The Memory of Noise

Christian Kaernbach

University of Leipzig, Germany

Abstract. The memory of auditory random waveforms (i.e., noise) is a special case of auditory memory for sensory information. Five experiments are reported that evaluate the dynamics of this storage system as well as interactions with new input. Periodic waveforms can be discriminated from uncorrelated noise by naive listeners up to a cycle length of 20 s, with the major decline in performance between 5 and 10 s. Even single repetitions of a piece of the waveform can be detected up to a stimulus onset asynchrony (SOA) of 6 s. The capacity of this storage system is limited to a few items of, in total, a few hundred milliseconds length. Within this capacity, however, items do not interfere strongly. These results are compatible with the view that auditory sensory memory is a modality-specific module of short-term memory.

Key words: sensory memory, short-term memory, auditory memory, categorical memory

Working memory and sensory memory are often considered unlikely brothers. Working memory refers to the active and attention-controlled maintenance of information in the service of complex cognitive tasks such as problem solving and planning. These tasks involve in general operations on categorical information. In contrast to this, sensory memory is preattentive, and the representation of information stored in sensory memory is acategorical, either because it has not yet been categorized, or because such an operation is not possible with this type of material. Sensory information is, in most cases, not used for complex operations but just stored for later transfer to categorical information.

In the multiple-components model of Atkinson and Shiffrin (1968) sensory storage, short-term memory, and long-term memory were conceived as separate structural components. In contrast to this, the one-store model of Shiffrin and Schneider (1977) has defined short-term memory as activated long-term memory, i.e., as a process rather than as a structural component. This view is still widely accepted. But also the view on sensory memory has changed. First in the auditory domain (Cowan, 1984; Massaro, 1972), and then generalized to all modalities (Cowan, 1988), it has been established that there are two different types of sensory stores. The so-called short sensory stores (200 ms) form part of sensation. Only the long sensory stores are perceived as memory. The memory model of Cowan assumes very similar mechanisms for categorical short-term memory and for the long sensory stores. The long sensory stores are also conceived as activated long-term memory, of acategorical, sensory content. *This would imply that memory for categorical and for sensory information are not that unlike after all.*

The present paper compares memory for sensory, acategorical auditory information with known facts on classical short-term memory for categorical information. The reported experiments on sensory information storage use a single class of stimuli, by this means avoiding unjustified synopses across tasks and material. An ideal stimulus for experiments on auditory sensory storage is auditory white noise. This stimulus cannot be recoded to be stored in a categorical representation. Any memory performance observed for noise must be due to sensory storage.

Noise is generally perceived as a homogenous, featureless stimulus, fully described by a single parameter: its loudness. It is hard to imagine that one could memorize a specific noise sample and discriminate it from another one of equal loudness. Physically, noise is a random waveform. It can be generated by feeding a sequence of random numbers to the sound card. Under normal circumstances, one sequence of random numbers sounds just like any other.

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The seeming impossibility to remember noise, i.e., to remember a specific random waveform and to discriminate it from other random waveforms, is due to the short lifetime of auditory sensory storage. In order to enable auditory sensory memory to detect the reoccurrence of a certain segment of a random waveform this segment is compelled to reoccur within a few seconds, and no other strong perceptual cues such as on- and offsets should intervene. If one wants to test memory for noise, the random waveform should be repetitive. And, indeed, the indistinctness of random waveforms ceases dramatically if the random waveform starts to repeat itself after a second or less (Guttman & Julesz, 1963). Even naive listeners perceive a striking difference between periodic and continuous random waveforms as long as the cycles are shorter than one or two seconds. Periodic random waveforms are perceived as rhythmically structured and filled with perceptual events such as "clanks" and "rasping." A demonstration of periodic noise stimuli can be found at

www.periodic-noise.de.

The perceptual events are the outcome of a memory process: If (and only if) the auditory system detects the reoccurrence of a part of the waveform, by "relistening" it can confirm small irregularities that would be drowned out in a single, non-repetitive presentation by those thousands of other small features of the noise stimulus to follow. Evidently, the form of the memory representation is not simply the waveform itself: The repetition seems to prime early auditory feature codes (Kaernbach, 2000; Kaernbach, Schröger, & Gunter, 1998).

It is important to distinguish periodic random waveforms from other types of frozen noise stimuli. Separately presented segments of frozen noise play an important role in studies on masking. Iterated with onset and offset ramps amplitude modulation dominates perception and the faint percepts characteristic of periodic random waveforms are suppressed.

