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Review

Individual differences in temporal information processing in humans

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Abstract. This article reviews some of our investigations concerning individual differences in temporal information processing. Two different levels of temporal information processing are discussed, namely the low-frequency (i.e., a few seconds time range) and the high-frequency processing level (i.e., some tens of milliseconds range) of temporal information with respect to various experimental paradigms. Evidence has been obtained indicating that the processing of temporal information on these two levels can be influenced by various subject-related factors, out of which age, gender, developmental disorders, auditory experience and localisation of damage in the brain seem to be the most significant.

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INTRODUCTION

Neuropsychological and psychophysical evidence has suggested that one of the characteristic features of human behavior is its patterning in time. Extensive research has clearly shown that many aspects of our functioning may derive, at least in part, from temporal information processing (TIP) which constitutes an essential component of, for example, perception, memory, attention, language or motor activity (Pöppel 1988, 2004).

Current research has also postulated that temporal perception is not veridical and subjective time is not a linear function of the clock time. Deviations from the exactly timed template have been commonly reported in studies on TIP. The way in which the human brain processes temporal information is still little understood and the search for mechanisms and principles that underlie the subjective experience of the passage of time has become, in recent years, an increasing interest of many life scientists. However, despite years of research, there remain many unanswered questions about TIP.

The basic question is: how is temporal information processed in our brain? As a first step towards answering this question a classification system of elementary temporal experiences is needed, to provide the background for the experimental work. Combined results from various areas of research suggest that there are different time ranges underlying TIP (e.g., Pöppel 1994, 1997, Wittmann 1999). Empirical evidence suggests the existence of at least two different processing systems employing discrete time sampling; these two systems are controlled by different neuronal mechanisms. According to Pöppel's model of time perception (Pöppel 1994), one domain is concerned with low-frequency processing, which constitutes the temporal range of approximately 3 s. The other domain is concerned with high-frequency processing, namely the time window of approximately. 30 ms, related to perception of succession and temporal order of events. It should be stressed that the values of approximately 3 s or 30 ms do not refer to the "constant numerical values" obtained in particular experimental studies, but rather indicate two temporal domains or operational processing windows: one of a few seconds, the other of some tens of milliseconds with intra- and inter-individual variability.

In the present article, we briefly present the results of some our investigations on the effect of various factors on TIP on these two time levels.

THE LOW–FREQUENCY PROCESSING LEVEL

A large amount of psychological and neuropsychological evidence has indicated that the human brain provides for our mental activity a temporal processing platform with a duration of a few seconds. This platform may reflect the functioning of the temporal integration mechanism (TIM) – one of the hypothetical mechanisms on the highest level of the time perception model proposed by Pöppel (1994, 1997, Szelag 1997, Wittmann 1999). The TIM binds the sequences of elementary events together into perceptual or conceptual units of approximately 3 s durations.

Experimental data published in the scientific literature provide support for the existence of such a processing platform. These data concern motor behavior, fluent speech, reproduction of temporal intervals, subjective accentuation of metronome beats, sensorimotor synchronization, spontaneous rate of ambiguous figures, binocular rivalry, short term memory, slow cortical potentials and mismatch negativity (for reviews see Pöppel 1994, 1997, 2004). The existence of a temporal limit of a few seconds has been discussed for a long time in the literature and is referred to as the "subjective present" or our feeling of "nowness" (e.g., Bechinger et al. 1969, Eisler 1996, Fraisse 1984, James 1890). According to these studies, the "subjective present" has no fixed duration. It typically lasts approximately 2-3 s (Pöppel 1994, 1997) and not often exceeds 5 s (Fraisse 1984) or even 10 s (Bechinger et al. 1969).

In the next sections of the present article we summarize an overview of the results of studies carried out in our laboratory concerning TIP on the low-frequency processing level, using observation of temporal segmentation in motor behavior and duration judgment.

Temporal segmentation in motor and language domains

As was mentioned above, the operation of the TIM may be observed in the temporal organization of human behavior. Many everyday observations as well as experimental data support the existence of such a few-seconds processing window. For example, in spontaneous behavior intentional motor acts (e.g., scratching, waving, patting, nodding, shaking hands) in human beings from different cultures and ethnic groups (e.g., Yanomami Indians, Kalahari bushmen) show a narrow range of durations, limited approximately from 1 to 3 s (e.g., Feldhütter et al. 1990, Kien et al. 1991).

The temporal segmentation of intentional motor behavior evoked by experimental instruction has been investigated in our laboratory (Kowalska et al. 1998). In this study normally developing children, aged 13-14 years, were requested to perform with either the right (dominant) or the left hand everyday activities, such as: waving goodbye, scratching, patting, stroking, showing "sh...", "a fig for you", etc. The investigated actions were classified into rhythmically repetitive behavior, defined as movements repeated in the same form a few times rhythmically (e.g., waving, scratching) and non-repetitive behavior, that is action units only comprising of one set of movements (e.g., showing "sh..."). The requested movements were recorded and the length of particular action units performed with the right and left hand were analyzed from the videotape. The results showed that the average length of action units was approx. 2 s, however, the rhythmically repetitive actions were longer (ca. 2.3 s) than the non-repetitive actions (ca. 1.1 s). Differences between the duration of actions performed with the right and left hand were not apparent. These results indicate that there is a similar segmentation in motor behavior evoked by specific experimental instructions to that reported in the literature for spontaneous behavior. Moreover, the temporal segments for 13-14-year olds investigated in our study appear to have a comparable length to those reported for adults from different cultures (Feldhütter et al. 1990, Schleidt and Feldhütter 1989). However, within the considered time window of a few seconds we found a differentiation depending on the category of behavior (rhythmically repetitive *vs* non-repetitive), as well as the kind of requested action.

Substantial evidence indicates that the phenomenon of temporal segmentation, comparable to that observed in motor behavior, can be also observed in fluent speech. Vollrath et al. 1992 showed that spontaneous utterances with ca. 10-14 syllables form usually a phrase, which has a defined syntactic structure and semantic load. These phrases in different languages last on an average ca. 2-3 s and usually are followed by pauses (Gandour et al. 1994, Vollrath et al. 1992). Turner and Pöppel (1988) showed that this segmentation may be also important for aesthetics of poetry. Individual lines of poetry in many languages that form rhythmic, semantic and syntactic units nearly always last in recitation from 2 to 4 s, with a strong peak in distribution between 2.5 and 3.5 s.

