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Development of auditory sensory memory from 2 to 6 years: an MMN study

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Abstract Short-term storage of auditory information is thought to be a precondition for cognitive development, and deficits in short-term memory are believed to underlie learning disabilities and specific language disorders. We examined the development of the duration of auditory sensory memory in normally developing children between the ages of 2 and 6 years. To probe the lifetime of auditory sensory memory we elicited the mismatch negativity (MMN), a component of the late auditory evoked potential, with tone stimuli of two different frequencies presented with various interstimulus intervals between 500 and 5000 ms. Our findings suggest that memory traces for tone characteristics have a duration of 1 to 2 seconds in 2- and 3-year-old children, more than 2 seconds in 4-year-olds and 3 to 5 seconds in 6-year-olds. The results provide insights into the maturational processes involved in auditory sensory memory during the sensitive period of cognitive development.

Keywords auditory sensory memory, duration of memory trace, event-related potential, mismatch negativity (MMN), children, maturation Introduction

Introduction

Short-term memory is thought to play a crucial role in many different cognitive processes (Gathercole 2001). For example, it is assumed that short-term memory is involved in learning new words, grammar processing and sentence comprehension (Baddeley et al. 1998). Deficiencies in short-term memory functioning are believed to cause problems in language acquisition (Baddeley 2003).

In a number of studies, auditory short-term memory deficits have been found in children with developmental language disorders (for review see Montgomery 2003) and dyslexia (Jeffries and Everatt 2004; Smith-Spark and Fisk 2007). A short-term memory deficit is considered to be a specific marker of language impairment and to be predictive of language development in children with language disorders (Botting et al. 2001; Conti-Ramsden and Hesketh 2003).

The term “short-term memory” refers to a system of temporary processing and information storage. Several models have been proposed to explain information processing in short-term memory, but none of them has been generally accepted as being able to explain all of the empirical findings. The most prominent model in the context of the relationship between memory and normal or disturbed cognitive development is the working memory model proposed by Baddeley and Hitch (1974).

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This model refers particularly to verbal processing in the phonological loop and to visual processing in the visuospatial sketch pad. A limitation of this model is, however, that the initial steps of information processing, i.e. the relationship between sensory input and the subsequent memory processes, are not explicitly described.

Reception and primary storage of sensory information is discussed in detail in the memory model proposed by Cowan (1988, 1995). According to this model, sensory information is gathered first in a pre-attentive sensory memory system. This system is considered to be a passively-held information store that can hold a large amount of sensory data with high accuracy, but only for a short period of time. Cowan described two phases of sensory memory. In a first phase of 200 to 400 ms, consecutively incoming information is integrated in a sliding time window for the purpose of resolving component features. In a second phase, the information is transferred to a longer-lasting memory store, where it is kept available for further processing in the working memory and where it can, for instance, be compared with new incoming information or with existing patterns in the long-term memory. The sensory memory store is said to lose information through decay over a period of about 10 to 20 seconds. Although it is claimed that this model applies to all modalities, the sensory memory store is best examined in the auditory modality.

Auditory short-term memory is usually assessed with behavioural tasks in which subjects are typically asked to repeat sequences of tones, syllables, words or numbers of increasing length. Such behavioural tasks demand responses from the subjects, and thus results are affected by attention and motivation. For this reason, behavioural tasks are not ideal for young children or individuals with attention or cognitive disturbances. Furthermore, most behavioural tests for assessment of short-term memory are verbal tests, particularly pseudoword repetition tests. Failing on such verbal tests may be due not only to memory deficits but also to language difficulties such as deficits in speech perception, poor encoding speed, limited vocabulary, difficulties in phonological processing and poor articulation skills (Barry et al. 2008). Therefore pseudoword repetition and other verbal tests are less appropriate for short-term memory evaluation in subjects with language deficits.

An objective method suitable for assessing sensory memory in young children is mismatch negativity (MMN) (Näätänen 2003). MMN recording requires no feedback from the subjects, and an MMN can be elicited even when stimuli are unattended. Therefore MMN studies are possible even in children and people with poor attention or problems understanding verbal instructions.

The MMN has been described by Näätänen et al. (1978) as a component of auditory event-related potentials (ERPs) that typically peaks between 150 and 200 ms after stimulus onset and that has a maximum at fronto-central sites. MMN is generally elicited in an oddball paradigm, in which occasionally occurring deviant sounds are presented in a stream of standard sounds. The deviants may differ from the standards in basic physical features (e.g. frequency, intensity, duration) or in more complex auditory characteristics (e.g. different syllables or words). MMN measurement is widely used for investigating sound discrimination ability and auditory sensory memory in both basic research and clinical applications (for a review see Bishop 2007; Kujala et al. 2007; Näätänen et al. 2007).

