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Auditory perception of temporal order in centenarians in comparison with young and elderly subjects

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Temporal information processing controls many aspects of human mental activity and may be assessed by examining perception of temporal order in the tens of milliseconds time range. Although existing studies suggest an age-related decline in mental abilities, the data on the deterioration of temporal order perception seems inconsistent. Moreover, any evidence on subjects aged over 70 years is lacking. The present experiment aimed to extend the existing data to extremely old people. Temporal order judgment (TOJ) for auditory stimuli was tested across the life span of approx. 80 years, i.e. in young (mean age 22 years), elderly (66 years) and very old (101 years) subjects. Age-related deterioration of performance was observed, with slight changes in elderly subjects and significant deterioration in centenarians which was more distinct in women than in men. The results confirm age-related decrease in temporal resolution which may be explained by slowing of information processing or of a hypothetical internal-timing mechanism. These effects may be influenced by different strategies used in particular age groups.

Keywords: temporal order perception, cognitive aging, centenarians, information processing speed

INTRODUCTION

Temporal information processing (TIP) is an essential feature of many aspects of human cognition (Pöppel 1997, 2004). Experimental studies have clearly indicated that TIP constitutes an essential component of perception, attention, memory, language and motor activity. From this point of view, experimental studies on time and timing can provide information about the neuronal basis of human cognitive functions.

Much neuropsychological and psychophysical evidence indicates deterioration in a broad spectrum of cognitive abilities as a result of chronological aging (e.g. Lezak 1995, Zec 1995, Reuter-Lorenz 1999), thus, the deterioration in TIP may also be expected. This assumption has been supported by results of many studies which have revealed TIP deficits in elderly population (see e.g. Martin and Jerger 2005 for a review). The evidence comes predominantly from experiments concerning gap detection and reveals the reduced temporal resolution accompanying chronological aging (see e.g. Robin and Royer 1989, Schneider et al. 1994, Snell 1997, Snell and Frisina 2000). Further support for deteriorated TIP as a result of chronological aging is derived from studies on duration discrimination (Fitzgibbons and Gordon-Salant 1994, 1995, Phillips et al. 1994, Gordon-Salant and Fitzgibbons 1999), temporal generalization (McCormack et al. 1999), temporal bisection (McCormack et al. 1999, Lustig and Meck 2001), tapping (Vanneste et al. 2001, Baudouin et al. 2004), time estimation (Block et al. 1998, Vanneste and Pouthas 1999, Rakitin et al. 2005, Gunstad et al. 2006), reaction time (e.g. Teichner 1954, Nebes 1978, Gottsdanker 1982, Reuter-Lorenz and Stanczak 2000, Der and Deary 2006) and auditory comprehension (Gordon-Salant and Fiztgibbons 1999, see also Wingfield 1999, Pichora-Fuller 2003, Pichora-Fuller and Souza 2003 for reviews).

However, in the existing literature much less attention has been paid to age-related changes in the perception of temporal order, i.e. the ability to sequence incoming information, considered as a neural basis of identification of events (Pöppel 1993, 1997, Szelag et al. 2004). Several studies have revealed that the

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identiication of temporal order of two acoustic stimuli is only possible when they are separated by an interstimulus interval (ISI) of approximately 20–60 ms (Hirsh and Sherrick 1961, Mills and Rollman 1980, see also Szelag et al. 2004, Wittmann and Fink 2004 or Kiss et al. 2008 for recent reviews). This information supports the notion of temporally discrete information processing in a time window of some tens of milliseconds. Considerable evidence on the existence of such a temporal processing platform has been provided by experiments using various paradigms (see e.g. Pöppel 1997, Wittmann 1999, Szelag et al. 2001 for reviews), supporting a view of a central timing mechanism that controls our sequencing abilities (Hirsh and Sherrick 1961, Güçlü and Murat 2007). However, recent studies have suggested that this mechanism may be influenced by many procedure and subject related factors (Fink et al. 2005, Fink et al. 2006, Szymaszek et al. 2006).