The similarity between temporal segmentation observed in both motor and language domains is in agreement with evidence indicating close anatomical and functional associations between the motor and language systems (Kien and Kemp 1994). Pöppel (1988) has postulated that the durations of semantic units, which are the equivalent of behavioral action units reflect the time over which the brain integrates the information to create a "conscious percept".

Reproduction of temporal intervals

One of the most convincing pieces of evidence for the existence of a few seconds processing platform comes from the reproduction of visual or auditory standards (i.e., filled with presentation of a light or a tone) of various durations. This method allows us to investigate the duration processing without the use of any conventional time units e.g., seconds or minutes. Using this paradigm, a standard is presented for the defined time and the subject's task is to reproduce its duration. Accurate reproduction implies that the reproduced interval is equal to the time of a standard presentation. Response deviations from standards are given by indicating the direction of the deviation: over-reproduction indicates that reproduction is longer than the standard presented, whereas under-reproduction means that the reproduction is too short.

Using the method of time reproduction, a very clear relationship has been commonly observed: subjects reproduce standards up to a few seconds almost veridically (or slightly longer, which is probably due to the reaction time component), whereas they under-reproduce longer intervals usually substantially (Kargerer et al. 2002, Kowalska and Szelag 2003, Pöppel 1971, 1997, Szelag et al. 2002). This pattern of relationships is usually interpreted that short intervals (usually up to ca. 2-3 s, in some experiments even up to 4 s) can be mentally preserved or grasped as a unit as a consequence of this integration process. These standards are relatively accurately reproduced because they fall within the temporal window characteristic for the above TIM. Thus, the capacity of TIM is limited in time: up to a few seconds information can be treated as a unit, but it disintegrates if longer lasting stimulus duration is processed.

In contrast, under-reproduction in the case of longer standards is probably due to qualitatively different processes, which are beyond this TIM. According to Block et al. (1999), in the case of longer standards, the subjects may be impatient and increase the amount of attention they allocate to time. This may result in the subject focusing on the time at which the duration will end and result in a shorter reproduction. Such impatience may cause difficulties because subjects find it hard to delay the response for the long interval, which appears as a shortening of reproduction.

Taken together, using the method of reproduction two distinct processing modes are postulated: one related to TIM, the other associated with processes that are beyond that of TIM. The experimental studies reviewed below carried out in our laboratory provide data directly corroborating the hypothesis that short and long intervals are processed by different mechanisms.

On the other hand, evidence shows that different physiological and cognitive factors have a great impact on time reproduction (Zakay 1993a,b, Zakay and Block 1996, 1997, see also Zakay and Block 2004 - in this issue). Several theorists have proposed various models that explain how these factors may influence our experience of duration (for reviews see Block 1990, Block and Zakay 1996). For example, the attentional-gate model proposed by Block and Zakay (1996) combines features of some existing models, described by Treisman (1963), Church (1984), Gibbon (1991), Gibbon et al. (1984), and Thomas (Thomas and Weaver 1975). In the present review we refer to the attentional-gate model in order to explain some of our data. This model assumes that during our experience of duration pulses are generated by a pacemaker at a defined rate and, next, transferred through the attentional gate and cognitive counter to a working memory store. The end of reproduction of a just encoded standard is signaled (for instance by pressing a button) when the momentary pulse count in working memory is equal to the total one stored during the standard presentation. At this moment the participants experience that the duration of the standard presented was reached.

In a prospective paradigm, i.e., a situation when the subject knows before a standard interval starts that its duration is to be estimated (Zakay and Block 1997), duration judgments are directly related to the amount of attention that a subject allocates to time and to external (nontemporal) events. Such allocation of attention influences the accumulation of pulses. With respect to future considerations in the present review, mechanisms responsible for over-reproduction seem to be especially important. Accordingly, a concurrent (nontemporal) task performed during the reproduction of the previously presented standard causes the attentional gate to open narrowly, resulting in fewer pulses passing through and being accumulated per objective time unit. In such a case, accumulation of pulses takes a longer time to achieve the total number stored during standard presentation, and as a consequence reproduction lengthens.

It should be also noted that some authors assumed that prospective time judgments are sensitive not so much to attentional processes but to those associated with executive control of working memory (Brown 1997). Accordingly, an alternative explanation of over-reproduction has been offered by Fortin and her co-workers (Fortin 1999, Fortin and Breton 1995, Fortin and Rousseau 1998). They concentrated on the role of working memory and assumed that time judgment requires some accumulation of temporal information emitted from an internal source (cf. Church 1984, Gibbon et al. 1984, Zakay and Block 1997). Fortin and co-workers found that performing an external (nontemporal) task, which consumed working memory during the reproduction of a previously presented standard, can result in longer reproduction. The processing of such concurrent information interrupts the process of pulse accumulation during the reproduction of a just encoded standard. It increases the time needed to reach the criterion of pulses stored during the standard presentation.

To summarize, it seems that the reproduction of temporal intervals may be influenced by different processes and mechanisms, specifically: TIM, attention, working memory and a subject's impatience. In our laboratory a series of experiments was run to investigate how different procedure-related and subject-related factors may influence the accuracy of reproduction.

The stability of reproduction

The first question to consider is whether the specific experimental conditions, e.g., the set of standards presented during an experiment, may influence the accuracy of reproduction. As during the testing many standard durations are usually presented, a specific time reference system might be implemented which could influence the accuracy of performance. Accordingly, in two experiments we investigated the effect of the set of exposed standards on the accuracy of reproduction (Kowalska, unpublished results). In these experiments we wanted to replicate the earlier finding made by Pöppel (1971), who reported a similar pattern of the relationships in the two experimental situations, i.e.: (i) when the subjects reproduced randomly-presented visual standards ranging from 0.5 to 7 s; and (ii) when each subject reproduced only one standard duration, and only once. Whereas in Pöppel's experiment only general relationships were described, indicated by the scatterplots of individual results without any statistical analysis, in our study we performed more precise comparisons of the accuracy achieved for particular standards.

In one experiment normally developing adolescents (aged 16-19 years) reproduced the durations of visual standards (a green light presented as an oblong on a screen), ranging from 1 to 5.5 s. In the second experiment, students (aged 21-34 years) reproduced the duration of 5 standards, which were included into the set of standards presented in the previous experiment, namely: 1, 2, 3, 4, and 5 s. Each subject in this group reproduced only one standard duration, thus, the participants had no opportunity to develop any reference system because only one standard of the defined duration was presented.

In the latter experiment, the accuracy of performance at particular standards was similar to that obtained in the former one, where each subject reproduced the whole set of standard durations. Between-experiment comparisons for particular standards did not show any significant differences. Specifically, in both experimental situations subjects reproduced shorter standards (up to ca. 4 s) relatively accurately and under-reproduced longer ones.