The MMN operates at the sensory memory level and reflects an automatic pre-attentive process of comparisons between acoustic stimuli. It is assumed that regular aspects of consecutively presented standards form a memory trace in the sensory store, and that violation of these regularities by deviants induces an MMN (Näätänen and Winkler 1999). The MMN is thought to be the neurophysiological outcome of an activated deviance detection system in the auditory cortex (Alho 1995). It can be recorded only if the memory trace of standard regularities in the sensory memory has not yet decayed. Hence the assumption is made that the duration of auditory sensory memory can be examined through variation of interstimulus intervals (ISIs). In Cowan’s memory model it is postulated that the lifetime of a memory trace determined by variation of the ISI in an MMN experiment corresponds to the second phase of sensory memory.

Several studies have used MMN experiments with variable ISIs to probe the duration of sensory memory in healthy adults and children and in patients of different ages. In healthy adults MMN responses were detected up to an ISI of approximately 10 seconds (Böttcher-Gandor and Ullsperger 1992; Sams et al. 1993). Pekkonen et al. (1996) demonstrated that the lifetime of a memory trace depends on age. They found that a prominent MMN was elicited with tones of different frequencies in both younger and older adults (mean ages: 22 and 59 years, respectively) if the ISI was 500 ms, whereas with an ISI of 4500 ms an MMN was detected in the younger subjects only.

Other studies have addressed the question of whether there is a deficit in sensory memory in patients with cognitive disabilities. The findings suggest that the duration of sensory memory is reduced in patients with chronic alcoholism and Alzheimer's disease (Engeland et al. 2002; Grau et al. 2001; Pekkonen et al. 1994; Zhang et al. 2001). Similar results have been reported for parents of children with developmental language disorders. In a study by Barry et al. (2008) the MMN was recorded with tones of different frequencies and with an ISI of 800 ms and 3000 ms. In comparison to parents with typically developing children, no differences in the MMN were found for an ISI of 800 ms, whereas there was an MMN attenuation for the long ISI condition of 3000 ms. The authors therefore postulated a shortened lifetime of sensory memory traces in parents of children with language impairment.

In children, studies of sensory memory using MMN experiments have been conducted only rarely. Cheour et al. (2002) addressed maturational aspects. They recorded MMN to frequency changes (1000 vs. 1100 Hz) with ISIs of 350, 700 and 1400 ms in 24 healthy newborns. The newborns exhibited a prominent MMN after a stimulus delay of 700 ms, but not after 1400 ms. In contrast, children between the ages of 6 and 10 years exhibited an MMN with an ISI of 1400 ms (Cheour et al. 1997). Gomes et al. (1999) investigated the auditory sensory memory in school-age children and adults (age groups: 6-7, 8-10, 11-12 and 22-38 years) with ISIs of either 1 or 8 seconds. At an ISI of 1 second they obtained a robust MMN to tone stimuli (standard 1000 Hz, deviant 1200 Hz) in all age groups, but at an ISI of 8 seconds in the groups with subjects older than 10 years only.

To our knowledge, among children with disabilities, the duration of auditory sensory memory has been investigated only in children with CATCH syndrome (Cheour et al. 1997) and with oral clefts (Ceponienè et al. 1999). The CATCH syndrome is caused by a microdelection in chromosome 22 and, apart from other abnormalities, is characterised by a cleft palate and speech and language deficits. In school-age children with CATCH syndrome (6-10 years) a distinct MMN to frequency changes was elicited at an ISI of 350 ms, but no MMN was detected at an ISI of 700 ms or 1400 ms. In contrast, age-matched healthy children showed an MMN at all 3 ISIs. With the same MMN paradigm Ceponienè et al. (1999) examined children with cleft lip or palate (7-9 years) and found a regular MMN with ISIs of 350 and 700 ms, but reduced MMN amplitudes for ISIs of 1400 ms in children with cleft palate. The attenuation of MMN amplitudes correlated with the severity of the anatomical abnormality. The authors suggested that memory traces in the auditory sensory memory store decay more rapidly in children with CATCH syndrome or cleft palate than in normal children. They postulated that a shortened storage of information in sensory memory could be the cause of language and cognitive deficits in these children.

