PARAMETERS OF ECHOIC MEMORY

Christian Kaernbach
Institut für Allgemeine Psychologie, Universität Leipzig
Seeburgstraße 14-20, D-04103 Leipzig, Germany
Email: christian@kaernbach.de

Abstract

Since the days of the multiple-components theory of memory it has become common practice to characterize and/or differentiate memory systems by specifying their lifetime, capacity and susceptibility to interference. Periodic noise was used to study these parameter of echoic memory for random waveforms and to compare them to those of short-term memory. In a first experiment, it was examined up to which cycle length it is possible to perceive the periodicity. With only a small amount of training periodicities as long as 10 s could be detected. In two further experiments it was quantified how much of each cycle was memorized in order to detect the periodicity. Independently of the cycle length, a surprisingly small amount of the cycle, on average 130 ms, served as a cue. The fourth experiment demonstrated that echoic memory is to a certain degree protected against interference. The similarity of the parameters of echoic memory to those of short-term memory strengthens the view of echoic memory as a modality-specific module of short-term memory.

It is now well established that storage of sensory information is at least two-fold. Massaro and Loftus (1996) differentiate sensory and perceptual storage, with the latter lasting much longer than the former. The first classification into short and long sensory stores was done by Cowan (1984) in the auditory realm. He reviews many studies relevant to auditory memory and classifies them into two groups: those revealing time constants of 200 ms or less, and those revealing time constants of 10 to 20 s. For the short store Cowan cites data from masking experiments, auditory persistence, and temporal integration. These phenomena form part of sensation. The long store accounts for phenomena of up to 20 s, which are perceived as memory. The auditory partial report falls into this category as well as dichotic listening experiments and the perception of periodic random waveforms (Guttman and Julesz, 1963).

According to Cowan (1988, 1995) long sensory storage and short-term memory are both activated parts of long-term memory. While the lifetime of traces in long sensory stores is compatible with the assumption of a close relation to short-term memory, the capacity of sensory stores is often thought of as being much higher than that of short-term memory, and sensory stores are thought of as being much more susceptible to interference. While this is true for short sensory stores, it needs not be so for long sensory stores. The goal of the present study was to examine these three parameters for the long auditory store using a single class of stimuli, by this means avoiding unjustified synopses across tasks and material.

Periodic random waveforms represent an excellent test of auditory sensory memory. They do not offer clues to categorical storage such as most other auditory materials do. The stimulus is produced by seamlessly connecting repetitions of a single segment of white noise.

At the connection points, no artifacts are introduced that could give rise to clicks or other artificial percepts. However, even naive listeners perceive a striking difference between periodic and continuous noise: periodic noise is perceived as rhythmically structured, and filled with perceptual events such as “clanks” and “rasping”. For the same noise segment, these perceptions are reproducible across different sessions of the same listener, and to a lesser degree correlated across listeners (Kaernbach, 1992). The temporal extent of the basis of these perceptual events is restricted to about 100 ms (Kaernbach, 1993). Periodic noise has been used as signal in masking experiments (Pollack, 1990), its perception has been compared with pitch perception (Warren & Bashford, 1981; Warren & Wrightson, 1981; Warren, Wrightson, & Puretz, 1988) and it has been used to study time order processing (Warren & Bashford, 1993). For a review on periodic noise research see Warren (1998). A demonstration of periodic noise stimuli can be found at www.periodic-noise.de

Experiment 1. Lifetime

Guttman and Julesz (1963) reported that for periods longer than 2 seconds periodicity detection would become difficult. Cowan, however, ascribes periodic noise perception to the long auditory store (10 to 20 s). Warren, Bashford, Cooley and Brubaker (2001) showed that cross-modal cueing helps experienced listeners to detect periodicity in cycles up to 20 s. In pilot studies it became obvious that only a small amount of training is needed for naive listeners to perceive long cycles. Experiment 1 was conducted to quantify the relation between training and maximum cycle length in naive listeners. The noise was generated as a sequence of Gaussian random numbers with a standard deviation of 10% of the conversion range. These were converted at 20 kHz and presented via headphones at 60 dB hearing level. To make this periodic, the random number sequence was recycled. For each of the 20 naive participants and each single trial a different noise sample was generated. The cycle lengths ranged from 0.5 to 20 s. The participants started the experiment without practice. The trial started when the participant hit the space bar. Participants were instructed to tap the space bar once per period. If the participant did not start tapping to a noise sample, this trial was considered a failure and the next trial started. Participants were randomly assigned to one of two groups. Group A passed through the cycle lengths in ascending order, group B in descending order. From trial to trial the cycle length was increased or decreased regardless of the success of the previous trial. All participants performed 3 blocks. From the obtained tapping data it was determined whether the participant had perceived the correct periodicity.