These data provided an argument against the influence of the set of presented standards on the general pattern of accuracy in time reproduction. Similar conclusions can be drawn from the experiment carried out by Pöppel (1971). The observed relationships, specifically the relatively accurate reproduction of standards up to 4 s and under-reproduction of longer standards, support the notion of two distinct processing modes: one operating within a few seconds' frames related to TIM, the other characteristic for longer durations. It can be proposed that TIP up to ca. 4 s consists of mechanisms that are qualitatively different from those for longer intervals.

Normal development of a child

Developmental changes in duration timing were recently investigated in our laboratory (Szelag et al. 2002). The purpose of these studies was to test whether ontogenetic changes in cognitive abilities, occurring usually across pre-school and early school education (in the life span between 6 and 14 years) can influence the judgment of duration. It would be important to note that this purpose might have an anatomical background. Developmental changes both in cognitive abilities and in TIP probably have common neural substrates, which can be localized in the prefrontal and parietal cortices (e.g., Elbert et al. 1991, Harrington et al. 1998, Maquet et al. 1996). The functional reorganization within these cortices may be related to processes associated with learning during a school education, as well as increasing of working memory capacities and the improvement of the ability to focus attention.

In our developmental studies our participants were normally developing children, who were classified into three age groups: pre-schoolers (aged 6-7 years) and school children aged either 8-10 years or 13-14 years. The participants reproduced visual (filled with a green rectangle presented on the screen) or auditory (200 Hz tone) standard durations, ranging from 1 to 5.5 s. We found that in these three age groups standards of approx. 2.5 s were relatively accurately reproduced, whereas those longer than 3 s were under-reproduced. Substantial age-related differences in accuracy of reproduction were observed for standards shorter than 2 s. While the pre-schoolers usually substantially over-reproduced these standards, both groups of school children showed relatively accurate reproduction (for detailed statistics see Szelag et al. 2002). Moreover, the youngest group in the case of longer standards tended to display higher under-reproduction than the older participants.

Our developmental studies proved, thus, substantial age-related differences in TIP. The changes concerned both the hypothetical time window of the operating TIM and longer durations. In general, our results indicate that the upper limit of TIM (ca. 2.5 s) was relatively stable across the life span investigated here. This limit was within the time frames characteristic for the TIM reported in the other studies published in the literature, which were also carried out on adolescents and adults (Kargerer et al. 2002, Kowalska, unpublished results, Kowalska and Szelag 2003, Pöppel 1997, von Steinbüchel et al. 1999a,b). In these studies, however, the upper limit of TIM seems to be a little higher (up to 4 s) than that observed in children investigated in our experiment presented here. It may be concluded that in time reproduction, the time interval of around 2-4 s may be interpreted as the upper temporal limit of TIM. However, age-related modulations within the time window related to TIM seem to be strongly linked to developmental changes in cognitive abilities.

The age-related changes observed for short standards may be explained on the basis of the attention-gate model (see above). Although in our experiment no concurrent tasks were applied, it may be supposed that pressing the button by the child to signal the end of reproduction of a just encoded interval may have some kind of distracting influence. Such a motor reaction needs planning, preparation for movement and performing the pressing. In the case of shorter standards, these nontemporal activities consumed proportionally more time during the reproduction phase than for the case of longer standards (above 2.5 s), thus, their influence may be more pronounced in the case of shorter standards. Moreover, young children have probably less attentional resources and are more sensitive to such a distraction than the older participants. On the basis of our data it would be difficult to answer whether these relationships could be caused by the lower overall amount of attention in young children as compared with the older ones, or by poorer functioning of certain aspects of attention, i.e., control, adaptation, planning or switching of attention (Flavell 1985). Referring to the attentional-gate model, less attention allocated to time during the reproduction of just encoded duration yields an over-estimation of the standard (compare above, also Zakay and Block 1997).

As a result of development of the child's ability to judge duration in a relatively accurate way, as well as the stabilization and optimalization of attention during ontogenesis, TIM may not only facilitate intervals linked to its upper temporal limit, but also those of durations within this time window. On the other hand, it may be expected that the higher under-reproduction of longer standards in pre-schoolers may be related to their higher impatience or difficulties in delaying a response in comparison with older participants (see also above).

To conclude, our developmental studies support the hypothesis that two different neuronal mechanisms may underlie temporal reproduction, one operating up to a few seconds related to TIM and the other mechanisms (nontemporal) responsible for longer intervals. Both of them seem to be vulnerable to the subject's age, however, the upper limit of TIM seems to be relatively stable across the life span investigated in our developmental studies, from 6 to 14 years of life.

Auditory experience

CONGENITAL DEAFNESS

The effect of ontogenetic experience on duration judgment has been supported by our investigations on congenitally deaf adolescents (Kowalska, unpublished results, Kowalska and Szelag 2003). The aim of these studies was to test whether auditory deprivation influences the accuracy of temporal reproduction in the time range of a few seconds. As mentioned earlier, this range has an important impact for our speech, because it corresponds to the length of uttered words and phrases. The question arises whether deaf persons, who showed very disturbed articulation and could not perceive oral speech in the natural way, displayed also disturbed TIP in the above time range.

The subjects were congenitally deaf adolescents (aged 16-19 years) and normally hearing individuals, matched for sex and age. The hearing loss in the deaf subjects was 90 dB or more in both ears. They communicated using sign language, finger spelling, lip reading and also oral speech, however, their articulation was very disturbed, often almost incomprehensible. The subject's task was to reproduce durations of visual standards (a green rectangle presented on the screen) ranging from 1 to 5.5 s.

The normally-hearing adolescents reproduced relatively accurately standards of up to 4 s and under-reproduced the longer ones (Kowalska, unpublished results). In contrast, in deaf adolescents the region of the accurate reproduction was more limited than in normally hearing individuals, and focused around 2.5-3 s standards. Moreover, the deaf, when compared to controls, over-reproduced standards shorter than 2 s and slightly under-reproduced those longer than 3 s.

These results indicate that profound hearing loss is characterized by a slightly lower upper limit of TIM than that observed in controls. However, it still remains within the time window characteristic for this mechanism reported in the other papers published in the literature (e.g., Pöppel 1994). It can be concluded that in the deaf, a few seconds temporal processing platform still exists, despite of auditory deprivation as well as the use of non-verbal forms of communication. It is interesting to note that this conclusion can find some support in observations on temporal segmentation of sign language made by Meier (1979). He found that in American Sign Language sentences produced by both deaf people and normally hearing signers are limited in time on average up to 1-2 s. This observation may be related to the existence of some kind of temporal chunking process in the deaf, which can be reflected in our studies on temporal reproduction by the operation of TIM.