Taken together, the results of previous MMN studies provide evidence that the duration of auditory traces in the sensory memory store is limited, that it is age-dependent and that it is reduced in patients with cognitive or language disorders. There is a lack of knowledge regarding developmental aspects of sensory memory, especially in children between infancy and school age. The present study addresses the question of how the duration of auditory sensory memory changes in children between the ages of 2 and 6 years. A better understanding of maturational effects in the sensory memory is of both theoretical and clinical interest because a sufficient lifetime of memory traces in the sensory store is believed to be crucial for language learning and cognitive processing.

Subjects and methods

Sample

The subjects were normally developing children between the ages of 2 and 6 years. Information about the children's developmental milestones, medical history (complications during pregnancy or birth, prematurity, chronic disorders, history of otitis media or other ear disorders) and socioeconomic characteristics was obtained from the parents via a questionnaire. Based on the parent reports there was no evidence for any developmental or general medical disorders in any of the children. None of the children had undergone language therapy, had participated in any other early intervention program or had attended a special care institution. All children had normal results on otoacoustic emission screening (for ages 2 and 3) or on pure tone audiometric screening (for ages 4 and 6). Two thirds of the children's mothers had a high school education (in Germany, 13 years of schooling).

The MMN was elicited with varying ISIs. Because MMN recording with long ISIs is very time-consuming (for example, in the study of Gomes et al. (1999) data acquisition with ISIs of 1 and 8 seconds lasted 2 to 3 hours), to avoid very long sessions or the necessity for more than one session per child we used different ISI conditions in different samples.

If a child's EEG contained fewer than 80 artefact-free sweeps, the child was excluded from the study (2-year-old children: $n = 5$; 3-year-old children: $n = 4$; 4-year-old children: $n = 1$). The characteristics of the remaining children are shown in Table 1.

Table 1 Characteristics of the groups

Age group	Age (months)	*N*	Boys / Girls	ISI condition (ms)
2 years	25 - 27	22	12 / 10	500 / 1000
		15	9 / 6	500 / 2000
3 years	37 - 41	24	14 / 10	500 / 2000
4 years	55 - 56	28	13 / 15	500 / 2000
		29	14 / 15	500
6 years	73 - 74	12	8 / 4	3000
		11	5 / 6	5000

All parents gave their written informed consent for their children to participate in the study. The study was approved by the ethics commission of the medical faculty of the University of Munich (LMU Munich).

Stimuli and procedure

In an oddball paradigm, standard tones of 1000 Hz and deviant tones of 1200 Hz were presented. Each tone had a duration of 100 ms, including a rise and fall time of 10 ms. A large frequency difference was chosen between standards and deviants to ensure that the stimuli were easily discriminable. The same frequencies had been used in previous studies exploring auditory sensory memory duration in children and adults (Barry et al. 2008; Gomes et al. 1999).

A time-saving paradigm described by Grau et al. (1998) was used to shorten the time required to run the experiments. Stimuli were grouped in trains of 4 tones separated from each other by a fixed interval of 500 ms within the trains (Fig. 1). An ISI (offset to onset) of 500, 1000, 2000, 3000 or 5000 ms was used between trains, depending on the age of the child. The trains began with either the standard stimulus or the deviant stimulus, and all non-leading stimuli were standards only. During later data analysis, only event-related responses to tones which occurred as the first tone in a train were averaged in order to ensure that the number and relative position of standards and deviants were comparable.

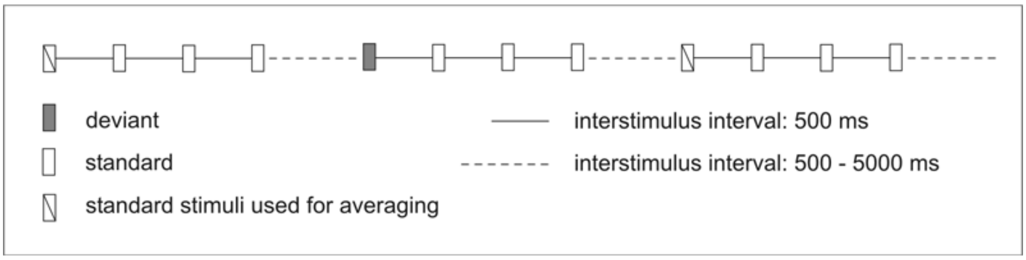

Fig. 1 MMN paradigm for probing the duration of auditory sensory memory

Within a given experimental ISI condition 1400 (86%) standards and 200 (14%) deviants were presented in 4 blocks of 400 stimuli, with a break of 4 seconds between the blocks. The experiment could be interrupted manually for a break if the child needed one. The trains were arranged in pseudo-randomised order within the blocks. If 2 ISI conditions were used within the same session the ISI conditions were arranged in balanced order.

