and behaviors without any awareness that one is influenced by memories of past experiences (e.g., Schacter, 1987; for a review see Schacter, Chiu, & Ochsner, 1993). In particular, such effects have been shown to occur even after very long retention intervals of several days (Musen & Treisman, 1990), months (Mitchell & Brown, 1988), or even years (Mitchell, 2006).

Thus, since conscious awareness seems not to be a necessary precondition of memory, it may be that even unattended information that does not reach the stage of conscious perception during initial encoding is stored in long-term memory. In fact, such an assumption seems to be supported by a number of studies showing that dividing attention during encoding does substantially reduce performance on explicit memory tests that require conscious recollection of previous experiences (e.g., free or cued recall) but not on implicit memory tests that do not rely on conscious recollection (e.g., Mulligan, 1998), suggesting that the withdrawal of attention during initial encoding does not decrease subsequent implicit memories. In particular, as shown in more recent studies, withdrawing attention from to-be-studied items seems sometimes even to enhance the ability to perceptually identify the items later (Voss, Baym, & Paller, 2008).

However, there are two problems with the mentioned studies in the domain of implicit memory that make it difficult to draw conclusions about the fate of unattended information. First, although the studied items were “unattended” in the sense of withdrawal of attention by a concurrently performed task, the “unattended” items were still relevant stimuli for the participants because no incidental encoding instructions were used. Second, although relatively attention-demanding secondary tasks were used (e.g., concurrently monitoring up to seven digits;

Mulligan, 1998), it may be that perceptual capacity was not fully exhausted by the secondary task so that attentional resources may have spilled over to the to-be-studied items, which seems to be likely as these items were not deemed as irrelevant.

In fact, several subsequent studies have consistently demonstrated that observers show a null memory effect for unattended stimuli in a subsequent old-new recognition (ONR) test, when incidental encoding instructions are used in combination with a high attentional load task (i.e., monitoring of a rapid continuous presentation of to-be-attended stimuli; Butler & Klein, 2009; Hoffman, Bein, & Maril, 2011; Lavie, Lin, Zokaei, & Thoma, 2009; Rees, Russell, Frith, & Driver, 1999; Ruz, Wolmetz, Tudela, & McCandliss, 2005; Ruz, Worden, Tudela, & McCandliss, 2005). Thus, it seems that unattended irrelevant information is not stored in long-term memory when the attentional load of the attended task is high enough.

However, this has been challenged by a number of recent studies in which the same high attentional load task was used as in the previous studies, but in which memory was assessed with more sensitive memory tests (Butler & Klein, 2009; Hoffman, Bein, & Maril, 2011). The most striking evidence comes from a recent study by Kuhbandner, Rosas-Corona, and Spachtholz (2017) where recognition was not measured with a recollection-dependent ONR as in the aforementioned studies, but with a two-alternative forced choice recognition test (2AFC) that relied on perceptual identification. Importantly, since a 2AFC test does measure memory only more sensitively than an ONR test if participants' responses are not only based on experiences of recollection or familiarity, participants were encouraged to guess and go with their "gut feelings"; as shown in other research, by encouraging unconsciously informed guessing, the amount of stored information is measured substantially more sensitively than when participants base their memory responses on experiences of recollection and familiarity (Voss & Paller, 2010). When dissimilar perceptual foils were used, memory performance (corrected for guessing) went up to a rate of 47.5%. Even more intriguingly, even when highly similar perceptual foils were used, memory performance was high (22.4%), indicating that high-fidelity representation of unattended stimuli had been stored. Furthermore, even when incidental memory for the unattended stimuli was tested for the first time after 24 hours, memory performance was still far above chance (dissimilar foils: 20.5%, similar foils: 10.9%).

Taken together, the latter studies demonstrate that humans store detailed representations of current sensory stimulations in long-term memory independently of current intentions and the current attentional focus. However, one potential limitation of this astounding ability may be that this holds only for unattended information that is processed in the same sensory processing channel as the attended information. In all of the above mentioned studies, both the attended and unattended information were presented within the same sensory modality (visual) so that it remains to be shown whether detailed long-term memory representations are also formed for unattended information processed in another sensory modality than the attended information. On the one hand, based on findings suggesting that different sensory modalities draw from separate resource reservoirs (e.g., Duncan, Martens, & Ward, 1997; Soto-Faraco & Spence, 2002), one may speculate that unattended information processed in other sensory modalities is stored in long-term memory with similar quality as well. On the other hand, based on findings suggesting that attention increases already the gain of responses from very early processing areas (e.g., Carrasco, 2009; O'Connor, Fukui, Pinsk, & Kastner, 2002), one may speculate that unattended information processed in other sensory modalities is stored in long-term memory with less quality. Preliminary evidence that at least some aspects of the unattended information processed in other sensory modalities is stored in memory comes from a study showing that words that were acoustically presented while participants performed a visual high attentional load task were remembered slightly above chance in a subsequent word recognition test (Sinnett, Costa, & Soto-Faraco, 2006). However, as participants were not instructed to ignore the acoustically presented words, it may still have been the case that attention spilled over to the auditory stream sometimes. Furthermore, as memory was tested only immediately after using a cross-modal recognition test where the words were presented in written form, both the durability and the quality of the stored representations is unknown.