In contrast, if repetitions of a single segment of white noise are connected seamlessly, no major amplitude modulations are introduced. No artifacts are introduced at the connection points that could give rise to clicks or other artificial percepts: a sequence of random numbers does not feature any coherence that could be disrupted. In consequence, cycles longer than one or two seconds sound, on first, inattentive listening, just as featureless as uncorrelated white noise. If periodic random waveforms elicit rhythmical perceptual events, this can only be due to the detection of the reoccurrence of parts of the waveform. These perceptual events are to a certain degree reproducible across different sessions of the same listener but vary from listener to listener (Kaernbach, 1992). The temporal extent of the physical basis of these perceptual events is restricted to about 100 ms (Kaernbach, 1993). Gerbils have been demonstrated to be able to discriminate periodic and continuous noise up to cycle lengths of 400 ms (Kaernbach & Schulze, 2002), and cats show a similar performance (Frey, Kaernbach, & König, 2003). For a review on periodic noise research, see Warren (1998).

The next two sections address the issues of the dynamics of and interactions in auditory sensory information storage. The final section discusses similarities and differences between sensory and categorical information storage. For a more extensive discussion of auditory sensory storage and categorical short-term memory, see Kaernbach (2004).

Dynamics of Sensory Information Storage

When studying the dynamics of a memory system, the focus is on decay as a function of time. It has often been questioned whether forgetting is due to decay. Interference could be responsible for the inability to remember. Decay and interference are, however, inseparable: During retention time there is always interference (be it through internal activity), and interference always needs time. The decay-interference dualism is comparable to that of waves and particles in physics: The aspect of the system under study depends on the methods. When varying the length of the retention interval one studies decay as a function of time, and when varying the stimuli presented during retention one studies interference as a function of material. This section deals with the decay of memory for an auditory random waveform as a function of time. The next section deals with internal interactions between the stored items and with interference from external stimuli.

The lifetime of short-term memory for syllables, words, or letters can be reliably assessed only if measures are taken to prevent rehearsal. In the classical Brown-Peterson paradigm (Brown, 1958; Peterson & Peterson, 1959), participants are prevented from rehearsing by articulatory tasks such as counting backwards. In this case, categorical information in short-term memory is known to last several seconds. Memory for auditory random waveforms does not seem to qualify for the same decay range. Guttman and Julesz (1963) reported that for periods longer than one or two seconds it would become difficult to detect the periodicity of periodic noise. Nevertheless, Cowan (1984) ascribes periodic noise perception to the long auditory store (time constants 10 to 20 s). Warren, Bashford, Cooley, and Brubaker (2001) showed that cross-modal cueing could help experienced and well-trained listeners to detect the periodicity in cycles of 10, 15, or even 20 s. In our own pilot studies, it became obvious that only a small amount of training is needed for naive listeners to perceive long cycles without cross-modal cueing. Experiment 1 was conducted to quantify the relation between training and maximum cycle length and hence give a more formal estimate of the lifetime of the memory for random waveforms.

Experiment 1: Maximum Cycle Length Perceived as Repeating

Methods

Twenty naive participants (11 female and 9 male), who had not served in psychoacoustic experiments previously, took part in this experiment as part of a course requirement. The participants were psychology students in the second year and had normal hearing. The noise was generated as a sequence of random numbers. These random numbers were converted at a sampling rate of 20 kHz and presented at 60 dB hearing level. To make this noise periodic, the random number sequence was recycled. For each participant and each single trial, a different noise sample was generated.

The participants did not hear any demonstration and started the experiment without practice. The presentation of the periodic noise stimulus started when the participant hit the space bar of the computer keyboard. Participants were instructed to tap any structure they perceived on the space bar, but only once per period. The timing of this tapping could be determined by the computer program with a precision of better than 1 ms. If the participant started tapping, eight taps were attended before the presentation of the noise ended. If the participant did not start tapping to a noise sample after a certain time (5 s plus 7 cycles) or started tapping but did not continue for seven cycles, this trial was considered a failure and the next trial started.

The participants were randomly assigned to one of two groups. Group A passed through the 22 different cycle lengths ranging from 0.5 to 20 s in ascending order, Group B through the same cycle lengths in descending order. From trial to trial the cycle length was increased (Group A) or decreased (Group B) regardless of the success or nonsuccess of the previous trial. All participants performed three (ascending or descending) sweeps.

From the obtained tapping data it was determined whether the participant had perceived the correct periodicity.

Results and Discussion

Figure 1 shows the results as a function of the cycle length, averaged over all participants regardless of presentation order and run. Periodic noise cycles of several seconds can be correctly detected. The performance decays monotonically with increasing cycle length, but there is a certain performance for naive participants even at cycle lengths of 10, 15, or 20 seconds.