During EEG recording the child sat comfortably in a child's seat and watched a soundless video. If necessary, younger children were kept occupied in quiet play. Stimuli were presented through a loudspeaker located in front of the child at a distance of 2.3 m from the child's head, resulting in a sound pressure level of 74 dB.

EEG recording

The EEG was recorded using 20 Ag/AgCl sintered electrodes placed at F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2, ML, MR and Fp2, according to the International 10-20 System. The electrodes were attached to an elastic EEG recording cap (Easy Cap, Herrsching, Germany). The right mastoid was used as a reference. Eye movements were monitored with electrodes at the outer canthus of each eye (horizontal EOG) and electrodes at Fp2 and below the right eye (vertical EOG). In 2-year-old children the activity from Fp2 was used for elimination of vertical eye artefacts because most of these children did not accept electrodes attached below their eye. The ground electrode was placed on the forehead.

Data acquisition was carried out using the BrainAmp system and the recording software "Vision Recorder" (Brain Products, Gilching, Germany). The amplifier bandwidth was set to 0.16 - 30 Hz and a sampling frequency of 250 Hz was used. The electrode impedances were reduced to below 5 kΩ at the beginning of the measurement. Off-line processing included re-referencing against linked mastoids, high-pass (0.8 Hz) and low-pass (20 Hz) filtering, level- sensitive artefact rejection (fronto-central electrodes > 80 µV, HEOG > 150 µV, VEOG > 150 µV or Fp2 activity > 110 µV), segmentation (from -100 to 600 ms relative to stimulus onset), baseline correction (from -100 to 0 ms) and averaging.

The mean number of accepted EEG segments was 141.3 (*SD* 29.9) for standards and 142.9 (*SD* 29.1) for deviants. All averages contained more than 80 sweeps.

Data analysis

Six electrodes in the fronto-central region of interest (F3, Fz, F4, C3, Cz and C4) were used for further analysis. Mean amplitudes of standard and deviant responses were calculated across a 40-ms time window centred around the grand mean peak of the MMN. Differences in MMN latency were taken into account by choosing 40-ms time windows for each age group and ISI condition separately. To determine the MMN latency the largest negative peak of the deviant-minus-standard grand mean waveform was automatically identified at Fz between 50 and 250 ms after stimulus onset. The MMN peak latencies in the 2-year-old children were 180 ms (ISI 500 ms), 228 ms (ISI 1000 ms) and 116 ms (ISI 2000 ms), in the 3-year-olds 180 ms (ISI 500 ms) and 136 ms (ISI 2000 ms), in the 4-year-olds 184 ms (ISI 500 ms) and 112 ms (ISI 2000 ms) and in the 6-year-olds 156 ms (ISI 500 ms), 116 ms (ISI 3000 ms) and 100 ms (ISI 5000 ms).

Mean amplitudes of standard and deviant responses across the calculated 40-ms time window of the 6 fronto-central electrodes were entered into an analysis of variance (ANOVA) as repeated measurements. Main effects and their interactions were calculated for the within-subjects factor *Stimulus Type* (standard, deviant) and the between-subjects factor *ISI*. Alternatively, if different experimental ISI conditions were used within a given group of children, repeated-measures ANOVA with *ISI* as an additional within-subjects factor was performed.

Results

MMN for the 500-ms ISI condition across all age groups

As illustrated in Figure 2, the difference waveforms for the 500-ms ISI condition show a clear negative deflection in all age groups. Such deflections were considered to be an MMN if there was a significant difference between standard and deviant response on at least 5 data points in series in the grand mean ($p < .05$; running t-test) (Guthrie and Buchwald 1991). Significant MMNs at Fz were found in 2-year-old children between 140 and 248 ms (both subgroups, see Table 1), in 3-year-olds between 132 and 248 ms, in 4-year-olds between 132 and 232 ms and in 6-year-olds between 108 and 212 ms.