The aim of the present study was to examine whether detailed long-term memory representations are also formed for unattended information processed in another sensory modality than the attended information. To examine this question, participants were simultaneously presented with a rapid stream of visually presented words and an auditory stream of everyday sounds, with the instruction to attend to the words and to press a button every time a word was repeated, and to avoid distraction by the irrelevant sounds as good as possible (for an illustration, see Fig. 1A). No mention was made that their memory for any stimuli would be tested later. Memory for the unattended and incidentally encoded sounds was tested immediately after encoding and after 24 hours. To test memory, a two-alternative forced choice recognition (2AFC) test was used with similar foils belonging to the same basic-level category so that a correct decision required the existence of stored detailed long-term memory representations of the unattended sounds.

Method

Participants

We decided to collect data from at least 41 participants based on the sample size in a similar study (Kuhbandner et al., 2017), and to continue data collection until the end of a semester. In total, 52 undergraduate students participated for course credit. The study was conducted in accordance with APA ethical standards in the treatment of participants; all participants provided written informed consent. One participant was excluded, because he had expected a memory test for the sounds according to the post-experimental questionnaire (see below), resulting in a sample of 51 participants (40 females, M_{Age} = 23.00 years, *SD* = 5.40). All data exclusions, manipulations, and measures in the study are reported.

Materials

The stimulus set consisted of 168 categorically distinct everyday sounds (e.g. the barking of a dog, the humming of a fridge, a starting motor, a glass being filled, a bird singing; sounds were taken from the IADS, Bradley & Lang, 1999, from a freely available online database, or self-created using a recording device; data and information about the stimuli can be downloaded at osf.io/3vgcu). For 72 of the 168 sounds, there was a second exemplar from the same basic-level category; these sound pairs were used in the 2AFC test. The differences between the two sounds of a pair were kept as small as possible while still being distinguishable. The other 96 sounds were filler items. The sound duration varied between one and five seconds, the length of the two sounds of a pair was identical. Volume normalization of the stimuli was performed using an open-source volume normalization software (Mp3Gain) based on the ReplayGain algorithm proposed by Robinson (2001) that estimates the perceived loudness level of a sample and adjusts the sounds to a reference level. This reference level was set to 60dB SPL. The words for the word repetition task were taken from the Berlin Affective Word List (BAWL-R; Vo et al., 2009). In total, 660 neutral, five- to six-letter German words were used (written in black and uppercase letters, valence from -1 to 1 on a scale from -3 to 3). The words were unrelated to the everyday sounds.

Design and Procedure. The procedure of the experiment was based on the high attentional load paradigm introduced by Rees et al. (1999). Participants were simultaneously presented with a rapid visual stream of words and an auditory stream of everyday sounds (for an illustration, see Fig. 1A). In the visual stream, the words were presented centered on a screen in black on a white background written in bold, capitalized letters in Calibri font at a size of 18 points. Each word was randomly rotated 45° clockwise or counterclockwise and presented for 250 ms, followed by an interstimulus interval of 250 ms. On average once every five words a word was repeatedly shown; there were never two repetitions in a row. On repetition trials, the words were shown in different orientations. In the auditory stream, the sounds were presented to participants via headphones. Each sound was presented only once during this phase of the experiment. In order to exclude primacy and recency effects, the first and last fifteen sounds were filler items only. The remaining 138 sounds (72 target and 66 filler items) were presented in one of four pre-experimentally generated orders that were randomly determined each. The position of target and filler items in the pre-experimentally generated orders was random. The assignment of the exemplars of a sound pair to the incidental study phase was counterbalanced across participants.

Participants were instructed to attend to the visual stream of words and to detect immediate word repetitions by pressing a button, and to ignore the auditory stream of sounds as good as possible. To maximize the focusing of attention on the words and the irrelevance of the sounds, participants were told that the aim of the study was to measure the ability of avoiding distraction by irrelevant sounds. No mention was made that their memory for any of the stimuli would be tested later. Immediately after completing the word repetition task, the participants' memory for half of the sounds was tested in a surprise recognition test. The other half was tested in a second delayed recognition test after 24 hours. The assignment of the sound pairs to the immediate and delayed recognition tests was counterbalanced across participants. In the recognition test, participants consecutively listened to the two sound exemplars of a pair, and they were asked to indicate which of the two sounds had been presented before (2AFC). Participants were told that this task will not be easy as they had ignored the sounds during the previous attentional task, and that they will probably have the feeling of not knowing the answer in many cases. They were also told that numerous previous studies have shown that participants can nevertheless perform remarkably well in such situations when they base their decisions on their intuition. Hence, the participants were asked to follow their “gut feelings” when not knowing an answer. Participants were allowed to proceed at their own pace; if they were not sure about their decision, they could listen to the two sounds of a pair again as often as they wanted. On half of the recognition test trials, the previously presented sound was presented first, on the other half second. Presentation order of the tested sound pairs was random. In the delayed recognition test, after having tested the sounds that had not been tested the day before, the sounds that had been tested the day before were tested again. To ensure that the sounds had been incidentally encoded, after completion of the immediate recognition test, the participants were asked whether they had expected a memory test for the sounds.