In total, there was not much training during this experiment. The entire session lasted only 30 minutes, i.e., about 10 minutes per (descending or ascending) sweep. Nevertheless, there was a significant training effect (performance across cycle lengths first run: 47 %, third run: 63 %). However, a remarkable performance was found already during the first run: Four participants of Group A could correctly tap a 20-s cycle after less then 10 min of training (i.e., during the first ascending sweep). Two participants of Group B successfully tapped a cycle of 12 s in the first descending sweep after about six min of exposure to longer cycles. This can hardly be called training as they did not hear any periodicities in these longer cycles. This experiment demonstrates that naive listeners can detect, with only little training, random waveform cycles of 10 s and more. To this end, they must have memorized parts of the waveform, and this memory must have survived several seconds.

Figure 1 illustrates the time course of sensory memory for auditory random waveforms. For comparison, it shows also data from Peterson and Peterson (1959) on the retention of consonant trigrams, considered to represent classical data on categorical information storage. The main purpose of the inclusion of these data in Figure 1 was to compare the approximate range of temporal decay for sensory

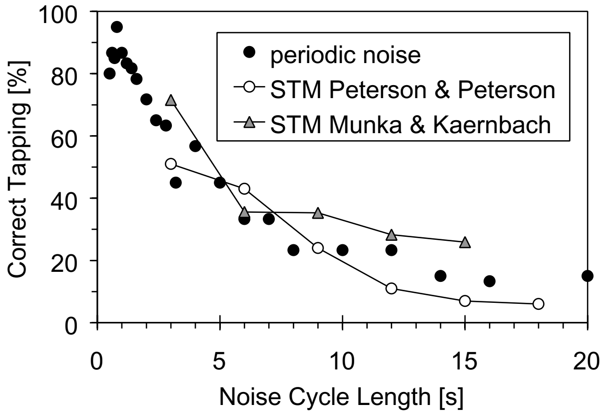

Figure 1. Results of Experiment 1. Percentage of trials with correct tapping to periodic noise as a function of cycle length (full circles). See text for details on the comparison data sets.

versus categorical information. In the face of Figure 1, one is compelled to conclude that the temporal decay is quite similar for these two types of information.

One might argue that in experiments dealing with categorical storage the material to be memorized is somehow presented to the senses. For instance, Peterson and Peterson presented their stimuli auditorily. Therefore, it might not be obvious that their data are really relevant to categorical storage. Munka and Kaernbach (2001) have tested memory for self-generated information. Participants had to add two four-digit numbers silently and to retain the result. During retention, participants had to perform a distraction task. The presented material (eight digits) exceeded the full-report limit given by Sperling (1960), while the to-be-retained sum (four digits) did not. This excluded retention of the presented stimuli and enforced retention of the self-generated information. The percentage of correct responses decayed as a function of time very similarly to the decay observed in Experiment 1. The data are included in Figure 1 for comparison. Even in the absence of any sensory trace, the decay of information occurred in the same temporal range of about five to ten s.

In this experiment, memory performance has been demonstrated with periodic noise. Memory is in general not dependent on a periodic presentation of the material. Informal tests with periodic noise stimuli with jittered periodicity do not show any degradation of performance for non-periodic representations. However, the most explicit test of "memory of noise" would be to demonstrate that a single repetition of a frozen noise segment is already detectable. This would then correspond to a classical S1–S2 paradigm. The next two experiments test this ability.

Experiment 2: Detecting a Single Seamless Repetition

Methods

Ten participants (5 female and 5 male, age range 19 to 34) took part in this experiment. The noise was converted at a sampling rate of 44.1 kHz and presented at 60 dB hearing level. The detection of a single repetition was tested for segments lengths from 0.1 to 6.4 s, with a factor of two between consecutive intervals. Each two-interval forced-choice (2IFC) trial consisted of a noise stimulus with 100-ms ramps at onset and offset. The noise stimulus started and ended with one second of uncorrelated noise before and after the test intervals. The test intervals were separated by another second of uncorrelated noise. The test intervals had twice the length of the segment to be tested. In one of the two intervals, the second part of this interval was an exact copy of the first part. In the other of the two intervals, the noise was again uncorrelated. The two intervals were marked with a visual cue. See also the illustration in the insert of Figure 2. Please note that the fact that the repeating segment is embedded in noise of equal loudness helps to detect the repetition. Switching the noise on and off close to the segments would produce strong on- and offset percepts that would supersede the faint percepts elicited by the repeating segment.