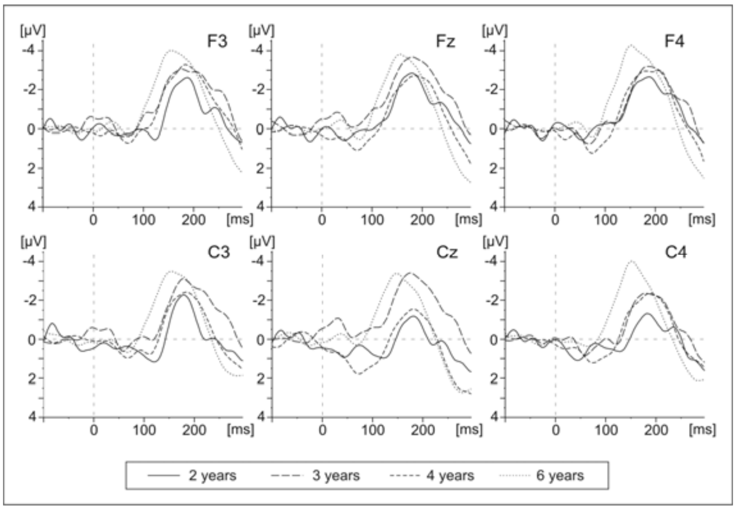

Fig. 2 MMN for the 500-ms ISI condition for all age groups (reference: linked mastoids)

Mean amplitudes were submitted to an ANOVA to determine whether there were significant differences in the MMN between the age groups. A significant main effect of *Stimulus Type* [$F(1,99) = 57.85$, $p < .001$] was found, that is, there was a statistically significant difference between responses to standard and deviant stimuli, indicating that an MMN was elicited and confirming the results of the running *t*-test (see above). The age effect (interaction *Stimulus Type* x *Age Group*) was however not statistically significant [$F(3,99) = 0.993$, $p = .399$], indicating that there is no major change in the MMN with age for short ISIs.

MMN for conditions with extended ISIs

In 2-year-old children a prominent MMN was found for the 500- ms and 1000-ms ISI conditions, but not for the 2000-ms ISI condition (Fig. 3a). ANOVA yielded a significant main effect of *Stimulus Type* (standards, deviants) in the 500- and 1000-ms ISI conditions (Table 3), confirming statistically the presence of an MMN. The difference between these 2 conditions was not significant (no significant interaction of *Stimulus Type* and *ISI*), though inspection of the waveforms in Fig. 3a suggests a slightly attenuated amplitude of the MMN for the 1000-ms condition. There was, however, a significant difference between the mean amplitudes of the 500- and 2000-ms ISIs, and a trend to a significant difference between the 1000-ms and 2000-ms conditions (Table 2). These findings provide evidence that the sensory memory traces were accessible for longer than 1 second but less than 2 seconds.

Fig. 3 MMN for different ISI condition at electrode Fz by age group (reference: linked mastoids)

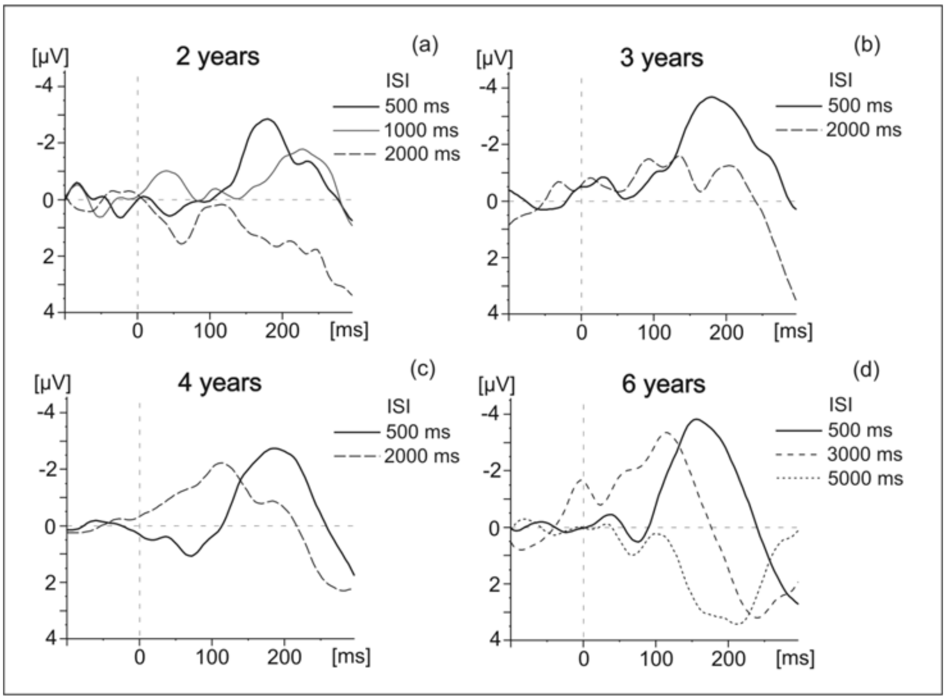

Table 2 Global analyses of ERP data: comparisons between the different ISI conditions (500, 1000 and 2000 ms) in 2-year-old children