The results are presented in Figure 1, summed over all participants and monotonized. Monotonizing was applied to all points except the first point of the first block of group A. The low performance here is due to the fact that it was the very first trial of the experiment so the participants were not well prepared for what they were to hear. This clearly demonstrates that the participants were naive. In the first block of group A, cycles up to 2.8 s are correctly tapped by half of the participants. But also cycles of lengths of 10-20 s can be detected, despite practice being limited to the presentation of previous, shorter cycles. Due to the effects of practice, in the third block cycles of 7 s are correctly tapped by more than 50% of the participants. Group B shows similar data. There is a smaller training effect. Apparently, descending periodicities are less efficient for training participants on periodicity detection than ascending periodicities. It is all the more remarkable that two participants of group B were able to tap correctly with cycles as long as 12 s in the first block. Their only training had consisted in listening for six minutes to even longer cycles in which they did not notice any periodicity. For comparison, Figure 1 shows data by Peterson and Peterson (1959) on the retention of consonant trigrams as a function of time (black diamonds, cf. Discussion).

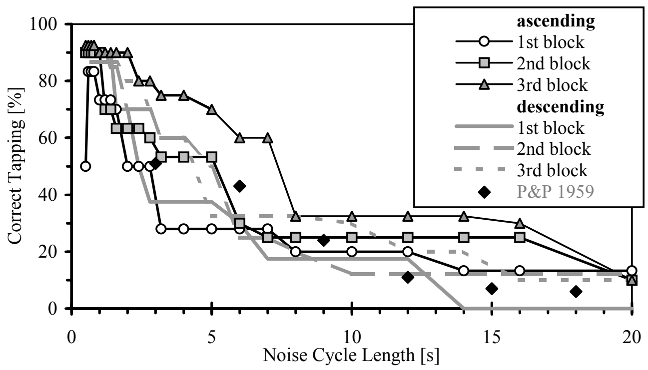

Figure 1. Results of Experiment 1. Percentage of participants with correct tapping as monotonic functions of cycle length. Symbols refer to group A (ascending presentation order), dotted lines refer to group B.

Experiments 2 and 3. Capacity

As an estimate of the capacity of echoic memory, one would like to know the amount of the cycle that is memorized while listening to periodic noise. For each experimental session, a cycle of white noise (length 1.2, 2.4, 4.2, or 6 s) was presented. The participant listened to this cycle carefully and then commenced tapping of the perceived rhythm. Once s/he had tapped ten times, the periodic noise stimulus continued but the task was changed: The participant had to detect changes in the waveform. The noise was internally segmented into $\mathbf{k}$=4, 8, 14, or 20 segments of $\mathbf{S}$ = 300 ms length. In every third cycle, a number $\mathbf{N} \leq \mathbf{k}$ of randomly selected segments was substituted by newly created noise. Control trials (20%) included no changed segments. The participant had to signal changes by pushing the space bar (go/no-go task). $\mathbf{N}$ was adapted in order to obtain 50% go responses (go: $\mathbf{N} \to \mathbf{N}-1$, no go: $\mathbf{N} \to \mathbf{N}+1$). The participants were aware that more than 2 false alarms (go response to a control trial) would necessitate a repetition of this session. The entire length of a session could be as long as 22 minutes (6 s cycles). All participants (n=5) were required to repeat all conditions 3 times.

For each segment $\mathbf{i}=1 \cdots \mathbf{k}$, the probability $\mathbf{p_i}$ was assessed with a maximum-likelihood algorithm that the participant will notice its substitution. This shows which segments of the cycle were important to the participant. The sum $\Sigma \mathbf{p_i} \cdot \mathbf{S}$ is an estimate of the change-sensitive length (**CSL**) of the cycle. A major part of long cycles could be changed without the participant noticing it: 2/3 of the $\mathbf{p_i}$ were equal to zero. The relevant segments ($\mathbf{p_i}$>.5) were situated mainly around the tapping points of the participant. Figure 2a shows the results. If the participants had remembered the entire noise cycle, the data should lie on the diagonal. It is obvious that only a small portion of the signal was remembered by the participants.