To the contrary, the over-reproduction of short standards found in the deaf may result, as it seems, from less effectiveness of working memory (Siple 2000). In fact, deaf people rely predominantly on the visual canal (Bellugi et al. 1975), which is usually slower in the coding of information than the acoustic canal (Lindsay and Norman 1972), mainly applied by the normally hearing. On the other hand, relying predominantly on visual processing in the deaf might result in overloading of this type of working memory, as well as a higher sensitivity to external (nontemporal) tasks that occur during the reproduction (e.g., pressing the button to signal the end of reproduction in the case of short standards). Thus, the over-reproduction of short standards in the deaf may result from the coexistence of two factors: less effectiveness of working memory and the existence of an external (nontemporal) task during our testing. However, the results obtained for hearing subjects indicated that during optimal functioning of working memory, the additional (nontemporal) task applied here did not disturb time estimation in adolescents.

Referring to the previous sections of this review, an alternative interpretation of the over-reproduction of short standards observed in the deaf may be due not so much to less effectiveness of working memory, but to the limited attentional resources (see above).

Considering the under-reproduction of longer standards, it might be supposed that the influence of some nontemporal factors, such as impatience or difficulties to delay the response, may be higher in the deaf than in controls. Such an assumption may find its support in studies published in the literature that showed a higher impulsiveness in the deaf than in controls (Lane 1992). Hence the influence of these subject-related, nontemporal factors can be more pronounced in the deaf than in controls.

These data suggest that although two distinct processing modes characterize temporal production in both investigated groups, congenitally deaf people show a reduced upper limit of TIM compared to controls. Moreover, congenitally deaf people display the remodeling in TIP both within and beyond the time window characteristic for this mechanism.

COCHLEAR IMPLANTATION

Nowadays, a prosthetic device called a cochlear implant (CI) is designed to restore normal hearing in profoundly deaf people by electrical stimulation of nerve cells inside the inner ear. A lot of models of CIs have been proposed as an aid to deliver auditory information necessary to make speech intelligibility possible. According to the existing literature, although CIs have a significant importance for the restoration of hearing, the ability of speech understanding in many cases develops after several months of post-operative auditory training (Tyler 1993). Compared with the limited success of monochannel stimulation with respect to the restitution of speech recognition, multichannel systems show much better results.

It is clear that a lot of studies have demonstrated a close relationship between language and TIP in the time range of a few seconds. This statement gains support also from our investigations of duration judgment in CI users (Kanabus et al. 2004 – this issue). In these studies we compared subjects' functioning for restored auditory processing and intact visual processing in postlingually deafened adults after multichannel (MED-EL Combi 40 and Combi 40+) or monochannel (MED-EL Comfort) implantation. After implantation the patients underwent intensive auditory training and speech therapy. The level of auditory comprehension (assessed with the following subtests: phonemic hearing, vowels, consonants, monosyllabic words, numbers and sentences) was much higher and less differentiated in the former group (the group mean score = 83.7%, the mean score in particular patients from 63 to 98% of speech understanding) than in the latter one (the group mean score = 45.5%, from 11 to 75%). Controls were normally hearing adults, matched for age, sex and education with CI patients.

The subjects reproduced visual (a green oblong) or auditory (300 Hz tone) standards of durations ranging from 1 to 9 s. In the case of multichannel CI users there were no differences in comparison with controls for both visual and auditory reproduction. Accordingly, two distinct processing modes were observed, namely relatively accurate reproduction up to ca. 4 s and under-reproduction of longer intervals. It should be noted that for auditory reproduction in multichannel CI patients, in general, a similar pattern of relationships was observed during standard presentations both in the free acoustic field and using a specific device (Research Interface Box, designed by the MEDEL Company), allowing the direct electrical stimulation of implant electrodes. Thus, for these patients the temporal reproduction seem to be unaffected both for the restored auditory and the intact visual modality. Similar relationships were observed in monochannel CI users, but only for visual reproduction. In contrast, in these patients for the auditory reproduction we found divergent relationships for the time window of operating TIM, depending on the level of auditory comprehension in particular patients. Poor auditory comprehension was accompanied by over-reproduction of standard durations up to 2.5 s. These results are described and interpreted on the basis of deficits in working memory in the other article in this volume (Kanabus et al. 2004).

In summary, the accuracy of time judgment after multichannel operation seems similar to that observed in subjects with normal hearing both for the restored auditory modality and the intact visual one. In contrast, after monochannel operation the persistent comprehension deficits are accompanied by the atypical auditory processing within the time range related to the operating of TIM (cf. Szelag E, Kowalska J, Galkowski T, Pöppel E, in press).

Infantile autism

Evidence suggests that in autism severe abnormalities in social behavior are accompanied by deficits in cognitive functioning, e.g., perception, attention, memory and/or language. As these functions are rooted in TIP (see above), the present study aimed at testing whether individuals with autism display the typical TIP in the time span of a few seconds (Szelag E, Kowalska J, Galkowski T, Pöppel E, in press). In this study we compared the performance of 9- to 16-year-old individuals with autism, showing high-functioning mental status with that of normally developing children, matched for age and sex. The subjects reproduced visual (a green rectangle presented on the screen) or auditory (200 Hz tone) standard durations ranging from 1 to 5.5 s. While the performance of normally developing children was rather typical, i.e., two processing modes were observed, in contrast, individuals with autism were totally unable to link their responses to the presented durations. Independently of the modality and standard duration, they reproduced standards with various response durations, clustered on an average around the value of 3-3.5 s. Although a clear "temporal neglect" was found in individuals with autism, the temporal platform related to the operation of TIM was still operative in this group. As modulations of responses by different standard durations were not possible, it seems that in autism the sensory information is disconnected from the temporal information.

These specific TIP disorders may be interpreted on the basis of psychological models of time judgment, which have postulated a crucial role for arousal, motor skills, memory and attention. Such an interpretation is in agreement with the view that an impairment of any of these factors may constitute the primary deficit in autism (for a recent review see Szelag E, Kowalska J, Galkowski T, Pöppel E, in press). Moreover, between-subject differences may be due to variations in these processes from one individual to another. Accordingly, autistics can make longer/shorter reproduction because of instable arousal, which recalibrates the pulse rate during the standard exposition, and reproduction. On the other hand, reproduction errors can result from disordered motor functioning, specifically a variable delay when making the motor reaction, i.e., pressing a button to finish the reproduction. An alternative interpretation may be based on scalar-timing theory, which assumes that duration judgment is influenced by three interrelated components: pacemaker, memory and decision processes. A dysfunction of any of these components may be related to erroneous duration judgment. The other possible interpretations of the specific form of "temporal neglect" in autism may postulate the deficits within the working memory or attentional processes. To identify which of the above mentioned factors has a crucial role in the specific TIP deficits in autism, future extensive studies are needed.