The participants had to decide whether the repetition occurred in the first or the second interval. They were given feedback on negative trials. Participants tested the different segment lengths in ascending order. Ten such sweeps constituted a block, which took about 15 min. All participants performed 10 such blocks. The 2IFC performance was then converted to *d*' values.

Before the experimental session, all participants performed several training blocks with a similar set-up, with the exception that participants could decide on the number of repetitions (1 to 9). This served to make them familiar with the set-up. They terminated this training phase at their own discretion, when they felt comfortable with the task for a single repetition. On average, they performed about four training blocks.

Results and Discussion

Figure 2 shows the *d*' values as a function of the stimulus onset asynchrony (SOA) which is identical to the segment length. The performance clearly drops as a function of time. The decay is faster than in Figure 1, indicating that longer cycles take more profit from continuous repetitions. Significant performance for a single repetition can, however, still be found for segments as long as 6.4 s.

At the left end of the curve, there is a deviation from monotony: The value for segment length 0.1 s is lower than the next value. This is most likely due to the fact that this value was always tested first within a sweep. Even mid-block (e.g., first trial of sweep 2, segment length 0.1 s) the test at this value might have been hampered by the fact that the previous trial (last trial of sweep 1, segment length 6.4 s) was so very different.

The ability to detect a single repetition of a random waveform has not been reported up to now. This is clear evidence that periodic noise perception represents a memory performance and not some kind of periodicity detection. It should be noted, however, that not only did the SOA change when changing the segment length, but also the amount of information

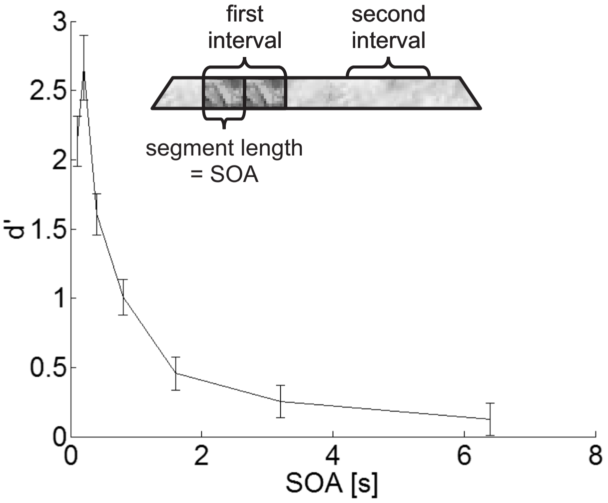

Figure 2. Results of Experiment 2. Performance in a 2IFC paradigm for the detection of a single seamless repetition of a noise segment as a function of the stimulus onset asynchrony (SOA). The errorbars correspond to upper and lower true performance limits that assuming a 2-σ deviation could have resulted in the observed performance.

that could be used to detect the repetition. The next experiment tested different SOAs for the same length of the noise segment to be retained.

Experiment 3: Detecting a Single Detached Repetition

Methods

In this experiment, the same 10 participants of Experiment 2 took part. The major difference to Experiment 2 was the composition of the stimulus: The SOA of the original and the repeated version of the frozen noise segment was now varied independently from its length (see the insert in Figure 3). The SOA is a better representation of the length of the retention interval than the inter-stimulus interval because of the transient nature of auditory stimulation: The relevant feature is not present during the entire segment. The length of the frozen segment was 0.05, 0.1, or 0.2 s. The SOAs ranged from 0.05 to 0.8 s. The SOA could of course not be shorter than the length of the segment. In total, this gave 12 different combinations of segment length and SOA. In order to avoid sequence effects, the order of presentation was randomized. Participants initiated each trial with a mouse click. With the prompt for this mouse click, they were informed about the type of trial to follow next. The visual cue was altered to better reflect the trial structure: It did not only indicate the intervals, but also the potential placement of frozen segments within the interval. Ten sweeps through all 12 conditions constituted a block, which took about 12 min. All participants performed 10 such blocks.

Results and Discussion

Figure 3 shows *d*' values as a function of the SOA for different segment lengths. With a constant segment length, performance drops faster than with a full repetition as in Experiment 2. For an SOA of 800 ms the frozen segment needs to be 200 ms to obtain a performance that is significantly different from chance performance. Shorter segments seem not to contain enough variation of auditory material to offer good clues for memorization. Nevertheless, the reported results demonstrate an astounding ability to detect a single repetition of only a small part of the waveform.