	500-ms vs. 1000-ms ISI				500-ms vs. 2000-ms ISI				1000-ms vs. 2000-ms ISI			
	df	*MSE*	*F*	*p*	*df*	*MSE*	*F*	*p*	*df*	*MSE*	*F*	*p*
Stimulus Type	1.00	397.38	7.46	**<.01**	1.00	54.55	1.48	.23	1.00	25.74	<1	
Stimulus Type x *ISI*	1.00	6.60	<1		1.00	165.80	4.50	**<.05**	1.00	111.60	4.04	**.05**

Table 3 Follow-up analyses of the main effect of Stimulus Type (standards, deviants) for the 500-, 1000- and 2000-ms ISI conditions in 2-year-old children

ISI	*df*	*MSE*	*F*	*p*
500 ms	1.00	253.18	5.31	**<.05**
1000 ms	1.00	150.79	4.65	**<.05**
2000 ms	1.00	12.68	<1	

In 3-year-old children a significant MMN was elicited for an ISI of 500 ms but not for one of 2000 ms, whereas in 4-year-old children an MMN was found for both of the ISI conditions (Table 5). However, a visual inspection of the MMN of the 4-year-olds shows that the amplitude is also slightly attenuated for the longer ISI (Fig. 3b,c). ANOVA yielded a significant difference between mean MMN amplitudes of the 500- and 2000-ms ISI conditions for 3-year-olds (significant interaction of *Stimulus Type* with *ISI*), but no difference for 4-year-olds (Table 4). The results for 3-year-olds suggest that the sensory memory traces were accessible for longer than 0.5 seconds but less than 2 seconds, whereas for 4-year-olds they were accessible for more than 2 seconds.

Table 4 Global analyses of ERP data for the 500- vs. 2000-ms ISI conditions in 3- and 4-year-old children

	3 years				4 years			
	df	*MSE*	*F*	*p*	*df*	*MSE*	*F*	*p*
Stimulus Type	1.00	598.48	14.17	**<.001**	1.00	727.25	24.11	**<.001**
Stimulus Type x *ISI*	1.00	129.23	4.96	**<.05**	1.00	20.18	1.25	.27

Table 5 Follow-up analyses of the main effect of Stimulus Type (standards, deviants) for the 500 and 2000 ms ISI conditions in 3- and 4-year-old children

ISI	3 years				4 years			
	df	*MSE*	*F*	*p*	*df*	*MSE*	*F*	*p*
500 ms	1.00	641.97	17.435	**<.001**	1.00	494.87	18.140	**<.001**
2000 ms	1.00	85.75	2.73	.11	1.00	252.56	13.25	**<.001**

The waveforms of the 6-year-olds show a distinct MMN for ISIs of 500 and 3000 ms but no negative deflection in the 5000-ms ISI condition (Fig. 3d). This was confirmed by ANOVA, which yielded a significant main effect of Stimulus Type for the 500-ms and the 3000-ms ISI conditions but no effect for 5000 ms (Table 7). The mean MMN amplitudes differed significantly between the conditions of 500 and 5000 ms as well as between 3000 and 5000 ms (significant interaction of Stimulus Type with ISI), whereas no difference was found between the 500- and 3000-ms ISI conditions (Table 6). Hence in 6-year-olds memory traces appear to be accessible for more than 3 seconds but less than 5 seconds.