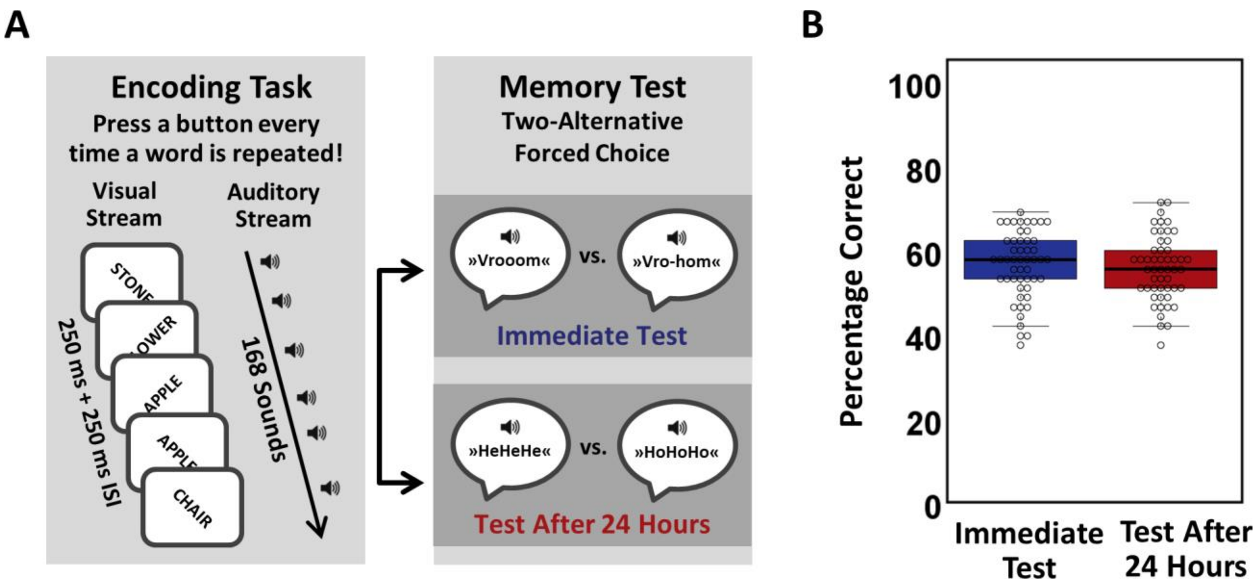

Figure 1. **Memory paradigm and recognition performance**. The procedure of the experiment is illustrated in (A). In an initial encoding phase, participants were simultaneously presented with a rapid visual stream of words and an auditory stream of everyday sounds. They were asked to attend to the visual stream and to detect immediate word repetitions, avoiding distraction by the irrelevant sounds. No mention was made that memory for any stimuli would be tested later. Memory for half of the sounds was tested in a surprise recognition test immediately afterwards, the other half was tested in a second recognition test after 24 hours. A two-alternative forced choice recognition test was used with foils that were similar to the sounds presented before. Recognition performance is depicted in (B). The box-and-whisker plots show participants' memory performance (percentage of correct responses) in the immediate memory test and in the memory test after 24 hours. Center horizontal lines show the medians. Box limits indicate the 25th and 75th percentiles. Whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Data points are plotted as open circles.

Results

Word Repetition Task. Participants' performance in the word repetition task was high (*M* = 70.01%, *SD* = 12.50%, 95% CI [66.58, 73.44]) and in the range of previous studies using the same high attentional load task (e.g., Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005), indicating that they successfully focused their attention on the words.