The relationships observed in individuals with autism might be also related to some anatomical indications, suggesting abnormalities in many brain areas, ranging from the cerebellum and medial temporal lobe structures (crucial for social and emotional cognition) to the dorsolateral prefrontal cortex (crucial for working memory) (e.g., Harrington et al. 1998, Maquet et al. 1996, Meck and Benson 2002, Nichelli et al. 1995, see also Rubia and Smith 2004 – this issue). Referring to clinical and neuroimaging studies in the normal population, for TIP the brain regions involved are similar to those related to the autistic syndrome. Thus, it may be postulated that abnormalities within different brain regions may constitute the neuronal substrate for the core symptoms in autism. This issue requires further investigation.

To summarize our considerations concerning temporal reproduction, we confirmed that the accuracy of performance may be influenced by the coincidence of many factors, specifically: TIM, attention, working memory, and subject-related features. In these studies the existence of TIM seems to be well documented in children and adults who demonstrated two distinct processing modes: one of them probably reflecting processes related to this hypothetical mechanism, and the other mode relating to processes beyond that of TIM frames. The former processing platform seemed to be active in a residual form even in individuals with autism, despite their severe temporal neglect.

Although the upper limit of TIM observed in our studies was comparable to that found in the other studies published in the literature, it seems to be slightly reduced in children and in congenitally deaf adolescents. The precise assessment of individual differences in the extent of this TIM needs future extensive studies. We found important remodeling within the processing window characteristic for TIM in 6- to 7-year-old, congenitally deaf adolescents and monochannel CI users with severe comprehension deficits. These changes may be interpreted by referring to limited attentional or working memory resources. The reproduction of durations, which were beyond that of TIM frames, can also be affected in younger children as well as in congenitally deaf adolescents.

A further question is whether the accuracy of performance using the other methods of duration judgment can be similarly influenced by different subject- and procedure-related factors.

Duration judgment methods

In the existing literature there is converging evidence that in prospective time judgement the important factor influencing the accuracy of performance may be the method used to collect subjects' responses (e.g., Nichelli 1993, 1996). Commonly, four different methods are applied in these studies: (i) temporal reproduction – the participant is presented with a standard duration and reproduces that duration (see previous section); (ii) temporal production – the participant is presented with a verbal command and produces a certain duration specified in conventional time units; (iii) verbal estimation – the participant is presented with a standard of a certain duration and estimates its duration in conventional time units; (iv) temporal discrimination – the participant is presented with two standards in a sequence and determines which of the two is longer.

Accordingly, an important distinction can be made between the method of reproduction and production. As was described in the previous section, for reproduction the subject reproduces a just-encoded interval on the basis of a comparison of experiences and the task does not need the use of conventional time units. Conversely, production is strongly rooted in the use of conventional time units (usually seconds) and requires a "translation" of these units into a specific duration. The subject can use long-term memory representations, which were acquired from their social environment. Therefore, to study individual differences in the use of clock units, the production of intervals can be applied. Referring to the terminology of Gooddy (1969), while reproduction reflects the "personal time", production reflects "government time".

In both these methods, the accuracy of estimation depends on both physiological factors (e.g., arousal level which influences the rate of a pacemaker) and cognitive factors (e.g., a necessity to devote attentional or working memory resources to concurrent tasks). The accumulation of pulses emitted from an internal source may run faster or slower than the objective time. During production this can be observed as a shorter/longer judgment than the real time. Hypothetically, underproduction of the standard duration may indicate that the biological pacemaker is fast, while overproduction may indicate that the clock is slow (compare also below). During reproduction it is not possible to determine the speed of the pacemaker because any difference in the rate or recalibration during standard presentation (coding phase) is also present during the reproduction phase.

The subjective experience of duration using both interval production and reproduction may also depend on cognitive processes (attention, working memory) as well as the specific conditions in which the task is performed (e.g., application of concurrent nontemporal tasks).

In the light of this data, in our laboratory we compared the accuracy of duration judgment using these two methods in 16- to 19-year-old adolescents, who were asked either to reproduce visual standards (a green rectangle), ranging from 1 to 5.5 s, or to produce durations (filled with a presentation of this rectangle), ranging from 1 to 6 s. The results showed that while the subjects produced nearly accurately all presented standard durations, they reproduced accurately (as described in the previous sections) only standards up to ca. 4 s and under-reproduced the longer ones. Thus, a quite different pattern of relationships was observed using the interval production and reproduction. Whereas reproduction reflected two different processing modes, as discussed above, the use of conventional time units in the case of interval production improved the accuracy of duration judgment also during the longer standards, which are typically beyond that of the TIM limit. These results suggest that the influence of TIM is unnoticed when conventional time units are used (production). It can be concluded that interval production is not the proper method to study the capacity of TIM. It seems interesting to note that in our study the Pearson correlations between the reproduced and produced estimates provided by particular subjects were significant for the majority of applied intervals. It implies that there are common factors underlying the duration judgment for these two methods. This conclusion supports the hypothesis postulating that there are similar cognitive factors (e.g., attention, working memory) underlying these two methods of duration judgment (Fortin 1999, Zakay and Block 1997). Thus, our data sheds some new light on the common view that "absolute" methods of duration judgment (e.g., production) are distinct from "relative" methods (e.g., reproduction).

The next question is whether the use of conventional time units can be changed as a result of normal chronological aging. Experimental evidence indicates the slowing of the rate of information processing as the most pronounced symptom of cognitive aging (e.g., Salthouse 1985, 1991). It appears to be accompanied by a slowing of many cognitive functions (Block et al. 1998). Several theorists have proposed that this prolongation might be also associated with the lower speed of the biological pacemaker, e.g., a decrease in the number of "ticks" occurring per unit time (Block et al. 1998, Craik and Hay 1999, Fraisse 1963). This hypothesis still remains controversial (see also below), as the existing literature on aging and duration judgment is clearly limited.