Interactions of Sensory Information

The information stored in a memory system is vulnerable. New input will interact with the stored information and degrade the memory performance to a greater or lesser extent. Two different classes of interactions can be observed: In short-term memory, the number of items that can be stored independently is small (Cowan, 2001). New input will compete with stored information for storage capacity. But

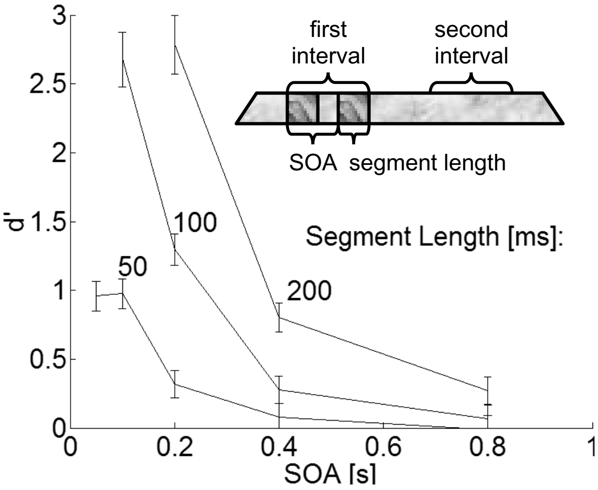

Figure 3. Results of Experiment 3. Performance in a for the detection of a single repetition of a short detached noise segment as a function of the stimulus onset asynchrony (SOA) and the length of the segment (labels)

even in memory systems with a high storage capacity such as the classical sensory registers (Neisser, 1967), new input can be detrimental to the stored information. The icon, for example, has been reported to be completely overwritten by subsequent input (Averbach & Coriell, 1961).

In contrast to the concept of classical sensory registers, short-term memory for categorical information features a low capacity limit, but (within this capacity) a low susceptibility to interference. From the aforementioned memory model of Cowan it would follow that this should also be the case for the long sensory stores, e.g., for the memory of noise. The following experiments were designed to test this assumption. Experiment 4 evaluates the capacity of the auditory sensory memory, and Experiment 5 tests its susceptibility to interference within the limits of its capacity.

Experiment 4: Capacity

Methods

Ten participants (psychology students in the second year, 6 female, 4 male) took part in the experiment. The stimulus was composed of a cycle of several 200-ms segments of frozen white noise, with 100-ms segments of uncorrelated noise between these segments, i.e., a frozen segment all 300 ms. This detached presentation aimed to isolate the percepts elicited by each of the frozen segments while avoiding undesirable amplitude modulations. The noise was converted at a sampling rate of 20 kHz and presented at 60 dB hearing level.

In a pilot study, participants selected their 20 favorites from 80 segments of white noise. They did so by rating the clearness of the percept in such a detached periodic presentation. In the main experiment, participants had to decide in a 2IFC paradigm, which of two test cycles was changed. A block was constituted by a noise presentation of several minutes in length. The cycles were composed of three to five of the individually selected favorite segments. The length of a cycle was always 1.5 seconds: In cycles with less than five elements, the remaining cycle length was filled with uncorrelated noise. The changed cycle had one to all of the frozen segments replaced with uncorrelated noise. The variation of total segment number (3 to 5) and number of exchanged segments (1 to all) gives 12 different conditions in total. A trial constituted of six cycles, with Cycle 3 and 5 constituting the test cycles. The response interval started with Cycle 6 and extended to the first cycle of the next trial, which followed seamlessly. A block comprised 30 trials and lasted about 5 min. In the first series of blocks, the sequence of the segments stayed the same between trials (“fixed”). Participants performed 25 blocks (750 trials, about 60 trials per condition) of this type. In a second series, the sequence was permuted between trials (“permuted”). This variation was introduced to evaluate the potential influence of chunking. Participants performed 18 blocks (540 trials, 45 trials per condition) of the permuted type.

Results and Discussion

The performance increased as a function of the number of exchanged segments. For a certain number of exchanged elements, performance was better in cycles with a small total number of elements than in a cycle with many items. All this is to be expected in case of a capacity limit: The higher the percentage of exchanged elements, and the lower the total number of segments, the higher the chance to exchange a sensitive item, i.e., one that has been memorized. The data for fixed versus permuted presentation of segment sequence between trials are rather similar.