Table 6 Global analyses of ERP data: comparisons between the 500-, 3000- and 5000-ms ISI conditions in 6-year-old children

	500-ms vs. 3000-ms ISI				500-ms vs. 5000-ms ISI				3000-ms vs. 5000-ms ISI			
	df	*MSE*	*F*	*p*	*df*	*MSE*	*F*	*p*	*df*	*MSE*	*F*	*p*
Stimulus Type	1.00	953.80	24.31	**<.001**	1.00	313.18	8.35	**<.01**	1.00	108.49	9.18	**<.01**
Stimulus Type x *ISI*	1.00	31.25	<1		1.00	311.81	8.31	**<.01**	1.00	107.80	9.12	**<.01**

Table 7 Follow-up analyses of the main effect of Stimulus Type (standards, deviants) for the 500-, 3000- and 5000-ms ISI conditions in 6-year-old children

ISI	*df*	*MSE*	*F*	*p*
500 ms	1.00	1136.34	23.51	**<.001**
3000 ms	1.00	226.12	14.10	**<.01**
5000 ms	1.00	.00	<1	

Discussion

Developmental changes in sensory memory duration

The results derived from the measurements using short ISIs of 500 ms showed a pronounced MMN with no age dependence, indicating that the chosen frequency difference between standard and deviant stimuli can be clearly discriminated even by the youngest subjects studied.

The findings from the extended ISI conditions suggest that the duration of sensory memory increases considerably between the ages of 2 and 6 years. Two-year-old children have a clear MMN for an ISI of 0.5 seconds. The MMN is somewhat attenuated for an ISI of 1 second and absent for an ISI of 2 seconds. Hence we postulate that in 2-year-olds the duration of sensory memory for tone characteristics lies between 1 and 2 seconds.

Three-year-olds also show a prominent MMN for an ISI of 0.5 seconds and no significant MMN for 2 seconds. Under visual inspection of the waveform, however, a small but non-significant negative deflection can be seen for the 2-second ISI condition. In 4-year-olds the deflection in the 2-second condition now constitutes a distinct MMN, though still with a tendency to a slightly reduced amplitude compared to the 0.5-second ISI condition. This can be interpreted as evidence that in 3-year-olds the lifetime of memory traces in the sensory store is shorter than 2 seconds and in 4-year-olds longer than 2 seconds.

In 6-year-olds the memory traces are still accessible after a delay of 0.5 seconds and 3 seconds but not after 5 seconds. We therefore infer that in this age group the duration of sensory memory for tone characteristics lies between 3 and 5 seconds.

Previous studies have investigated auditory sensory memory in newborns, in children older than 6 years and in adults, but so far there have been no studies on the duration of sensory memory in toddlers and preschool children. The present findings close this gap and extend our knowledge about maturational changes in sensory memory. To summarize, newborns appear to be able to store information about tone characteristics in the auditory sensory memory for between 0.7 seconds and 1.4 seconds (Cheour et al. 2002). We found the limit to lie between 1 and 2 seconds for 2- and 3-year-olds, over 2 seconds in 4-year-olds and between 3 and 5 seconds in 6-year-olds. In children between 6 and 10 the lifetime of memory traces has been reported to be longer than 1.4 seconds and shorter than 8 seconds (Cheour et al. 1997; Gomes et al. 1999), and in young adults it appears to reach approximately 10 seconds (Böttcher-Gandor and Ullsperger 1992; Sams et al. 1993) before decreasing again for older ages (Pekkonen et al. 1996).

It remains unclear, however, whether there is an MMN amplitude reduction or an abrupt disappearance when the ISI is extended. A reduction in MNN amplitude in the grand mean waveform has been reported in several studies (Barry et al. 2008; Pekkonen et al. 1996). We also found a tendency to decreased MMN amplitudes when the ISI approached a certain limit. However, unfavourable signal-to-noise ratios for individual average waveforms prevented accurate determination of individual MMNs. Therefore it was not possible to deduce from our data whether a reduction in grand mean amplitude resulted from attenuated amplitudes in all children or the disappearance of MMN in some children in combination with unchanged MMN waveforms in others. Similarly, it is not yet clear whether the reduction in the MMN amplitude in experiments with longer ISIs reflects a successive decay of memory traces or a total loss of the traces in some subjects and fully intact traces in others.

MMN and auditory sensory memory

There is much controversy, however, about how to interpret MMN data. Some authors question the memory-trace explanation for the MMN and others the method of estimating the duration of sensory memory by means of ISI variation in MMN experiments.

Jääskeläinen et al. (2004) proposed that in an MMN paradigm the negative deflection of deviant-minus-standard difference waveforms is the result of an adaptation of N1a generators to frequently-occurring standards and not the neurophysiological outcome of a memory-based comparison process. They argue that a repetition of standard stimuli leads to an adaptation of frequency-specific neurons in the auditory cortex resulting in a diminished N1a response. They emphasize that frequency deviants are processed by other neurons and therefore deviants would elicit a non-adapted and therefore larger N1a response. In their view, subtracting the waveform of the adapted response to standards from the non-adapted one to deviants would then yield a negative deflection in the difference curve, which in turn could be falsely interpreted as a “real” component of the late auditory evoked potential, the MMN.