It is a common observation that people usually report that larger time units (such as days, months or years) seem to pass more rapidly as they aged (Fraisse 1963). One of the possible explanations of this subjective acceleration of time passage is that older people may use their total subjective time as a frame of reference when assessing the speed of time passing during these time units. A majority of laboratory studies indicated that older participants, compared with younger ones, produce shorter intervals than requested durations because they either underestimate the real time more or overestimate it less than younger adults (for a review see Wearden et al. 1997). An important piece of evidence concerning aging and duration judgment comes from the meta-analysis performed by Block et al. (1998), who searched data on duration judgment published in the literature between 1923 and 1997. They found, in general, that compared with younger adults older persons gave shorter productions and larger verbal estimates, but they made comparable reproductions. The results concerning production and verbal estimation are opposite to the proposal put forward by some theorists who anticipated the slowing of the pacemaker as a result of chronological aging. In fact, a slower pacemaker should lengthen the time production, and thus yield the opposite pattern of relationships than that reported in the meta-analysis by Block and co-workers (1998). These authors concluded that probably in older people the pacemaker runs faster and perhaps they produced shorter intervals as a result of overcompensation for a slower pacemaker. This statement is still not adequately verified in the literature.

To investigate further age-related changes in time production, in our recent investigations we compared the accuracy of performance in young adults (aged 19-25 years) and elderly participants (aged 65-67 years). They produced durations ranging from 1 to 60 s, filled with the presentation of a 300 Hz tone. In general, we did not find any age differences in the accuracy of production. In both groups the subjects made slightly longer productions than the requested intervals for all durations applied in our study. It may be concluded that both younger and older people are equally skilled in using classical time units, thus, the use of these units seems not to change during approx. forty years of our life (from the age of 19 up to 67 years of life). However, according to the assumption proposed by Block et al. (1998) and by Wearden et al. (1997) it would be difficult to interpret our results referring to a similar speed of a hypothetical pacemaker in younger and older people. The elderly participants might learn to recalibrate their response, considering potential changes in the pacemaker speed, thus, some units may be identified with fewer ticks than previously. Such an assumption can be supported, to some extent, by the relatively high level of cognitive abilities observed in subjects included into both groups investigated in our study, and moreover, by the lack of significant between-group differences in these abilities. The young participants scored on average in the 79th percentile and the older ones the 87th percentile in Raven's progressive matrices. Further support for our interpretation concerning the lack of age differences in interval production can be provided by Snowden et al. (1996), who indicated that clever brains probably age more slowly (cf. Rabbit et al. 2003).

To summarize our considerations concerning time judgment, we provide some new evidence on the dissociation between the methods of temporal reproduction and production. The use of conventional time units (seconds) in duration judgment (production) improved the accuracy of performance in the case of standards that are beyond those of the typical time frames characteristic for TIM. Both the younger and older people investigated in our studies seemed to be comparably skilled in using classical time units. This result needs future extensive studies, which focus on the influence of the cognitive abilities in particular age groups on the accuracy of production, as well as the rate of a hypothetical pacemaker, using various experimental methods.

THE HIGH–FREQUENCY PROCESSING LEVEL

The existence of the high-frequency processing level has been known for a long time to play an important role in human TIP. This level is well documented with results from experiments using different paradigms, e.g., choice reaction time, latency of eye movements, midlatency responses of the auditory evoked potentials or execution of simple movements (for reviews see Pöppel 1994, 1997, Wittmann 1999). These data have supported the notion of temporally discrete information processing within an approximately 30 ms time window. According to the Pöppel's model of time perception, the high-frequency processing system is probably created by neuronal oscillations with a frequency of approx. 25-40 Hz triggered by stimuli. Each period of such oscillations reflects an elementary processing unit (a system state) of a duration of ca. 30 ms. The periodicity of neuronal oscillations might be modified by a hypothetical pacemaker. A higher pacemaker rate would lead to shorter periods of temporal oscillations. At a theoretical level, it was hypothesized that two events occurring within one such a system state are treated as co-temporal and are integrated into one unit, thus, the relationships between these events with respect to the dimension before/after cannot be established.

Considerable information on the nature of the high-frequency processing level is provided by experiments on the perception of temporal order (TO). In these experiments subjects are exposed to a succession of two events with a short inter-stimulus interval (ISI), and are required to evaluate the order of these events within the sequence. The data shows that depending on the duration of the applied ISI, people are often not able to report the TO correctly. The minimum time interval between two stimuli successively presented that is required to identify correctly the order of these stimuli is defined as the temporal order threshold (TOT). A number of experiments have shown that the typical TOT is about 20-60 ms (Mills and Rollman 1980, von Steinbüchel et al. 1999a,b, Wittmann and Fink 2004). The TOT may be influenced by many procedure-related factors, e.g., the spatial location of sensory stimuli, the features by which stimuli differ or the duration of each stimulus presented in a sequence (Jaskowski 1996, Swisher and Hirsh 1972, Tallal et al. 1998, von Steinbüchel et al. 1999a,b).

The TOT appears to have a similar value for different sensory modalities (visual, auditory, tactile), suggesting a common central mechanism responsible for the perception of TO of events (Hirsh and Sherrick 1961, Pöppel 1994, 1997). The similarity of TOT for the visual and auditory systems was also reported in our investigations (Kanabus et al. 2002).

Cross-modal comparisons

In our experiment students reported the TO of either two auditory (tones of 300 and 3 000 Hz presented for 15 ms to both ears through headphones) or two visual stimuli (pulses of red or green light presented for 15 ms to both eyes). The auditory and visual stimuli were presented in a rapid succession with an ISI that varied randomly from 5 to 500 ms.

In general, the level of performance was similar for these two modalities. The minimum time interval necessary to report the TO with an accuracy of at least 75% correct was reached at ISIs longer than 40 ms, independently of the stimulus modality. This finding is in accordance with results of previous studies on cross-modal comparisons for the perception of TO. It indicates that both the auditory and visual systems may be constrained by a central temporal mechanism which operates within a defined time window, responsible for the perception of TO of events (Kanabus et al. 2002).

However, we found an interesting relationship: at the shortest ISI (5 ms) a significantly higher level of accuracy was observed for the auditory task when compared to the visual one. Such a tendency was observed up to ISIs of 40 ms. The more accurate auditory processing may result from peripheral influences, namely different transduction mechanisms at the level of receptive cells in each modality. The shorter transduction in the auditory system than in the visual one has an apparent influence on the availability of events arriving from these two systems at a hypothetical "temporal central comparator". Accordingly, the shorter transduction is probably related to the higher temporal resolution of the auditory system than the visual one, which was reflected in our experiment by the higher level of correctness at very short ISIs. It seems also possible that in the auditory system the short transduction may foster a specific strategy to form an apparent complex pattern consisting of a low and high tone, which form a 'perceptual construct', despite the use of the typical temporal ordering strategy.