Although a large amount of literature has been devoted to the perception of temporal order, only a few papers have concentrated on age-related changes in this task. The hypothesis of age-related deterioration in auditory sequencing abilities is derived predominantly from experiments by Fitzgibbons and Gordon-Salant (1998, Gordon-Salant and Fitzgibbons 1999) who found that deficits in temporal-order judgment (TOJ) may be increased by the stimulus complexity, i.e. sequences containing bidirectional frequency shifts. These studies examined the TOJ in sequences of three pure tones presented in a rapid succession without any ISI, but with adaptively varied tonal durations. In a series of experiments the authors found deficits in both identification and discrimination of temporal order in subjects aged 65–76 years, as compared with younger subjects, aged 20–40 years, but only for the most difficult stimulus sequences.

Age-related deterioration in TOJ has been also observed in the studies in which two-stimulus sequences were applied. For example, Philips and coauthors (1999) found that elderly people (aged approx. 72 years) needed longer ISIs than the younger ones (aged approx. 22 years) to report correctly the temporal order of illumination of two diodes. A similar conclusion may be drawn from experiments on auditory perception (Fink et al. 2005, Szymaszek et al. 2006). In these studies two stimulus presentation modes, i.e. monaural vs. alternating binaural, were applied. In the monaural presentation, two identical stimuli were presented with an ISI: one stimulus was presented to the left ear and the other to the right ear and the task was to indicate their temporal order (i.e., ‘left-right’ or ‘right-left’). In the binaural presentation mode, two tones of various frequencies separated by an ISI were exposed to both ears and the subject was again asked to indicate their temporal order (i.e., ‘high-low’ or ‘low-high’). These two modes involve, besides TIP, also mode-specific processing related to different underlying processes and mechanisms. This issue was discussed in detail in our earlier report (Szymaszek et al. 2006, see the Discussion section). Briefly, we found that performance in the monaural mode was more resistant (thus less deteriorated) to subjects’ age than in the binaural mode. For the monaural mode the deterioration was not significant when comparing the performance of young (20–29-year-olds) and elderly (60–69-year-olds) listeners with normal hearing sensitivity. In contrast, for the binaural mode a significant age effect was observed. Similar presentation-mode influences were observed by Fink and coworkers (2005).

The present investigation extends the existing studies on aging and temporal order detection to a population of extremely old subjects, i.e. Polish centenarians. Existing studies on age-related changes in TOJ have concentrated on subjects up to no more than 80 years of age and any evidence in older listeners is lacking. The present experiment is a unique investigation of the sequencing abilities across a life span of 80 years, from 20 to 100 years of age. In the present study the monaural presentation mode was applied because no significant decline for this procedure was found in earlier reports in subjects aged up to 70 years (see above). This mode, therefore, seems more resistant to age-related deterioration in the perception of temporal order.

In the existing literature there are some indications that sequencing abilities can be also modified by subjects’ gender and men often display better performance than women in temporal order tasks (Lotze et al. 1999, Wittmann and Szelag 2003, Szymaszek et al. 2006). Thus, in the present study we analyzed the gender effect on the performance of each age group.

METHODS

Subjects

Forty-six volunteers without previous experience in the task were included and divided into 3 age groups:

Table I

Characteristics of the three age groups

Group	*n*	Sex (M/F)	Age (years; months)	Education time (years; months)
Young	17	8/9	22 (± 1;11)	14;8 (± 1;11)
Elderly	18	10/8	66 (± 0;7)	14;8 (± 3;1)
Very old	11	6/5	101;1 (± 0;11)	6;1 (± 4;5)

young (19–25 years), elderly (65–67 years), and very old (95–103 years) adults. For detailed characteristics of each group see Table I.

Subjects in the two younger groups were right-handed, as verified by the Edinburgh Handedness Inventory (Oldfield 1971). They were screened for hearing level for the frequencies of 250 and 500 Hz and only those whose differences in hearing threshold between the right and the left ear were smaller than 20 dB HL were included in the study. None had a history of neurological disorders or serious head injury in the past. People using drugs that could influence the nervous system, as well as those who scored below 25th percentile in Raven Progressive Matrices (Raven 1977) were not included in the study. Informed, written consent was obtained from every subject before the experiment.