Näätänen et al. (2005) strongly dispute this adaptation hypothesis. They refer to MMN experiments which have shown that latency, duration and scalp distribution of the MMN are different from those of the N1a, and that an MMN also occurs in the absence of an N1a response. They conclude that MMN cannot be explained by the adaptation hypothesis and that instead there is strong evidence for a relationship between MMN and sensory memory processes.

Measurement methods and sensory memory duration

A further issue concerns the relationship between ISI and duration of sensory memory. The findings of several studies are not consistent with an assumption of a general lifetime of memory traces or a uniform sensory memory store. For example, in normal young adults, studies yielded different results with respect to the lifetime of sensory memory traces. According to the findings of Mantysalo and Näätänen (1987) the duration of memory traces is approximately 4 s, whereas Böttcher-Gandor and Ullsperger (1992) estimated trace duration to be approximately 10 seconds. In a reactivation experiment Winkler et al. (2002) presented sounds with reminders and found an MMN response even after a silent interval of 30 seconds. They concluded that there is a link between short-term storage and permanent storage and that some of the information is also stored as a permanent memory trace and can therefore be reactivated.

In addition, in behavioural experiments Gaeta et al. (2001) showed that subjects were able to detect deviants after a delay, which, when used as the ISI in an MMN experiment, did not elicit an MMN. Barry et al. (2008) found no significant correlation between the presence or mean amplitude of MMNs for longer ISI conditions and pseudoword repetition ability in parents of children with developmental language disorders. To explain these inconsistencies it has been suggested that different types of stimuli may fade away from the sensory memory store with different delays and that neurophysiological experiments and behavioural measures may assess different memory characteristics (Kujala et al. 2007).

Finally, a word about methodological aspects. For the MMN recording we used a time-saving paradigm introduced by Grau et al. (1998). Standards were grouped in trains of 4 stimuli, with a fixed ISI of 0.5 seconds between stimuli and with ISIs extending up to 5 seconds between the trains. It could be speculated that with such a paradigm grouping effects change the auditory perception of stimuli and therefore individual deviants are not compared with the regularities of the standards. Thus the absence of an MMN in a paradigm with grouped standards might not necessarily be attributed to a decay of memory traces but perhaps to changed auditory perception instead (Kujala et al. 2007).

Empirical studies which have addressed this concern have yielded conflicting results. Grau et al. (1998) did not find significant differences in MMN parameters between recordings with constant ISIs and those with grouped stimuli. In contrast, Winkler et al. (2001) detected MMN in all subjects if a constant ISI of 7 seconds was used, but only in 9 of 16 subjects with grouped standards. Our results using the paradigm put forward by Grau et al. demonstrate that the occurrence of MMN under conditions with extended ISIs is age-dependent. In 2- and 3-year-olds no MMN was found after an ISI of 2 seconds, whereas in 6-year-olds the MMN disappeared only after an ISI of 5 seconds. In our view grouping effects are unlikely to explain this kind of age-dependence. Because the perception of grouping is assumed to be a higher level of auditory processing, it could be postulated that grouping effects become stronger with maturation of auditory abilities (i.e. with increasing age). In that case one would expect possible grouping effects to lead to lower ISI thresholds with increasing age, rather than to the observed higher ISI thresholds.

Implications

In conclusion, our results provide evidence of a considerable increase in the duration of auditory sensory memory during the sensitive phase of cognitive development. The findings close a gap in knowledge about developmental aspects of the lifetime of sensory memory traces between infancy and school age. They suggest that the time during which a memory trace of regularities in the auditory input is available in the sensory memory store increases from between 1 and 2 seconds in 2-year-old children to between 3 and 5 seconds in 6-year-olds. Whether the duration of auditory memory traces estimated through variation of ISI in an MMN experiment is identical with the real duration of sensory memory is the subject of much discussion. Nevertheless, it can be assumed that MMN experiments with extended ISIs provide insight into important aspects of auditory sensory memory and therefore that they can be recommended for studies in children with cognitive disabilities and language disorders. MMN experiments are independent of motivation and understanding of tasks and provide a tool for studying normal and disturbed maturational processes of sensory memory in young children.

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