

Temporal order judgement for auditory and visual stimuli

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Abstract. The ability to perceive temporal order for pairs of auditory and visual stimuli was investigated in 12 volunteers. They were asked to make judgements about the order of presented stimuli by pressing two response buttons in a certain order. The performance on auditory and visual tests was studied in relation to the Inter-Stimulus-Interval (ISI), which varied from 5 to 500 ms. In general, the level of performance was similar for the two modalities and the criterion of 75% of correct responses was reached at ISI longer than 40 ms, independently of the modality. These findings are consistent with previous research. However, at ISI of 5 ms, a significantly higher level of correctness was observed for the auditory than visual task. Such a tendency was also observed for ISIs of 10, 20 and 40 ms. Better processing in the auditory compared to the visual task at shorter ISIs may result from a different kind of transduction mechanism at the level of receptive cells in each modality. Alternatively, subjects may use two different kinds of response strategies in the auditory modality, only one being comparable to the response strategy in the visual modality.

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INTRODUCTION

A number of experimental studies have provided evidence that the minimal inter-stimulus-interval (ISI) between two successive stimuli for correctly reporting their temporal order is about 20-40 ms (Hirsh and Sherrick 1961, Pöppel 1997). This order threshold (OT) appears to be remarkably invariant for auditory, visual, tactile and two-modality stimuli in normal subjects (Hirsh and Sherrick 1961, Swisher and Hirsh 1972). Such a perceptual phenomenon is probably due to a central mechanism responsible for temporal ordering, which is independent of the sensory stimulus itself, the temporal cortex of the left hemisphere probably being responsible for temporal order judgement (TOJ), (e.g., Efron 1963a, Tallal et al. 1998, von Steinbüchel et al. 1999a and b).

If the TOJ ability is governed by the same mechanisms across different sensory modalities, then patients with language deficits following brain damage may be expected to demonstrate general, cross-modal deficits in sequencing abilities. Although the majority of studies on TOJ in the language-impaired population was limited to auditory perception (e.g., Lackner and Teuber 1973, Sherwin and Efron 1980, Robin et al. 1989, Tallal et al. 1996, von Steinbüchel et al. 1999a and b), it appears that such patients do not always demonstrate deficits in TOJ for different sensory modalities. For example, Paula Tallal and her co-workers in a series of studies (Tallal and Piercy 1973, Tallal et al. 1981, Tallal et al. 1998), using temporal sequences presented in one spatial location, clearly showed that, in dysphasic children, aphasic adults or dyslexics, specific rapid temporal processing deficits are restricted to auditory modality, whereas visual processing is characterised by a normal rate. It has been suggested that an impairment in auditory temporal processing might underlie certain language problems (Tallal et al. 1996, von Steinbüchel et al. 1999a and b). In contrast, other reports using temporal sequences separated in space have suggested that dysphasic children or aphasic adults have difficulties in sequencing for both visual and auditory stimuli (Doering 1960, Efron 1963a and b, Stark 1966, Poppen et al. 1969, Swisher and Hirsh 1972). These cross-modal deficits were attributed to a specific perceptual disability in the processing of rapidly presented sequential stimuli.

It is remarkable that the studies of Tallal and co-workers (Tallal and Piercy 1973, Tallal et al. 1981,

Tallal et al. 1996, Tallal et al. 1998) are focussed more on differences between language-learning-impaired children and controls and less on studying the character of the neural mechanism underlying TOJ in normal-healthy individuals. These experiments were designed to properly detect the temporal order with the accuracy at least 75% of correct responses in the control group even at an ISI of 8 ms, thus, at the shortest ISI applied in their experiments.

Although a full explanation of discrepancies with respect to uni- vs. cross-modal impairments in dysphasia is still lacking, some hypotheses attempting to explain these disagreements seem promising (e.g. Tallal et al. 1981). For example, the effect of age in language-learning-impaired children was postulated. Moreover, many experimental studies reported the influence of the applied experimental procedure (Swisher and Hirsh 1972, Stelmach and Herdman 1991). The results in normal subjects have indicated that the OT, usually situated in a time domain of approx. 20 to 40 ms, is dependent on stimulus parameters. Lower thresholds (correctly reported order at shorter ISIs) were characteristic when two stimuli varied in both quality and spatial location (i.e. two tones presented one to each ear / two light flashes exposed in different positions in the visual field), whereas, higher thresholds when the same position was stimulated (Swisher and Hirsh 1972). Moreover, the OTs can also be influenced by the duration of a single stimulus presented in succession – lower thresholds (ca. 8 ms) were found for relatively long stimuli (tones of 40 ms duration, e.g. Tallal et al. 1998), whereas, higher thresholds (ca. 20 up to 60 ms) for 1 ms clicks (Pöppel 1978, Mills and Rollman 1980, von Steinbüchel et al. 1999a). Thus, there exists substantial evidence supporting the hypothesis that many components may contribute to the judgement required by temporal ordering, e.g., spatial location of sensory stimuli and features by which stimuli differ (Swisher and Hirsh 1972, Jaśkowski 1996), luminance profile (Jaśkowski 1993), stimulus dimension (McFarland et al. 1998), attention directed to one stimulus and away from the other stimuli (Stelmach and Herdman 1991, Zackon et al. 1999, Jaśkowski and Verleger 2000), and inhibitory mechanisms (Gibson and Egeth 1994).