A simple three-parameter model featuring a capacity limit (in terms of the number of items to be memorized) and two lapse rates (a single-item lapse rate and a total-response lapse rate) can predict the data. The likelihood of the exact outcome of the experiment can be calculated, and it clearly depends on the setting of the parameters (capacity, lapse rates). These can be optimized to give the highest possible likelihood for the experimental data. Figure 4 shows

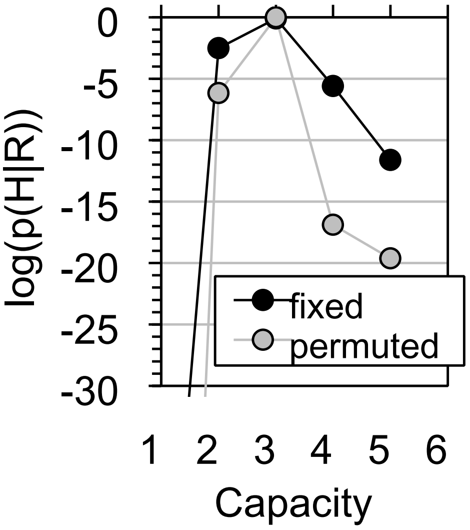

Figure 4. Results of Experiment 4. Maximum likelihood for the observed results as a function of the capacity parameter of a simple memory model.

the maximum likelihood for the experimental data for various values of the capacity parameter. It obtains its maximum value for a capacity of three items. The outcome of this analysis does not depend on the presentation order between trials (fixed versus permuted). This indicates that chunking did not play a role in this experiment. This capacity estimate comes close to the often-mentioned capacity limit of short-term memory of four items (for an extensive discussion of evidence that point to this capacity limit see Cowan, 2001). Apparently, auditory sensory memory for random waveforms and short-term memory for categorical information are subject to comparable capacity limitations.

Experiment 5: Susceptibility to Interference

The second type of interactions between new input and stored information concerns the situation where there is sufficient capacity to hold both the old and the new information. In general, this would then imply that the effect of new input is less detrimental to the storage of old information. This is, however, not always the case: The vulnerability of the short sensory stores towards new input is not due to capacity limitations. Long sensory stores, on the other hand, should be comparable to short-term memory, with its low susceptibility to interference within its narrow limits of capacity. This was tested in the following experiment for the memory of noise.

Methods

Three psychology students (2 female and 1 male) of the second year took part in this investigation. A trial consisted of a presentation of a noise stimulus of 17 s length that was ramped on and off over 250 ms at both ends. The noise was converted at a sampling rate of 20 kHz and presented at 60 dB hearing level. It was periodic in its first 7 s, consisting of 14 500-ms periods of detached frozen noise (250 ms frozen noise, 250 ms uncorrelated). In order to help the participant to detect the periodicity, a visual cue was flashed on the computer screen whenever the frozen segment was present. During the retention interval of 8.25 s, the noise went on but without further reoccurrence of the frozen 250-ms segment and without any visual signal. In the last second of the stimulus, the visual cue reoccurred. In half of the cases, this last visual cue was accompanied by the same frozen segment that was present during the first 7 s. It was the (main) task of the participant to decide whether the frozen segment had reoccurred at the end of the stimulus. See also the illustration in the insert of Figure 5.

Three different conditions of retention of sensory auditory information were tested: without interference, with visual and with auditory interference. In the condition without interference, there was no additional task during the retention interval. The use of silence is often suggested instead of ongoing white noise during the retention interval for the no-interference condition. It is, however, much more difficult to solve the main task if the noise is switched off during the retention interval. This is due to the strong interference resulting from the off- and onset. In the condition with auditory interference, another periodic noise was embedded in the 8.25-s retention interval of the 17-s stimulus (see insert of Figure 5). It started 750 ms after the last frozen segment of the main task, and consisted of 15 cycles (i.e., 7.5 s) of 250-ms frozen/250-ms uncorrelated periodic noise with a different frozen segment. In 25 % of the cases, the final two cycles were replaced by uncorrelated noise. This interference task was also accompanied by a flashing visual signal, which always ran for 15 cycles. The interference task was a go/no-go task: The participant should in case of the absence of the final two cycles of the interference task press a special key and could then ignore the main task. In the condition with visual interference there was no periodicity noise present in the retention interval. The visual signal, however, flashed 15 times with the same rhythm as it did during the retention period of the auditory interference condition. This time, the participant had to watch the size of the visual signal. In 25 % of the cases, one of these 15 signals was slightly larger than the others. In this case, the partic-