The very old subjects were identified by the Polish Centenarian Project on the base of the Civil Registration System. Next, their age was verified on the basis of birth certificates or any other reliable documents. As a very limited number of centenarians is cognitively intact (see also below), from a total number of over 200 recruited only 11 were included in our study. These subjects were born between August 1900 and November 1903[1]. All were able both to enter into communication with the researcher and to carry out the instructions. The centenarians fulfilled similar criteria as those described above for younger people with respect to handedness and hearing level. The very old people were screened for neurological status and neither serious neurological problems nor marked neurodegenerative diseases were found. On this basis it may be assumed that the very old subjects included in the present study constituted a group of relatively healthy centenarians.

The centenarians scored between 17 and 27 (mean score 22) in the Mini-Mental State Examination (MMSE; Folstein et al. 1975). Despite low scores on the MMSE obtained by some subjects (see Table II), the results of this test were not treated as an exclusion criterion because normative data for such an old population is lacking. Moreover, the low MMSE scores might have been related to the low educational level of some subjects in this group. Because of the cohort effect and important changes in the education system over generations, it would be very difficult to find people with such a low education in the two younger groups (see Table I). All 11 centenarians lived with their families, 4 of them (36%) in the countryside and 7 (64%) in the cities.

Table II

Detailed characteristics of the centenarians

No	Age (years; months)	Gender	Education (years)	MMSE
1	100;4	M	15	20
2	100;7	M	6	26
3	100;4	M	13	24
4	101	M	3	22
5	100;6	M	no information	27
6	100;8	M	5	23
7	102;5	F	3	21
8	101;8	F	3	17
9	100;7	F	3	24
10	103;2	F	3	18
11	100;7	F	7	21

[1] In case of one subject (no 7) the validation of age was impossible; another (no 2) turned out to be about 95 years old.

Procedure

Subjects in the two younger groups were tested individually in a soundproof room at the Nencki Institute. The very old people were tested at their homes, as the transportation to the Institute would be difficult and stressful for such old people. The very simple experimental paradigm created a relatively easy task for the very old participants.

The stimuli were 'square' tones of 300 Hz generated by a 16-bit SoundBlaster Card and presented for 15 ms monaurally *via* headphones at a comfortable listening level. The tones were presented in pairs; each pair consisted of one tone presented to the left (L) and the other to the right (R) ear. Between the tones in each pair there was an ISI (i.e. time between the offset of the first tone and the onset of the second one) of either 10, 20, 40, 60, 80, 100, 150, 300, 500 or 1 000 ms. The subject's task was to report the temporal order of stimuli in the tone pairs (R-L vs. L-R). If the tones were perceived by the subject as simultaneous, she/he could answer 'I do not know' (D-n-K), however, this answer was counted as an error. During the experiment, 12 presentations of each ISI were randomly ordered. Thus the experimental session consisted of 120 trials. The order of tones in half of the trials was R-L, whereas in the other half it was L-R. The time between the subject's response and the presentation of the first tone in the next trial was 2 s.

The proper experiment was preceded by a practice session to familiarize the participants with the task. At the beginning of the practice session, single tones were presented and the subjects were requested to indicate the stimulated ear. Next, they were requested to report the order of two tones presented in pairs with a constant ISI of 500 ms. If during the presentation of 24 consecutive trials the order of at least 20 pairs was reported correctly, the proper experiment began. In the two younger groups the experiment took approx. 30 minutes. For the centenarians it lasted about 1 hour.

Data elaboration and statistical analyses

The analyzed variable was the temporal-order threshold (TOT), defined as the ISI at which the probability of correct response was 75%. To calculate the TOT for each subject, the psychometric functions were fitted to his/her experimental data using the psignifit toolbox version 2.5.41 for Matlab (see http://bootstrap-software.org/psignifit) which implements the maximum-likelihood method described by Wichmann and Hill (2001). Then, the ISI was assessed for which the psychometric function reached 75% of correct responses. TOTs obtained by individual subjects were then submitted to Analysis of Variance (ANOVA). A *post-hoc* analysis was performed using the Tukey test. Moreover, the frequency of D-n-K responses was analyzed with Kruskal-Wallis and Mann-Whitney tests.