Moreover, the different sensory systems are characterised by principally different mechanisms of transduction. As a consequence, the time course of transduction is also different. Whereas transduction in the visual modality takes approx. 30-40 ms (Woodworth and Schlosberg

1954, Pöppel 1988), it lasts considerably shorter (approx. 2 ms) in the auditory modality (Eggermont 1979, Ryuggero 1992, 1994). Such a difference has an apparent effect on the temporal central availability of events from these two systems. The question is how the similar OT value could be achieved for these two sensory domains? Specifically, how the performance for shorter ISIs is influenced by the stimulus modality? Such a problem was a neglected topic in the existing literature.

In light of these observations it appears that the role of stimulus modality remains unexplored. The present study is an attempt to investigate whether similar temporal constraints of nonverbal sequencing abilities in two different sensory modalities characterise normal subjects. Using a methodology similar to the one originally employed by Tallal and co-workers (e.g. Tallal and Piercy 1973), we provide more detailed information on the nature of temporal information processing in the visual and auditory systems in naive volunteers.

METHODS

Subjects

Twelve students aged 20–25 years (6 males, 6 females) participated in the experiment. They had normal hearing and vision, no signs of daltonism (Velhagen Tables, Velhagen and Broschmann 1997), were right-handed as verified by the Edinburgh Handedness Inventory (Oldfield 1971), had no signs of left-handedness during development, and there was no incidence of left-handedness in their families. All subjects were within the normal limit of cognitive abilities (Raven Standard Progressive Matrices). They had no history of neurological disorders nor did they use any medication affecting the central nervous system. Subjects were required to provide informed consent prior to participation in the study.

Stimuli

Auditory stimuli consisted of two "square" tones presented for 15 ms binaurally (to both ears) through headphones at a comfortable listening level. Tones were presented in succession with different ISIs. Tone 1 had a frequency of 300 Hz and Tone 2 of 3000 Hz. A third complex tone was used as a warning signal. Stimuli were generated by a 16-bit Sound Blaster Card. Tone 1

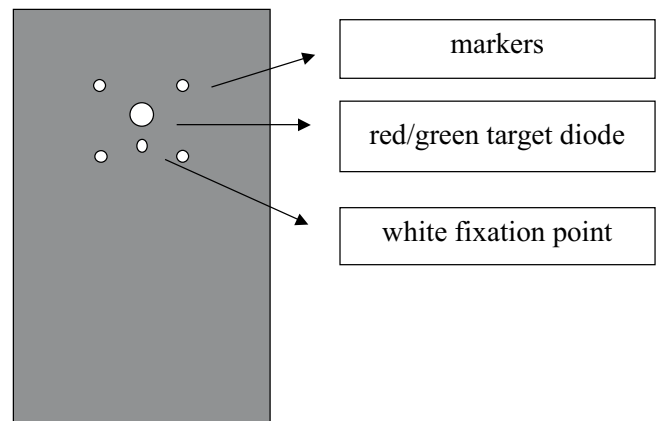


Fig. 1. The panel used in the visual test.

and 2 were adjusted to equal loudness using the method of competent judges (Heffner and Heffner 1992). Accordingly, in the preliminary series, four judges evaluated two presented tones to select the pair of equal loudness.

Visual stimuli were two 15 ms "square" pulses of light (red or green), generated by a convertible light emitting diode and exposed under binocular (to both eyes) viewing conditions. The lights were, thus, flashed in the same location in the visual field and presented in succession with different ISIs. The diode was placed at eye level on a black panel (29.8 x 54.5 cm) in the centre of a rectangle area delimited by four markers (small orange diodes). A white fixation point was permanently located below the target diode (Fig. 1). At a viewing distance of 126 cm, the target diode, the fixation point and the distance between the diode and the fixation point subtended 0.23 degrees each, the marked rectangle corresponded to 1.27 degrees vertically and 1.82 degrees horizontally. The luminance level of the red diode was 1.1 cd/m², the green one 0.7 cd/m², whereas that of the markers 2.9 cd/m².