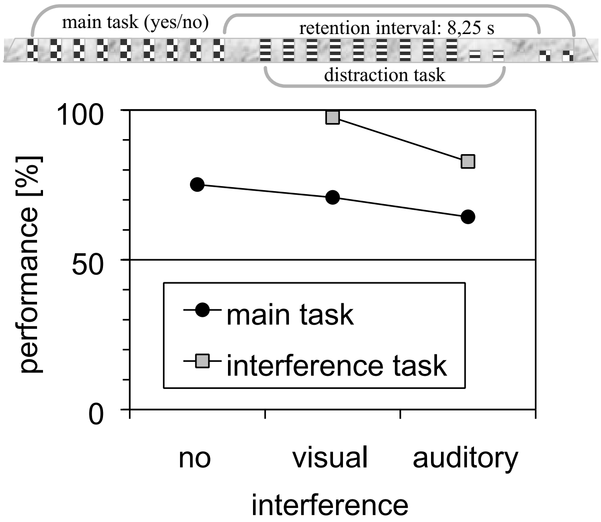

Figure 5. Results of Experiment 5. Performance in main and interference tasks, averaged across participants, as a function of interference task type.

ipant had to press a special key and could ignore the main task.

On each trial, a new segment of frozen noise was selected for the main task, and another new one for the interference task in the auditory interference condition. The participants performed blocks of 20 trials per condition, with conditions in cyclical order (no, visual, auditory interference). They performed 300 training trials and 420 experimental trials. Performance in the main task was calculated over no-go trials in the interference task only.

Results and Discussion

Figure 5 shows the results of Experiment 5. The performance in the main task was 75% (halfway between perfect and random) in the case that there was no interfering task. This threshold performance is due to the fact that the retention interval is rather long (compare Figure 1).

The difficulty of the two types of interference tasks was not matched: The auditory interference task was more difficult than the visual interference task. With both interference tasks, performance dropped in the main task. This drop was slightly more marked in the auditory interference condition than in the visual interference condition. This might well be due to the greater difficulty of the auditory interference task. The important observation is that the performance in the main task, being already close to threshold even without any interference, still remained significantly better than chance when a difficult interference task had to be performed during the retention interval. These results demonstrate that interference in the long auditory store is less absolute than in short sensory stores.

General Discussion

In working memory, operations are possible that are inconceivable in sensory memory. Amongst these operations reserved for categorical storage are complex manipulations of the stored items, but also simple strategies to improve memory performance such as rehearsal of the stored information (Demany, Clément, & Semal, 2001; Kaernbach & Hahn, 2004). The higher versatility of working memory results from the more processed state of the information stored in it. This does not rule out that both memory systems share a basic mechanism for maintaining the activation for some seconds, which is subject to some capacity limitations. According to the view of Cowan, the difference between sensory and categorical memory is the code (sensory or categorical) that is memorized, whereas the process of maintaining a high level of activation for some seconds could be the same. The data presented in this paper support this view: Sensory memory and categorical memory show similar dynamics and interaction patterns.

The long sensory stores can be clearly differentiated from the early concepts of sensory registers (Neisser, 1967) that were thought of as storing huge amounts of information for less than a second and being highly susceptible to interference. The similarity in decay rate (Experiment 1), the low capacity (Experiment 4), as well as the comparatively low susceptibility to interference (Experiment 5), can be considered evidence that the long sensory storage is more closely related to short-term memory than to the traditional notion of sensory register.

It has been questioned whether the decay observed in memory experiments is due to the decay of a trace or due to interference. Proactive (Keppel & Underwood, 1962) and/or retroactive (see e.g., Waugh & Norman, 1965) interference could be the real cause of the observed decay. The decay/interference debate is somewhat intractable as it is possible to mimic decay by retroactive interference by internal states, that is, even in the absence of external interfering stimuli. In the case of the memory of noise, it is not plausible to assume that the decay of the performance for longer cycles is caused by the increasing amount of external interference by the ongoing noise. Sensory memory performance decays in S1–S2 paradigms without any interfering sound during the retention interval (Deutsch, 1973).

The memory model of Cowan stands the test with noncategorical stimulus material such as noise. Auditory sensory memory can well be considered a specialized module of short-term memory, a kind of *auditory short-term memory.* There seems to be, however, a major difference between categorical and sensory storage that deserves consideration: Categorical storage can be sustained with rehearsal techniques (mimicking a difference in lifetime), while it seems that this is not the case for sensory storage (Demany, Clément & Semal, 2001; Kaernbach & Hahn, 2004). In addition to these studies, there is nonformal but clear-cut evidence for this difference apparent in Experiment 1: With sensory memory for noise there is no need to suppress rehearsal. This contrasts to categorical memory experiments where there would be no decay at all without rehearsal suppression.