RESULTS

A two-way ANOVA with between-subject factors 'age' (young, elderly and very old adults) and 'gender' (men vs. women) showed a significant effect of 'age' ($F_{2,40}$=44.2, P<0.001), 'gender' ($F_{1,40}$=12.2, P<0.002) and a significant interaction between these two factors ($F_{2,40}$=7.1, P<0.003).

The TOTs increased with the subjects' age (Fig. 1). The mean TOT was relatively low in young subjects (37 ms), slightly higher in elderly ones (60 ms) and considerably higher in centenarians (191 ms). The difference in TOTs between the two younger groups was not significant, whereas differences between the centenarians and both younger groups were significant at the level of P<0.001.

The significance of 'gender' reflected, in general, the lower TOT in men (73 ms) than in women (120 ms). The interaction between 'age' and 'sex' resulted from different relationships in TOTs between men and women, depending on the age group (Fig. 1). Specifically, in the centenarians women obtained much higher TOT values than men (P<0.001). In the two younger groups sex differences were not significant (see Fig. 1). It should be also noted that the age-related declines in TOTs were parallel in both sexes. For both men and women there were no significant differences between young and elderly subjects, whereas such differences appeared between elderly and very old adults. However, in women this difference was greater (P<0.001) than in men (P<0.04). A similar relationship was observed when comparing young and very old subjects: the difference between women was more distinct (P<0.001) than between men (P<0.004). If one looks at Fig. 1, it seems clear that the deterioration of performance observed in centenarians was more pronounced in women than in men.

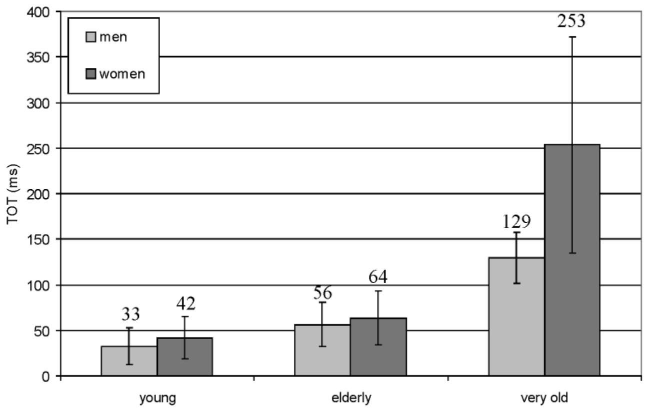

Fig 1. The TOT values in men and women in three age groups

It is known that in paper-and-pencil tests elderly people display the tendency to choose "don't know" response more frequently than the young (Schwarz and Knäuper 1999). Since D-n-K responses were counted as errors, thus influencing the TOT value, another analysis was carried out to examine whether the number of D-n-K responses differed between groups. Significant group-differences were observed for ISIs from 10 to 300 ms ($P<0.01$ for ISIs from 20 to 150 ms and $P<0.05$ for 10 and 300 ms, Kruskal-Wallis ANOVA). Centenarians gave significantly more D-n-K responses than the two younger groups for ISIs from 10 to 100 ms ($P<0.05$, Mann-Whitney test), whereas the differences between the two younger groups were non significant for any ISI.

DISCUSSION

The results of the present study clearly suggest that the perception of temporal order declines with subjects' age. The deterioration was non significant up to 65 years of age, but very pronounced in centenarians. This pattern of age-related changes in TOJ was similar in both genders, however, the deterioration was more distinct in women than in men (Fig. 1). Moreover, men displayed, in general, lower TOTs than women, this difference was mainly due to the poor performance of women in the oldest group.

The age-related decline in TOJ observed in the present experiment supports results of other studies, suggesting worsened temporal resolution in elderly people (see e.g. Martin and Jerger 2005 and Pichora-Fuller 2003 for reviews). The elevated TOTs in centenarians cannot be explained by their poor comprehension of the experimental instruction or general temporal ordering deficits, because they displayed a perfect performance (100% of correctness) for the longest ISI applied here (1 000 ms). The factors that may be responsible for such age-related decline are: (1) the general slowing of information processing in the nervous system (Salthouse 1996, Fitzgibbons and Gordon-Salant 1998, Gordon-Salant and Fitzgibbons 1999); (2) the slowing of a hypothetical internal timing mechanism, i.e. a pacemaker (see e.g. Surwillo 1968, Craik and Hay 1999, Vanneste et al. 2001, Baudouin et al. 2004) and (3) differences in the strategies applied to the task (Lemaire et al. 2004, Szymaszek et al. 2006).