Procedure

The experiment was conducted in a soundproof chamber. Each subject was tested individually. The subject sat at the table in front of the panel. The task was to report the order of two tones (auditory test) or of two lights (visual test) presented in a rapid succession with ISIs of 5, 10, 20, 40, 80, 150, 300 or 500 ms. The responses were given by pressing with the right index finger the two buttons in order of stimulus presentation.

These identical depressible buttons were mounted one above the other on a metal response box (12.5 x 25.5 cm), located on the table in front of the subject. The upper button corresponded to the higher tone (auditory test) or with the red light (visual test); the lower button with the lower tone or green light. The subject could also press a third button (also located on the response box) if he was unable to identify the order and perceived the stimuli as presented simultaneously.

Consecutive stimulus pairs were separated by 2 s inter-trial-intervals. Each pair was preceded with a 11 ms warning signal (a complex tone in the auditory test or four markers in the visual test) presented 900 ms before the onset of the first stimulus. Additionally, in the visual test the subjects were asked to concentrate on the fixation point after the warning signal.

The visual and auditory stimuli were presented in two different experimental sessions lasting approximately 30 min each. The sessions were controlled by the same computer program. Each session consisted of 64 trials. In half of trials, the 3,000 Hz tone or the green light was given first, whereas in the other half the 300 Hz tone or the red light was given first. During each session, 8 presentations of 8 different ISIs were randomly ordered. The OT was assessed in terms of the ISI at which the order was detected with an accuracy of at least 75% correct responses (Tallal et al. 1998).

The proper experiment was preceded by preliminary experimental sessions similar to those applied in the proper experiment. In these series the conditions of stimulus exposure in visual and auditory tests were adjusted (changing the luminance of the diode with photo-

graphic filters) to equate the level of performance for these two modalities as much as possible.

The experimental protocol

Table I summarises the procedure of testing. At the beginning of each test, subjects were trained to respond to each single separate stimulus (a tone or a coloured light) by pressing the proper response button. Next, discrimination training was performed. Sequences of 2 stimuli were exposed with an ISI of 500 ms and subjects were trained to respond to a 2-element stimulus pattern by pressing the buttons in the correct order. This training was continued until a criterion of 20 correct responses in a series of 24 consecutive trials was reached ($P < 0.001$, Binomial Test). Following an additional period of 20 practice trials with ISIs from 5 to 500 ms presented randomly, the experiment was begun.

RESULTS

The Mean Percent of Correct Responses (MPCR) was analysed for each ISI and stimulus modality. The values were submitted to a four-way analysis of variance (ANOVA). The design included "modality" (auditory, visual), "ISI" (8 various levels), "stimulus sequence" (Tone1-Tone2 vs. Tone2-Tone1 in the auditory test or green-red vs. red-green in the visual test) as within-subject variables and "sex" (men, women) as a between-subject variable. After the analysis, to determine the sources of significance, the Newman-Keuls test was applied to both within- and between-subject comparisons.

Table I

Experimental design for auditory and visual tests						
Order of sessions	Number of applied stimuli	Number of elements in stimulus pattern	ISI (ms)	Stimulus duration (ms)	Number of trials	Task
1	2	1	-	15	20	Discrimination between stimuli 1 and 2
2	2	2	500	15	To criterion*	Motor response to 2-element stimulus pattern
3	2	2	Random** (5-500)	15	20	Motor response to 2-element stimulus pattern
4	2	2	Random*** (5-500)	15	64	Motor response to 2-element stimulus pattern

*, 20 correct responses in 24 consecutive trials; **, training trials; ***, experimental trials.