Memory Performance. Figure 1B shows the participants' memory performance (percentage of correct responses) in the immediate and the 24-hours delayed recognition tests. In the immediate test, memory performance was far above chance, M = 56.86%, SD = 9.87, 95% CI [54.16, 59.57], $t(50) = 4.97$, $p < .001$, $d = 0.70$. In the 24-hours delayed test, memory performance for sounds that were tested for the first time was still far above chance, M = 55.83%, SD = 9.58, 95% CI [53.20, 58.46], $t(50) = 4.35$, $p < .001$, $d = 0.61$. There was no significant forgetting observed across the delay of 24 hours, $M_{Difference}$ = 1.03%, SD = 11.81, 95% CI [-2.21, 4.27], $t(50) = 0.63$, $p = .534$, $d = 0.09$. Memory performance in the delayed test for sounds that had already been tested in the immediate test was above chance as well, M = 54.19%, SD = 6.39, 95% CI [52.44, 55.95], $t(50) = 4.69$, $p < .001$, $d = 0.66$. Performance did not significantly differ between sounds that were tested for the first time after 24 hours and sounds that had already been tested in the immediate test, $M_{Difference}$ = 1.63%, SD = 11.51, 95% CI [-1.52, 4.79], $t(50) = 1.01$, $p = .316$, $d = 0.14$.

Additionally, we also calculated a sensitivity index d'_{FC} corrected for response bias (for details, see Wickens, 2002, p. 101). The sensitivity index corrected for bias differed significantly from zero for both the immediate test, $d'_{\text{FC}} = 0.36$, SD = 0.53, 95% CI [0.21, 0.50], $t(50) = 4.84$, $p < .001$, $d = 0.68$, and the 24-hours delayed test, $d'_{\text{FC}} = 0.31$, SD = 0.51, 95% CI [0.17, 0.45], $t(50) = 4.38$, $p < .001$, $d = 0.61$. There was no significant decrease of d'_{FC} across the delay of 24 hours, $d'_{FC\text{-}Difference} = 0.04$, SD = 0.63, 95% CI [-0.13, 0.22], $t(50) = 0.51$, $p = .612$, $d = 0.07$. Memory performance in the delayed test for sounds that had already been tested in the immediate test was above chance as well, $d'_{\text{FC}} = 0.23$, SD = 0.35, 95% CI [0.13, 0.32], $t(50) = 4.73$, $p < .001$, $d = 0.66$. The sensitivity index did not significantly differ between sounds that were tested for the first time after 24 hours and sounds that had already been tested in the immediate test, $d'_{FC\text{-}Difference}$ = 0.09, *SD* = 0.62, 95% CI [-0.09, 0.26], $t(50) = 0.99$, $p = .329$, d = 0.14.

To address the possibility that the observed memory performance for the sounds might be attributable to a covert allocating of attention to the sounds during encoding, a number of additional analyses were performed (see Figure 2).

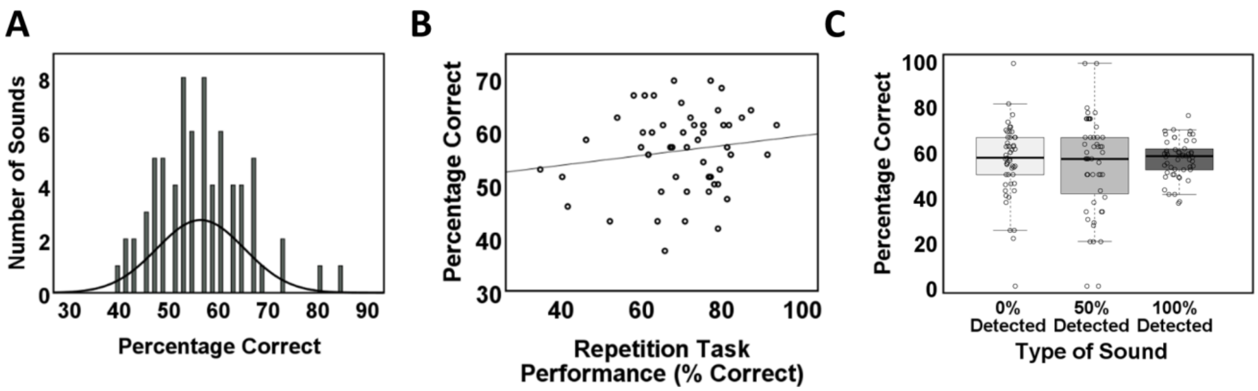

***Figure 2*. Results of the Additional Analyses.** The distribution of the percentage of correct responses across the 72 sound pairs is depicted in (A). The relation between the participants' performance in the word repetition task and the average percentage correct is depicted in (B). The box-and-whisker plots depicted in (C) show participants' memory performance for sounds during whose presentation no word repetitions were detected (11.1% of sounds), 50% of the word repetitions were detected (24.9% of sounds), and all word repetitions were detected (64.1% of sounds). Center horizontal lines show the medians. Box limits indicate the 25th and 75th percentiles. Whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Data points are plotted as open circles. The percentage of correct responses was collapsed across the immediate test and the delayed test for sounds tested for the first time.