The age-related deterioration observed between both 20–100 and 65–100 years of age may support the hypothesis of slowing of information processing, commonly postulated as the earliest and most distinct symptom of cognitive aging (Cerella 1985, Birren and Fisher 1995, Salthouse 1996, Wearden et al. 1997). As TOJ does not require any motor response, it is thought to provide more direct information about the real speed of mental processes in the human brain than reaction time tasks or paper-and-pencil tests, commonly used to estimate processing speed (Phillips et al. 1999, Shipley et al. 2002). The slowing of mental processes may be associated with damage to white matter structures, often reported in elderly population (Birren and Fisher 1995, Tisserand and Jolles 2003).

On the other hand, age-related deterioration in TOJ can be also interpreted in terms of an internal timing mechanism that is postulated to slow down with advanced age (see e.g. Surwillo 1968, Craik and Hay 1999, Vanneste et al. 2001, Baudouin et al. 2004). This 'internal clock' consists of a pacemaker emitting pulses and an accumulator in which these pulses are collected (see e.g. Treisman 1963, Gibbon and Church 1984, Block and Zakay 1996). A slower pacemaker rate in old people may result in reduced temporal resolution.

Another explanation of age-related declines assumes that different strategies are used to perform the task by young and old people. Existing studies suggested that in temporal order tasks at least two strategies may be possible: an analytical and a global one (Warren 1982, see also Wittmann and Szelag 2003, Szymaszek et al. 2006). Although in our study the instruction fostered an analytical approach (to report the order of stimulus presentation, thus, to identify the separate stimuli), the use of the global strategy may cause lower TOTs

(Divenyi and Hirsh 1974). When using the global strategy, there is no need to identify the separate stimuli, but to recognize a modulated pattern left-to-right or right-to-left (Szymaszek et al. 2006).

It is known that strategy adaptivity (i.e. the ability to choose the most appropriate strategy for the task) declines with age (Lemaire et al. 2004). Thus, younger subjects were probably more prone to modify the advised strategy into a more global one which improved their performance, whereas old people relied more on the advised analytical strategy.

The lack of significant differences between the young and the elderly subjects confirms the results reported by other authors, who found only a small deterioration of TOJ in subjects aged between 20 and 70 years for monaurally presented clicks, but a significant deterioration for tones of different pitch presented either monaurally or binaurally (Fitzgibbons and Gordon-Salant 1998, Gordon-Salant and Fitzgibbons 1999, Fink et al. 2005, Szymaszek et al. 2006). Our results are in agreement with these observations and confirm that TOT for monaurally presented sounds remains relatively stable up to the age of about 70. However, a huge decline is observed in very old people.

The distribution of D-n-K responses suggests that age-related increase of TOT could be in part related to the avoidance of guessing displayed by the oldest subjects. This pattern of performance in very old people was reported in paper-and-pencil tests, where old people were more prone to answer D-n-K than younger ones (Schwarz and Knäuper 1999). Since in our study D-n-K was classified as an error, it could contribute to the level of performance. However, in 16 subjects who never used D-n-K (i.e., 6 young, 8 elderly and 2 centenarians), similar age-related deterioration in TOTs was still observed (mean TOTs 26, 60, and 124 ms for 20-, 65- and 100-year-olds, respectively). This observation supports our interpretation of age-related changes in information processing speed, internal clock rate or strategy adaptivity (see above). However, these influences could have been modified by the age-related differences in avoidance of guessing.