While these data demonstrate that the amount of information remembered by the participants does not depend on the cycle length and does hence represent a quantity different from lifetime, it cannot be seen as a valid estimate of the capacity of echoic memory. If the participants did remember an infinitely small part of the waveform (but this perfectly), they would detect the change of an entire segment of length $\mathbf{S}$. Let us assume that the participant is able to remember a coherent "learned piece" of length λ. Any change of a part of that piece, however small, will be detected. Any other change of the waveform will remain undetected.

The mean estimate for the **CSL** is **S**+λ, assuming a uniform distribution of positions of the piece relatively to segmentation borders. If the participant can remember **n** pieces of length λ at different positions, one obtains **CSL** = **n** (**S**+λ). In Experiment 3 **S** was varied to see whether one would obtain this linear relation. Four of the 5 participants of Experiment 2 participated in Experiment 3. This time only two cycle lengths were tested (2.4, 4.8 s). The length of the segments to be changed was either 200 ms or 400 ms. All participants repeated all conditions 4 times. Figure 2b presents the results. Again, they are independent of cycle length. More important, there seems to be a fairly linear relation between the obtained **CSL** and the segment length **S** (dotted line: slope 1.4, y-axis intercept 130 ms). The participants memorized on the average **n** = 1.4 pieces of a length λ = 90 ms, i.e. a total of 130 ms.

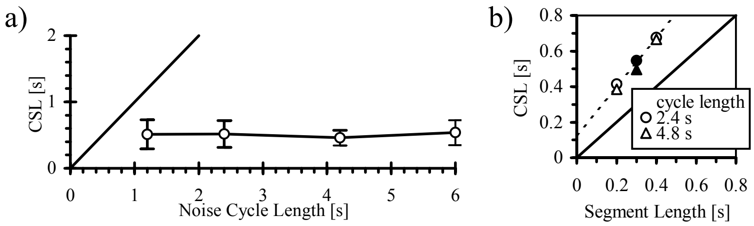

Figure 2. Results of Experiments 2&3. a) CSL as a function of the cycle length. The error bars indicate the standard deviation. The CSL is constant across the entire range of cycle lengths. b) Dependence of CSL on segment length S. The standard deviations are similar to a) and are not shown. The solid symbols stem from Experiment 2.

Experiment 4. Interference

It was the goal of Experiment 4 to test the degree of interference in echoic memory using the same stimulus material that served for the evaluation of the lifetime and capacity parameters. It was tested whether it is possible to solve both a main task based on periodic noise and an interfering task that is also based on periodic noise but with a different repeating segment. In order to control the amount of information to be memorized, semiperiodic noise (Kaernbach, 1993) was applied. It differs from periodic noise in that only a part of the period is exactly replicated. The rest of the period is filled with different noise amplitude values in each period. For this experiment, both the frozen and the variable part were 250 ms (period 500 ms).

Three different conditions were tested: without, with visual and with auditory interference. Without interference (NI), for each trial a noise stimulus (17 s) was presented. It was semiperiodic in its first 7 s (14 periods). A visual signal was flashed whenever the frozen segment was present. During the retention interval (9 s), the noise went on but without reoccurrences of the frozen segment and without visual signal. The last 1 s of the noise stimulus could contain (50%) two partially frozen periods with the same frozen segment as before, or there was no frozen segment in this 1 s. The visual signal for these two final cycles was, however, always present. The participant had to decide whether the frozen segment did reoccur.

This was the only task in the NI condition, and the main task in conditions with interference. With auditory interference (AI), another semiperiodic noise was embedded in the retention interval. It started .75 s after the last frozen segment of the main task, and consisted of 15 (75%) or 13 (25%) cycles (i.e. 7.5 s) of semiperiodic noise with a different frozen segment, accompanied by a flashing visual signal, which always ran for 15 cycles. The participant should in case of absence of periodicity in the final two cycles of the AI task press a special key and then would ignore the main task. With visual interference (VI) there was no semiperiodic noise embedded in the retention interval. The visual signal flashed with the same rhythm as for the AI condition. The participant had to watch the size of the visual signal: in 25% of the cases, one of the 15 signals was slightly larger. In this case, the participant had to press a special key and would 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 AI condition. The participants (n=3) performed the three conditions in blocks of 20 trials in cyclical order (NI, VI, AI). They performed 300 training trials and 420 experimental trials. Performance in the main task was calculated only over no-go trials in the interference task.