To rule out that the observed memory performance was driven only by a few specific sounds that may automatically have attracted attention, we determined the average percentage correct for each sound pair across participants (collapsed across the immediate test and the delayed test for sounds tested for the first time; this was done for all of the following analyses). As shown in Figure 2A, performance was normally distributed across the sounds, $W(72) = 0.973$ $p = .125$. To rule out that the observed memory performance was driven by a transient shift of attention away from the visual stream of words during encoding, two further analyses were performed. First, we correlated the participants' performance in the word repetition task with their later memory performance. If the observed memory performance is attributable to a switching of attention away from the word repetition task, a negative correlation should be observed. However, performance in the word repetition task and memory performance were not significantly correlated, $r = .15$, $p = .296$ (see Figure 2B). Second, we compared memory performance for sounds during whose presentation all word repetitions were detected (64.1% of the target sounds), only 50% of the word repetitions were detected (24.9% of the target sounds), and no word repetitions were detected (11.1% of the target sounds). Memory performance did not differ between the three types of sounds ($M_{\text{All Detected}} = 57.15\%$, $SD = 8.66$, 95% CI [54.77, 59.53]; $M_{\text{50\% Detected}} = 54.67\%$, $SD = 21.72$, 95% CI [48.71, 60.63]; $M_{\text{0\% Detected}} = 56.25\%$, $SD = 16.30$, 95% CI [51.78, 60.72]), $F(2,100) = 0.355$, $p = .702$, $\eta^2_p = 0.007$ (see Figure 2C).

Discussion

At any moment, a myriad of information reaches our senses, of which only a small fraction is attentively processed. Early on, it has been suggested that the unattended information is only weakly processed and partially analyzed, leaving no recognizable trace in memory (Broadbent, 1958), an assumption that is still believed to be true at least if the demands of the attended task are high and the unattended information is irrelevant for one's current goals (Lavie, 2010), supported by numerous studies (e.g., Lavie et al. 2009; Rees et al., 1999; Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005). By using a more sensitive recognition test (2AFC test) than in the previous studies (ONR test), the present results challenge this assumption. Participants were able to recognize unattended and irrelevant auditory information that was incidentally encoded in a visual high attentional load task, even though a correct response required detailed knowledge about the auditory information, and even when memory was tested for the first time after a delay of 24 hours, without significant forgetting across time. These results corroborate previous findings in the visual domain (Butler & Klein, 2009; Kuhbandner et al., 2017) and extend them by showing that detailed and durable long-term memory representations are even formed for unattended information processed in a different sensory modality than the attended information.

Together with the findings of Butler and Klein (2009) and Kuhbandner et al. (2017), the present study provides clear evidence that humans store detailed copies of current sensory stimulations in long-term memory, independently of current intentions and the current attentional focus. In fact, based on findings in the domain of implicit memory, showing that past perceptual experiences can influence behavior without conscious awareness even after only a single observation and longer retention intervals (e.g., Musen & Treisman, 1990; Mitchell & Brown, 1988; Mitchell, 2006), it has been postulated that there is a perceptual representation memory system that operates independently of the episodic memory system (Schacter, 1990; for a similar account see Johnson, 1983). However, the operating characteristics and representational format of such a potentially existing memory system have remained relatively unclear to date (e.g., Butler & Berry, 2001). Regarding operating characteristics, the present results indicate that the perceptual representation memory system operates independently of one's current attentional focus and intentions. Regarding the representational format, the present results suggest that perceptual experiences are stored in detail. In particular, since it is commonly assumed that attention is required for the binding of features into coherent object representations (e.g., Treisman & Gelade, 1980), it seems that the unattended information is stored in the form of independent feature representations. Indeed, such an assumption is supported by previous findings showing that low-level feature information can be retained with high precision in long-term memory (e.g., Magnussen & Dyrnes, 1994), and that the quality of object representations in perceptual long-term memory can be predicted from early preattentive brain activities (Spachtholz & Kuhbandner, 2017). In line with that and as far as the processing of auditory stimuli is concerned in particular, it has been demonstrated that participants are able to remember specific spectro-temporal peculiarities in noise stimuli (i.e., to remember specific, fine-grained features of the presented stimuli; Agus & Pressnitzer, 2013; Agus, Thorpe, & Pressnitzer, 2010).