Thus, on one hand, the 75% level of correctness reached for both modalities for ISIs longer than 40 ms indicates the existence of a common mechanism underlying these two tasks. On the other hand, the peripheral influences can modify the perception of TO for the case of ISIs shorter than 40 ms.

Biological aging

The next question to consider is whether there are age-related differences in a subjects' ability to perceive TO. As was already mentioned in one of the previous sections, it is well known that a slowing of information processing accompanies cognitive aging (e.g., Salthouse 1985, 1991). In order to test the effect of normal chronological aging on the perception of TO, we studied three age groups, consisted of young, older and very old subjects, aged between 19-25, 65-67 and above 100 years, respectively (Kolodziejczyk and Szelag, unpublished results). It should be noted that only the results of women are reported here, because the number of men in the oldest group was not sufficient for data analysis. The subjects included into the two younger groups were within the normal limit of cognitive abilities (Raven Progressive Matrices), whereas all centenarians obtained a score of at least 17 points in the Mini Mental State Examination. The participants were asked to report the TO of two consecutive auditory stimuli (15 ms tones of 300 Hz frequency), presented to the right or left ear in a rapid succession with various ISIs.

There was no significant difference in the level of performance between young and older adults. In contrast, the centenarians showed much poorer perception of the TO than each of younger groups for most of the ISIs from 10 to 300 ms. Moreover, a 75% level of correctness was achieved in young women at the ISI of about 60 ms, for elderly participants at above 80 ms, whereas centenarians needed ISIs between 150-300 ms to attain this level of performance.

The deterioration in the performance of the TO task found in centenarians may be caused by a slowing of information processing as is observed in old age in many domains. It might also be explained on the basis of the potential decrease in the speed of a hypothetical pacemaker, which results in poorer temporal resolution. As was mentioned earlier, longer elementary processing units (system states), which are implemented by the lower rate of the pacemaker, might cause the information to be treated as co-temporal for longer time spans than for the case of shorter processing units. Referring to our earlier considerations on the slowing of the pacemaker rate (compare above), this hypothesis is controversial and requires further investigation.

The lack of differences between young and older women contradicts the results of some studies concerning the effect of aging on the perception of TO. In these studies it was found that older subjects had difficulty with an auditory sequencing task, indicating the likelihood of age-related dysfunction of central perceptual auditory processing (Fitzgibbons and Gordon-Salant 1998). However, in these studies age-related differences were found only for relatively complex three-tone sequences containing a bi-directional frequency shift, but for simple unidirectional tonal patterns the differences were lacking. The latter situation corresponds to that in our study, where only two tones were applied, so only the unidirectional spatial shift (left-right or right-left) was possible. Moreover, the relatively high intelligence level in the older people tested in our study (about 80th percentile) could help them to maintain their cognitive skills, despite their advanced age (compare the above section).

In summary, our results suggest that the ability to perceive the TO seems to be relatively stable in the two younger groups, thus, across the life span from approx. 19 to 67 years of life, but is significantly reduced in very old age. The question arises as to at which age a serious deterioration in TIP at the high frequency level starts.

Gender differences

Although differences between men and women in various cognitive tasks are still disputed in the literature, much less attention has been paid to gender differences in TIP at the high-frequency level. In fact, there are few reports on this topic; in many studies the gender differences are not taken into account.

For example, Rammsayer and Lustnauer (1989), who studied the time bisection task for auditory standards in the milliseconds range, found that the minimum time interval necessary to detect the difference between the durations of these standards was shorter in men than in women. Also Geffen et al. (2000) found that in a tactile task men were able to distinguish between simultaneity vs. nonsimultaneity for shorter ISIs than women. This finding was interpreted as a better temporal resolution in men. Moreover, Lotze et al. (1999) in the experiment on auditory TOT found a lower TOT in men than in women; however, in this experiment only 6 men and 6 women were tested.

In our studies the gender differences in TIP at the high-frequency level were investigated with an experiment in which students reported the order of two auditory stimuli exposed *via* headphones in rapid succession with various ISIs (Kolodziejczyk and Szelag 2003). We used interhemispheric stimulus presentation, so both stimuli had identical acoustic parameters (two 15 ms tones of 300 Hz) and were presented one tone to each ear. In this situation the TO could be identified in space (left or right ear first).

The results showed that the level of accuracy was higher in men than in women. Moreover, the minimum time interval necessary to indicate correctly the TO with an accuracy of at least 75% correct was reached with a shorter ISIs in men (around 40 ms) than in women (around 60 ms). These relationships indicate that distinct auditory events require a shorter separation in men than in women to identify the TO correctly.

A similar relationship was established in our clinical investigations (Wittmann and Szelag 2003) in which we re-analyzed the results of our earlier studies (von Steinbüchel et al. 1999a,b) to find out whether men and women in the aforementioned studies differ in their ability to perceive the TO of two events. Participants were patients (aged 20-70 years) with focal-brain injury after infarction in either the left or right hemisphere or subjects without any damage of the central nervous system. The TOT was assessed as the minimum interval between two 1 ms clicks, presented consecutively through headphones (one to each ear) for which the participants could indicate correctly (at 75% level of correct responses) the order of these clicks (left or right ear first). We consider here only the gender differences; the effect of the specific brain lesions is discussed in the next section (cf. von Steinbüchel et al. 1999a,b).

In general, the results showed that men needed shorter ISI than women to indicate correctly the TO of these clicks. Thus, the results of our experiments carried out on both students and brain-lesioned patients suggest a lower TOT in men than in women. This finding is in accordance with predictions that could be made on the basis of data published in the literature cited above. It can be explained based on several hypotheses (for a detailed discussion see Wittmann and Szelag 2003). First, a higher pacemaker rate (shorter periods of temporal oscillations) may lead to a better temporal resolution (Rammsayer and Lustnauer 1989), hence, a higher accuracy in the perception of TO. If men are characterized by such a higher clock rate, they may detect TO correctly at shorter ISIs. Second, men may be characterized by faster transmission of information because of the greater proportion of white matter (myelinated connective tissue) in male brain (Geffen et al. 2000, Gur et al. 1999). Third, the more global strategy of problem solving used typically by men (Kimura 1992, 1999) may improve their performance in such a task. Using this strategy, identification of sequence is based on whole stimulus pattern recognition without the need to recognize precisely each individual stimulus in a sequence (Fitzgibbons and Gordon-Salant 1998). Future research is needed to verify factors responsible for a lower TOT in men than in women.