Another question is whether the relatively low scores on the MMSE in some centenarians could influence their TOTs. As mentioned above in the Subject Section, the score on the MMSE was not an inclusion criterion, because normative data for such an old population is lacking. It should be noted that centenarians with low scores on the MMSE included in the study showed a relatively high level of mental functioning, good contact with the researcher during the testing as well as a lack of serious neurological problems (see above). Using the value of 23 in MMSE as a cut-off score for centenarians with lower (n=6) vs. higher (n=5) mental status, we obtained TOTs of 230 vs. 132 ms, respectively. Looking at Fig. 1, we conclude that although the low score on MMSE accompanied elevated TOTs, the pronounced deterioration of the TOTs was still observed in centenarians, independently of their mental status.

Another factor that could contribute to the age-related decline in TOTs may be education. As seen in Table I, centenarians had significantly less formal education than people in the two younger groups. Because of important transformations in the educational system across generations, it would be impossible to balance our age groups with respect to the amount of education. Although any evidence on the direct influence of education on TOT is lacking, some authors suggested its relation to cognitive functioning in old people (Letenneur et al. 1999, Le Carret et al. 2003). It may be reflected in results of our study, where 2 centenarians with the highest education (13–15 years) and 5 centenarians with the lowest education (3 years) showed mean TOTs of 140 vs. 221 ms, respectively. Therefore, we argue that although low education accompanies the elevated TOTs in centenarians, serious deterioration could be observed in this group, independently of education. To summarize, although both education and mental status could influence the performance of the very old subjects, the decline in TIP was still evidenced in this group.

Age-related differences in the perception of temporal order were also influenced by subjects' gender with better performance, in general, in men than in women. This difference was significant only in centenarians (Fig. 1). Referring to the existing studies, the data concerning the gender effect on the perception of temporal order are few and inconsistent. For example, Kanabus and colleagues (2002) reported the lack of a gender effect in young subjects, whereas Wittmann and Szelag (2003) as well as Szymaszek and others (2006) proved better performance in men than in women in the age range from 20 to 70 years. In another paper the gender effect was not clear in subjects aged 20–70 years (Fink et al. 2005). Thus, on the basis of these studies it is difficult to make any clear conclusion on the gender effect on TOJ in people aged 20–70 years.

The men's better performance in centenarians is in accordance with results of some previous studies in younger subjects (see e.g. Wittmann and Szelag 2003, Szymaszek et al. 2006). In the case of our study, it cannot be related to education or mental status, because no significant gender differences on these two factors were observed. The better men's performance may support the thesis of less age-related decline observed in some cognitive tests in men in comparison with women (Meinz and Salthouse 1998, Ho et al. 2001, Deary et al. 2004). For example, Meinz and Salthouse (1998) showed men's superiority in tests of speed and reasoning. These findings were explained by differential survival of men and women (Deary et al. 2004), suggesting that very old men might represent a relatively cognitively spared survivor group. It may be concluded that factors underlying age-related decline in sequencing abilities, i.e. information processing speed or strategy adaptivity could interact with subjects' gender.

As postulated above, in the temporal order task the use of a global strategy may lead to better performance than the use of an analytical strategy (Divenyi and Hirsh 1974, Szymaszek et al. 2006). As postulated in many previous studies (see Kimura 1999 for a review), a holistic strategy is more typical for men, and an analytical one for women. On the other hand, according to Lemaire and coauthors (2004), in cognitive tasks older subjects show lower strategy adaptivity than younger ones (see above). As our experimental instruction facilitated the analytical strategy, it may be postulated that in case of centenarians women relied less than men on holistic transformations because first, this kind of processing is not typical for women, and second, it was not advised by the instructions. As in men the application of holistic processing is probably more natural, the very old men despite their decline in strategy adaptivity may have still applied the holistic processing. On the other hand, it may be hypothesized that women in the two younger groups, because of greater strategy adaptivity than those in centenarians, could improve their performance using more holistic processing, resulting in the lack of gender differences.

CONCLUSIONS

Our study confirmed the decrease of temporal resolution across the life span. Using a monaural presentation mode, we found significant deterioration in TIP beyond 65–70 years of our life which was more distinct in women than in men. It should also be stressed that the eleven centenarians included in the present study were selected as the best-functioning ones from the pool of over 200 people identified in the Polish Centenarian Project. Thus, the results reported here can not be generalized on the whole population of extremely old people.

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