In the present study, similar pairs of sounds were used. As in numerous previous studies (e.g. Brady, Konkle, Alvarez, & Oliva, 2008; Hutmacher & Kuhbandner, 2018), similarity was defined as semantic similarity, that is, sounds were considered as similar when they belonged to the same basic-level category. For instance, participants had to differentiate between the humming sounds of two different fridges or the sound of filling two different glasses with water. From the perspective of memory, the consequence is that remembering a sound at the level of semantics was insufficient for a correct response. Rather, to reach a correct response, perceptual information about the initially presented sounds had to be stored and retrieved. Beyond semantics, the similarity of sounds can also be defined on the sensory-perceptual level. However, previous research has shown that determining the sensory-perceptual similarity of everyday environmental sounds is non-trivial for several reasons. First, everyday environmental sounds differ along many more dimensions than simple laboratory-generated stimuli so that defining similarity for this kind of sounds becomes vastly more difficult (see e.g. Dickerson & Gaston, 2014). Second, complex auditory stimuli such as everyday environmental sounds seem to be more than simple linear combinations of single discrete properties. For instance, simply varying the position of a tone in a sequence or adding a tone to the sequence affects discrimination performance dramatically, although the changes are quite small from a quantitative perspective (Watson, Wroton, Kelly, & Benbassat, 1975). This means that even if all different stimulus dimensions can be quantified, it is difficult to see how these different dimensions could be integrated into a single similarity score that can be related to the participants' perception (e.g., Susini, Lemaitre, & McAdams, 2012). Hence, we decided to make the pairs of the used everyday environmental sounds perceptually similar only by controlling for object-unrelated features such as length and volume of the sounds. Nevertheless, systematically exploring the influence of similarity at the sensory-perceptual level using optimized acoustic stimuli seems to be a promising topic for future research.

In view of the percentages of correct responses observed in the immediate test (56.86%) and the 24-hours delayed memory test (55.83%), at first glance, the overall memory effect seems rather small given a guessing probability of 50%. However, first, it is important to note that the percentage of presented objects that were stored so that they were successfully discriminated from the foil objects in the test is not simply the difference between the observed percentage of correct responses and the guessing probability, but two times the difference (e.g., Brady, Konkle, Alvarez, & Oliva, 2013). Second, one has to take into account, that similar foils were used in the memory tests so that a correct response required that detailed memory representations were stored. Research in the visual domain has shown that performance is much better when less similar foils are used (Kuhbandner et al., 2017), suggesting that representations of many more objects are stored but partly in less quality. Third, in view of previous studies that have used old-new recognition tests, suggesting that memory for attended sounds is relatively poor (Cohen, Horowitz, & Wolfe, 2009) and memory for unattended stimuli generally absent (e.g., Lavie et al., 2009; Rees et al., 1999; Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005), the finding that memory is significantly above chance when measured with a two-alternative forced choice test seems relatively surprising.

In view of recent findings in the domain of visual memory, showing that observers can successfully recognize details of thousands of visual images after having studied them only for a few seconds each (e.g., Brady, Konkle, Alvarez, & Oliva, 2008), it has been conjectured that existing cognitive and neural models of long-term memory storage and retrieval are challenged given the large amount of stored information (Brady et al., 2008). The finding that detailed representations are even formed for a significant fraction of the incoming unattended, irrelevant, and incidentally encoded information suggests that this challenge may even be larger than initially believed.

Context of the Research

We are fascinated by the question of how many of the thousands of perceptual experiences we make every day are stored in long-term memory. Whereas earlier studies demonstrating phenomena such as change blindness (Simons & Rensink, 2005) or inattentional amnesia (Wolfe, 1999) seemed to support the idea that long-term memory representations for perceptual experiences are rather sparse, more recent studies have shown that in fact detailed memory representations are stored. This does not only hold true for visual information (e.g., Brady et al., 2008; Kuhbandner et al., 2017), but also for haptic (Hutmacher & Kuhbandner, 2018), and – as demonstrated in the present study – for auditory information. Building on these results, in future research, we want to explore the nature of these detailed memory representations. Preliminary evidence suggests that there are at least two options: storing information as independent features or as bound objects (e.g., Spachtholz & Kuhbandner, 2017). Furthermore, we are also interested in investigating potential selection mechanisms. Apparently, not all incoming information is stored in long-term memory so that it is important to unravel the mechanisms by which the perceptual long-term memory system separates important from unimportant information (e.g., Seitz, Kim, & Watanabe, 2009; Swallow & Jiang, 2010).

References

Agus, T. R., & Pressnitzer, D. (2013). The detection of repetitions in noise before and after perceptual learning. *The Journal of the Acoustical Society of America*, *134,* 464-473. doi:10.1121/1.4807641

Agus, T. R., Thorpe, S. J., & Pressnitzer, D. (2010). Rapid formation of robust auditory memories: insights from noise. *Neuron*, *66*, 610-618. doi:10.1016/j.neuron.2010.04.014

Bradley, M., & Lang, P. J. (1999). *International Affective Digitized Sounds (IADS): Stimuli, Instruction Manual and Affective Ratings*. *Technical Report B-2.* The Center for Research in Psychophysiology, University of Florida.