The neuroanatomical substrates of the perception of TO

In the existing literature there is strong evidence for the association of TIP with language functions. The mechanism underlying temporal ordering is strongly related to speech comprehension, especially for the perception of phonemes (phonemic hearing). Spectrographic analyses showed that stop consonants, like "k", "g", "b", etc., have a defined duration restricted to ca. 40 ms. The rapid changes in the formant frequencies observed during the articulation of these consonants occur within about 40 ms (Fitch et al. 1997, Tallal et al. 1998). The similar value of TOT and the average durations of stop-consonants may suggest a similar neuronal mechanism, which governs both language and TIP at the high-frequency level. A survey of the clinical literature has consistently reported that the temporal cortex of the left hemisphere is probably responsible for the perception of TO (e.g., Swisher and Hirsh 1972). A similar conclusion can be drawn from our clinical studies in which we investigated the effect of unilateral focal brain damage on the perception of TO in right-handed patients with pre- and postcentral lesions in the left and right hemisphere and in individuals without any damage to the nervous system (von Steinbüchel et al. 1999a,b).

The TOT was assessed as the minimum interval between two 1 ms clicks presented consecutively through headphones (one to each ear) for which the participants could indicate correctly the order of these clicks. The results of these studies showed that patients with left-hemisphere postcentral lesions suffering from Wernicke's aphasia showed prolonged TOT to more than 100 ms, compared to approx. 60 ms in the control group. These deficits were accompanied by the impaired detection of single phonemes and words in speech reception. Interestingly, patients suffering from Broca's aphasia, characterized mainly by nonfluent effort speech were unaffected in the TOT task (Szelag and Pöppel 2000). This observation points to a dissociation between the TIP at the high-frequency level and the kind of aphasia: Wernicke's aphasics who demonstrated disordered auditory comprehension and phonemic hearing were parallelly affected in the perception of TO, whereas Broca's aphasics showing preserved comprehension and phonemic hearing remained unaffected in this TOT task. Thus, the ability to perceive the TO of events is differentiated depending on the kind of aphasic syndrome demonstrated (cf. Szelag et al. 1997).

These results support the thesis that Wernicke's area within the temporal cortex of the left hemisphere constitutes the neuronal substrate of sequencing abilities for both verbal and non-verbal information within the time window of some tens of ms. These findings point to a neuroanatomical association between language processing and temporal ordering of events. It is worth noting that parallel deficits in both the language and temporal domains were observed in the other studies on speech-disordered populations, i.e., aphasic patients, children with language-learning impairments and dyslexic individuals (Eden et al. 1995, Tallal et al. 1996, 1998).

Cochlear implantation

In the previous section we presented accumulated data indicating that people with language disorders of various etiologies demonstrated parallel deficits in speech reception and in the perception of TO for non-verbal stimuli. It was of particular interest to investigate whether a similar relationship can be observed also for the case of comprehension deficits of the other etiology. We focused on postlingually deafened adults after cochlear implantation (Kanabus et al. 2003). These experiments were designed to gain a greater understanding of the relationship between language and TIP at the high-frequency level. As mentioned in the previous section, the restoration of auditory comprehension after such an operation develops after post-operative auditory training (Tyler 1993) and its success may depend on many factors, e.g., the type of implanted device.

In our experiment we tested postlingually deafened adults after either a multichannel implantation (MED-EL Combi 40 and Combi 40+) or a monochannel one (MED-EL Comfort). In the former group, the level of auditory comprehension was higher (the group mean score = 83.7%, the mean score in particular patients from 63 to 98% of speech understanding) than in the latter group (the group mean score = 48.6%, the mean score in particular patients from 23 to 75%). The subjects were requested to report the order of two 15 ms tones (of 300 and 3 000 Hz), presented in the free acoustic field in rapid succession with ISIs ranging from 10 to 500 ms. We analyzed the mean percent of correct responses for each ISI and also the ISI at which the order was detected with an accuracy of at least 75% correct responses.

In monochannel CI users, the level of performance was significantly poorer than in controls. Nearly all ISIs patients achieved a lower percentage of correctness than subjects with normal hearing. Also patients did not achieve a 100% correct response level even for the longest ISI applied here, whereas controls were able to achieve this level for the two longest ISIs (300 and 500 ms) applied in our study. Moreover, patients needed an ISI longer than 80 ms to achieve the 75% level of correctness, whereas in controls this level was observed at ISI of 40 ms. In contrast, there was no difference in performance between multichannel CI users and subjects with normal hearing. Both groups achieved a 75% level of correctness at ISIs longer than 40 ms and a 100% correctness level for the two longest ISIs (300 and 500 ms).

Thus, the deficits in auditory TO judgment found in monochannel CI users were not observed in multichannel recipients. These deficits can be related to difficulties in speech comprehension in the time domain of some tens of milliseconds, which corresponds to the duration of phonemes in the fluent speech. In monochannel CI users deficits on this level are accompanied by poor auditory comprehension. There is a lack of such deficits in multichannel CI recipients, who showed much better comprehension in comparison with monochannel CI users. The results of the present experiment provide another example of the co-existence of TIP deficits and language deficits.

CONCLUSIONS

To summarize the results of the many experiments presented in the present review, it becomes clear that TIP is not a simple phenomenon. We would like to emphasize that our studies confirmed the existence of two different processing systems that are governed by different neuronal mechanisms: one of them operating in the range of milliseconds, the other one in the domain of a few seconds. TIP on these two levels can be influenced by different factors, for instance: cognitive development in ontogenesis, cognitive decline during chronological aging, severe developmental disorders, cochlear implantation in postlingually deafened adults and acquired brain damage. As these factors do not account for all our findings, a detailed discussion of the processes underlying time-related behavior would require another extensive review.

It should be noted that the results of our studies showed that language disorders of different etiologies can be related to atypical TIP. These language deficits concerned not only single units of language – phonemes (corresponding with the high-frequency processing level), but also fluent speech on the level of words and sentences (the low-frequency level). The question, which should be answered in our recent research, is whether the atypical performance of language-disordered individuals on temporal tasks could be improved by the specific temporal training. The further question is whether the improvement in the trained temporal domain can be transferred into the untrained language domain. The first attempts have been made to train children with language-learning impairment in their ability to process temporal information (Tallal et al. 1996, 1998). Of our primary interest is obtaining converging evidence on the success of such training during speech therapy for different language disorders.

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