It might well be that the unavailability of complex operations such as rehearsal is the only essential difference between short-term memory for categorical and noncategorical information. Studies on sensory memory would then provide a valuable crosscheck to studies on working memory, with predictable differences in case that complex operations plays a role. And the memory of noise represents an excellent probe of sensory memory.

References

Atkinson, R. C., & Shiffrin, R. M (1968). Human memory: a proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: advances in research and theory* (Vol. 2, pp. 89–195). New York: Academic Press.

Averbach, E., & Coriell, A. (1961). Short-term memory in vision. *Bell System Technical Journal, 40,* 309–328.

Brown, J. (1958). Some test of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology, 10,* 12–21.

Cowan, N. (1984). On short and long auditory stores. *Psychological Bulletin, 96,* 341–370.

Cowan, N. (1988). Evolving concepts for memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin, 104,* 163–191.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24,* 87–114.

Demany, L., Clément, S., & Semal, C. (2001). Does auditory memory depend on attention? In D. J. Breebaart, A. J. M. Houtsma, A. Kohlrausch, V. F. Prijs, & R. Schoonhoven (Eds.), *Physiological and psychophysical bases of auditory function* (pp. 461–467). Maastricht: Shaker Publishing BV.

Deutsch, D. (1973). Interference in memory between tones adjacent in the musical scale. *Journal of Experimental Psychology, 100,* 228–231.

Frey, H.-P., Kaernbach, C., & König, P. (2003). Cats can detect repeated noise stimuli. *Neuroscience Letters, 346,* 45–48.

Guttman, N., & Julesz, B. (1963). Lower limits of auditory periodicity analysis. *Journal of the Acoustical Society of America, 35,* 610.

Kaernbach, C. (1992). On the consistency of tapping to repeated noise. *Journal of the Acoustical Society of America, 92,* 788–793.

Kaernbach, C. (1993). Temporal and spectral basis of the features perceived in repeated noise. *Journal of the Acoustical Society of America, 94,* 91–97.

Kaernbach, C. (2000). Early auditory feature coding. In A. Schick, M. Meis, & C. Reckhardt (Eds.), *Contributions to psychological acoustics: Results of the 8th Oldenburg Symposium on Psychological Acoustics* (pp. 295–307). Oldenburg, Germany: University of Oldenburg.

Kaernbach, C. (2004). Auditory sensory memory and short-term memory. In C. Kaernbach, E. Schröger, H. Müller (Eds.), *Psychophysics beyond sensation: Laws and invariants of human cognition* (pp. 331–348). Mahwah NJ: Erlbaum.

Kaernbach, C., & Hahn, K. (2004). Pitch memory with and without rehearsal. Manuscript submitted for publication.

Kaernbach, C., Schröger, E., & Gunter, T. C. (1998). Human event-related brain potentials to auditory periodic noise stimuli. *Neuroscience Letters, 242,* 17–20.

Kaernbach, C., & Schulze, H. (2002). Auditory sensory memory for random waveforms in the Mongolian gerbil. *Neuroscience Letters, 329,* 37–40.

Keppel, G., & Underwood, B. J. (1962). Proactive inhibition in short-term retention of single items. *Journal of Verbal Learning and Verbal Behavior, 1,* 153–161.

Massaro, D. W. (1972). Prepeceptual images, processing time, and perceptual units in auditory perception. *Psychological Review, 79,* 124–145.

Munka, L., & Kaernbach, C. (2001). Lifetime of memory for self-generated information. In E. Sommerfeld, R. Kompass, & T. Lachmann (Eds.), *Proceedings of the 17th Annual Meeting of the International Society for Psychophysics* (pp. 541–546). Lengerich, Germany: Pabst Science Publishers.

Neisser, U. (1967). *Cognitive Psychology.* New York: Apelton-Century-Crofts.

Peterson, L. R., & Peterson, M. J. (1959). Short-term retention of individual items. *Journal of Experimental Psychology, 58,* 193–198.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review, 84,* 127–190.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs, 74,* (Whole No. 498).

Warren, R. M. (1998). *Auditory perception, A new synthesis.* Cambridge: Cambridge University press.

Warren, R. M., Bashford, J. A., Cooley, J. M., & Brubaker, B. S. (2001). Detection of acoustic repetition for very long stochastic patterns. *Perception & Psychophysics, 63,* 175–182.

Waugh, N. C., & Norman, D. A. (1965). Primary memory. *Psychological Review, 72,* 89–104.

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Christian Kaernbach

Institute for Experimental Psychology
University of Leipzig
Seeburgstraße 14–20
D-04103 Leipzig
Germany
Tel.: +49 341 973 5968
Fax: +49 341 973 5969