Brady, T. F., Konkle, T., Alvarez, G. A., and Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Acadademy of Sciences*, *105*, 14325–14329. doi:10.1073/pnas.0803390105

Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2013). Real-world objects are not represented as bound units: Independent forgetting of different object details from visual memory. *Journal of Experimental Psychology: General*, *142*, 791–808. doi:10.1037/a0029649

Broadbent, D. E. (1958). *Perception and Communication*. Oxford: Oxford University Press. doi:10.1037/10037-000Butler, B. C., & Klein, R. (2009). Inattentional blindness for ignored words: Comparison of explicit and implicit memory tasks. *Consciousness and Cognition*, *18*, 811-819. doi:10.1016/j.concog.2009.02.009

Butler, B. C., & Klein, R. (2009). Inattentional blindness for ignored words: Comparison of explicit and implicit memory tasks. *Consciousness and Cognition, 18*, 811–819. doi:10.1016/j.concog.2009.02.009

Butler, L. T., & Berry, D. C. (2001). Implicit memory: Intention and awareness revisited. *Trends in*

Cognitive Sciences, 5, 192–197. doi:10.1016/S1364-6613(00)01636-3

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*, 1484-1525. doi:10.1016/j.visres.2011.04.012

Cohen, M. A.,Horowitz, T. S.,&Wolfe, J.M. (2009). Auditory recognition memory is inferior to visual recognition memory. *Proceedings of the National Academy of Sciences, 106*, 6008–6010. doi:10.1073/pnas.0811884106

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87–185. doi:10.1017/S0140525X01003922

Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70*, 80–90. doi:10.1037/h0039515.

Dickerson, K., & Gaston, J. R. (2014). Did you hear that? The role of stimulus similarity and uncertainty in auditory change deafness. *Frontiers in Psychology*, *5*, 1125. doi:10.3389/fpsyg.2014.01125

Driver, J. (2001). A selective review of selective attention research from the past century. *British Journal of Psychology*, *92*, 53–78. doi:10.1348/000712601162103

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature, 387,* 808-810. doi:10.1038/42947

Glucksberg, S., & Cowen, G. N. (1970). Memory for nonattended auditory material. *Cognitive Psychology, 1,* 149–156. doi:10.1016/0010-0285(70)90010-1

Hoffman, Y., Bein, O., & Maril, A. (2011). Explicit memory for unattended words: the importance of being in the “no”. *Psychological Science, 22*, 1490–1493. doi:10.1177/0956797611419674

Hutmacher, F., & Kuhbandner, C. (2018). Long-term memory for haptically explored objects: Fidelity, durability, incidental encoding, and cross-modal transfer. *Psychological Science*, *29*, 2031-2038. doi:10.1177/0956797618803644

Johnson, M.K. (1983). A multiple-entry, modular memory system. In G.H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 17, pp. 81-123). New York: Academic Press.

Kuhbandner, C., Rosas-Corona, E. A., & Spachtholz, P. (2017). High-Fidelity Visual Long-Term Memory within an Unattended Blink of an Eye. *Frontiers in Psychology*, *8*, 1859. doi:10.3389/fpsyg.2017.01859

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 451–468. doi:10.1037/0096-1523.21.3.451

Lavie, N. (2006). The role of perceptual load in visual awareness. *Brain Research, 1080,* 91–100. doi:10.1016/j.brainres.2005.10.023

Lavie, N. (2010). Attention, distraction, and cognitive control under load. *Current Directions in Psychological Science*, *19*, 143–148. doi:10.1177/0963721410370295

Lavie, N., Lin, Z., Zokaei, N., & Thoma, V. (2009). The role of perceptual load in object recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1346–1358. doi:10.1037/a0016454

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281. doi:10.1038/36846

Magnussen, S., & Dyrnes, S. (1994). High-fidelity perceptual long-term memory. *Psychological Science, 5*, 99-102. doi:10.1111/j.1467-9280.1994.tb00638.x

Mitchell, D. B. (2006). Nonconscious priming after 17 years: Invulnerable implicit memory? *Psychological Science*, *17*, 925–929. doi:10.1111/j.1467-9280.2006.01805.x

Mitchell, D. B., & Brown, A. S. (1988). Persistent repetition priming in picture naming and its dissociation from recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *14*, 213–222. doi:10.1037/0278-7393.14.2.213

Mulligan, N. W. (1998). The role of attention during encoding in implicit and explicit memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 27–47. doi:10.1037/0278-7393.24.1.27

Musen, G., & Treisman, A. (1990). Implicit and explicit memory for visual patterns. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 127–137. doi:10.1037/0278-7393.16.1.127

Norman, D. A. (1969). Memory while shadowing. *Quarterly Journal of Experimental Psychology*, *21*, 85–93. doi:10.1080/14640746908400200

O'Connor, D. H., Fukui, M. M., Pinsk, M. A., & Kastner, S. (2002). Attention modulates responses in the human lateral geniculate nucleus. *Nature Neuroscience*, *5*, 1203–1209. doi:10.1038/nn957

Peterson, L. R., & Kroener, S. (1964). Dichotic stimulation and retention. *Journal of Experimental Psychology*, *68*, 125-130. doi:10.1037/h0039989