Figure 3 shows the average performance. The performance in the main task was quite low even without interference: The task was solved in 75% of the trials. Given a chance performance of 50%, this represents a threshold performance. While there is obviously a decrease in performance with interference, and especially so with auditory interference, it is remarkable that at a difficulty level close to threshold an auditory interference task does not completely disrupt the retention of the frozen segment of the main task. The modality effect might be due to the higher difficulty of the auditory interference task, visible both in the hit and the false alarm rate. By adapting those difficulties, and by decreasing the difficulty of the main task, one might expect to get a smaller modality effect. However, the present results are sufficient to demonstrate that interference in the long auditory store is less absolute than in short sensory stores.

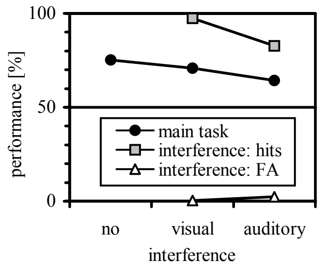

Figure 3. Performance in main and interference tasks of Experiment 4, averaged across subjects, as a function of task type.

Discussion

Long sensory memory shares many features with categorical short-term memory. The present study measured lifetime, capacity and susceptibility to interference for the long auditory store using the same type of stimulus material. With respect to all three parameters, echoic memory for random waveforms showed more similarities to storage phenomena for categorical information than to classical sensory registers (Neisser, 1967):

- The maximum cycle length of periodic random waveform corresponds more to the lifetime of categorical information (Peterson & Peterson, 1959; for non-sensory storage cf. Munka & Kaernbach, 2001, in this issue) than to that of classical sensory registers.
- The capacity of sensory registers is considered to be rather high. The capacity of short-term memory is limited to a small number of items (cf. Cowan, 2001). While the present study measured capacity of echoic memory in seconds and found a rather small value, further studies will focus on the (probably small) number of items in echoic memory.
- Classical sensory storage is considered to be prone to strong interference effects. Short visual storage can, for instance, be overwritten by subsequent visual input (Averbach & Coriell, 1961). As for short auditory store, one of the classes of experiments cited by Cowan (1984) as evidence for this type of storage was masking experiments. Echoic memory for random waveforms is much less susceptible to interference, comparable to short-term memory (as long as the capacity limit is not exceeded).

This strengthens the view of Cowan (1988, 1995) who described long sensory stores as an activated part of long-term memory. According to this view, the difference between long sensory stores and categorical short-term 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. Long auditory storage would then correspond to "short-term memory running on auditory areas". The involvement of sensory areas during tasks comprising periodic noise stimuli has been demonstrated by Kaernbach, Schröger, and Gunter (1998).

In summary, the memory model of Cowan stands the test with noncategorical stimulus material such as white noise. Given the correspondence of lifetime, the narrow capacity limit, and the low susceptibility to interference, echoic memory for random waveforms can well be considered a specialized module of short-term memory.

References

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

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. (1995). *Attention and memory: An integrated framework.* Oxford: Oxford University Press.

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

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

Massaro, D. W., & Loftus, G. L. (1996). Sensory and perceptual storage: Data and theory. In E. L. Bjork & R. A. Bjork (Eds.), *Memory*. San Diego, CA: Academic Press.

Munka, L., & Kaernbach, C. (2001). Lifetime of memory for self-generated information. In *Proceedings of the Seventeenth Annual Meeting of the International Society for Psychophysics* (Leipzig, 2001).

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

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

Pollack, I. (1990). Detection and discrimination thresholds for auditory periodicity. *Perception & Psychophysics,* **47**, 105-111.

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

Warren, R. M., & Bashford, J. A. (1981). Perception of acoustic iterance: Pitch and infrapitch. *Perception & Psychophysics,* **29**, 395-402.

Warren, R. M., & Bashford, J. A. (1993). When acoustic sequences are not perceptual sequences: The global perception of auditory patterns. *Perception & Psychophysics,* **54**, 121-126.

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.

Warren, R. M., & Wrightson, J. M. (1981). Stimuli producing conflicting temporal and spectral cues to frequency. *Journal of the Acoustical Society of America,* **70**, 1020-1024.

Warren, R. M., Wrightson, J. M., & Puretz, J. (1988). Illusory continuity of tonal and infratonal periodic sounds. *Journal of the Acoustical Society of America,* **84**, 1338-1342.