Rees, G., Russel, C., Frith, C. D., & Driver, J. (1999). Inattentional blindness versus inattentional amnesia for fixated but ignored words. *Science, 286*, 2504–2506. doi:10.1126/science.286.5449.2504

Robinson, D. (2001, July 10). Replay Gain – A Proposed Standard. Retrieved from http://replaygain.hydrogenaud.io/proposal/

Ruz, M., Wolmetz, M. E., Tudela, P., & McCandliss, B. D. (2005). Two brain pathways for attended and ignored words. *Neuroimage*, *27*, 852–861. doi:10.1016/j.neuroimage.2005.05.031

Ruz, M., Worden, M. S., Tudela, P., & McCandliss, B. D. (2005). Inattentional amnesia to words in a high attentional load task. *Journal of Cognitive Neuroscience*, *17*, 768–776. doi:10.1162/0898929053747685

Schacter, D. L. (1987). Implicit memory: history and current status. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 501–518. doi:10.1037/0278-7393.13.3.501

Schacter, D. L. (1990). Perceptual representation systems and implicit memory: Toward a resolution of the multiple memory systems debate. *Annals of the New York Academy of Sciences*, *608*, 543-571. doi:10.1111/j.1749-6632.1990.tb48909.x

Schacter, D. L., Chiu, P. C. -Y., & Ochsner, K. N. (1993). Implicit memory: A selective review. *Annual Reviews of Neuroscience*, *16*, 159–182. doi:10.1146/annurev.ne.16.030193.001111

Seitz, A. R., Kim, D., & Watanabe, T. (2009). Rewards evoke learning of unconsciously processed visual stimuli in adult humans. *Neuron*, *61*, 700-707. doi:10.1016/j.neuron.2009.01.016

Serences, J. T., & Kastner, S. (2014). A multi-level account of selective attention. In K. Nobre & S. Kastner (Eds.), *The Oxford Handbook of Attention* (pp. 76-104). Oxford: Oxford University Press.

Simons, D. J., & Rensink, R. A. (2005). Change blindness: Past, present, and future. *Trends in Cognitive Sciences*, *9*, 16-20. doi:10.1016/j.tics.2004.11.006

Sinnett, S., Costa, A., & Soto-Faraco, S. (2006). Manipulating inattentional blindness within and across sensory modalities. *The Quarterly Journal of Experimental Psychology*, *59*, 1425–1442. doi:10.1080/17470210500298948

Soto-Faraco, S., & Spence, C. (2002). Modality-specific auditory and visual temporal processing deficits. *Quarterly Journal of Experimental Psychology*, *55A*, 23–40. doi:10.1080/02724980143000136

Spachtholz, P., & Kuhbandner, C. (2017). Visual long-term memory is not unitary: flexible storage of visual information as features or objects as a function of affect. *Cognitive, Affective, and Behavioral Neuroscience, 17*, 1141-1150. doi: 10.3758/s13415-017-0538-4

Susini, P., Lemaitre, G., & McAdams, S. (2012). Psychological measurement for sound description and evaluation. In B. Berglund, G. B. Rossi, J. T. Townsend, & L. R. Pendrill (Eds.), Measurements with persons: Theory, methods, and implementation areas (pp. 227 – 253), New York: Psychology Press.

Swallow, K. M., & Jiang, Y. V. (2010). The attentional boost effect: Transient increases in attention to one task enhance performance in a second task. *Cognition, 115*, 118-132. doi:10.1016/j.cognition.2009.12.003

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*, 97-136. doi:10.1016/0010-0285(80)90005-5

Vo, M. L., Conrad, M., Kuchinke, L., Urton, K., Hofmann, M. J., & Jacobs, A. M. (2009). The Berlin affective word list reloaded (BAWL-R). *Behavior Research Methods, 41*, 534–538. doi:10.3758/BRM.41.2.534

Voss, J. L., Baym, C. L., & Paller, K. A. (2008). Accurate forced-choice recognition without awareness of memory retrieval. *Learning and Memory, 15*, 454–459. doi:10.1101/lm.971208

Voss, J. L., & Paller, K. A. (2010). What makes recognition without awareness appear to be elusive? Strategic factors that influence the accuracy of guesses. *Learning & Memory, 17*, 460-468. doi:10.1101/lm.1896010

Watson, C. S., Wroton, H. W., Kelly, W. J., & Benbassat, C. A. (1975). Factors in the discrimination of tonal patterns. I. Component frequency, temporal position, and silent intervals. *The Journal of the Acoustical Society of America, 57,* 1175-1185. doi:10.1121/1.380576

Wickens, T. D. (2002). *Elementary signal detection theory*. Oxford University Press, USA.

Wolfe, J. M. (1999). Inattentional amnesia. In V. Coltheart (Ed.), *Fleeting Memories* (pp. 71–94), Cambridge, MA: MIT Press.