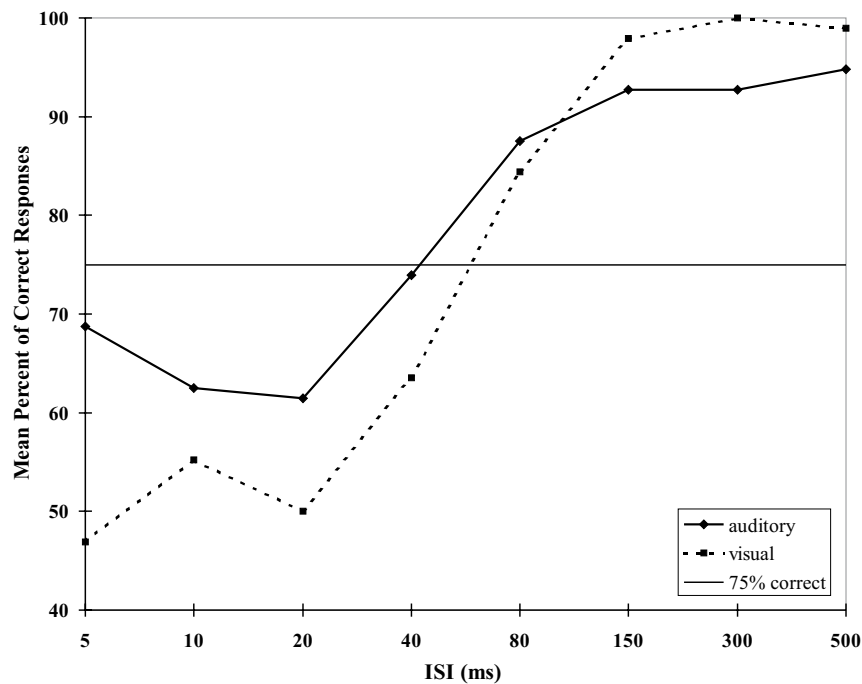


Fig. 2. Mean Percent of Correct Responses for auditory and visual stimuli. The following differences were proven to be significant: for auditory stimuli $P < 0.05$ between 40-80 ms; for visual stimuli $P < 0.01$ between 40-80 ms; auditory vs. visual $P < 0.01$ for 5 ms).

The analysis yielded a significant "ISI" main effect ($F_{7,70}=47, P < 0.000$) whereas "sex", "modality" and "stimulus sequence" were nonsignificant. The two-way interaction: "modality" by "ISI" ($F_{7,70}=3.4, P < 0.03$) proved significant. Other interactions were nonsignificant.

MPCR increased systematically with increasing ISI and the subjects reached a criterion of 75% correct at an ISI of approx. 40 ms, independently of the stimulus modality, stimulus sequence and sex (Fig. 2).

The interaction, "modality" by "ISI", probably resulted from a significantly higher MPCR level ($P < 0.01$) for ISI of 5 ms for auditory (68.8%) than visual modality (46.9%). The cross-modal comparisons for the other ISIs remained nonsignificant. Although the tendency for better performance for the auditory than visual test might also be observed for ISIs between 10-40 ms, the additional ANOVA using 7 various levels of ISI (between 10-500 ms, excluding 5 ms) showed nonsignificant interaction "modality" by "ISI" ($F_{6,60}=2.04, P < 0.15$). Within-modality comparisons showed a significant improvement in MPCRs for ISIs between 40 and 80 ms ($P < 0.05$ and $P < 0.01$ for auditory and visual tests, respectively). As can be seen in Fig. 2, the sharp jump of MPCR values corresponds with achieving a cri-

terion of 75% correct responses for both auditory and visual tests.

DISCUSSION

The results of the present study show that the minimal time interval necessary to indicate the correct temporal order (above 75% of correct responses) of 2 acoustic or 2 visual events is above 40 ms. Thus, independently of the sensory modality, distinct events require a temporal separation longer than 40 ms to be perceived as successive. This finding confirms the results observed in previous studies, cited in the Introduction. Although it is difficult to equate the auditory and visual stimulus pairs in complexity or difficulty, OTs reflect a time-organising system that is independent of peripheral sensory mechanisms and corresponds to the lower temporal limit for event identification.

Pöppel (1971, 1997) has suggested one possible explanation on the neural basis of TOJ. According to his hypothetical model of time perception, the brain creates endogenously elementary processing units, or "atemporal" system states, within which incoming information is treated as co-temporal. Such system states

are probably implemented by relaxation-type neuronal oscillations with a duration of ca. 30-40 ms (Pöppel 1970). Each period of such oscillations represents one elementary processing unit (one system state). At a theoretical level, it is postulated that two events occurring within one such system state are treated as co-temporal, thus, a relationship between the two stimuli with respect to the "before / after" dimension cannot be identified. "Atemporal" system states with a duration of 30-40 ms provide the logistical basis for the identification of elementary events and succession. This operating range has been assessed in a variety of studies using different paradigms, e.g., choice reaction time (Pöppel 1970, Jokeit 1990), latency of eye movements (Pöppel and Logothetis 1986) and auditory evoked potentials (Galambos et al. 1981, Schwender et al. 1994). There also exist, of course, a number of perceptual phenomena that are characterised by other time constants than the operating level advocated here, e.g., 2-3 seconds range (Pöppel 1994, Mates et al. 1994, Szeląg 1997, Kagerer et al. 2002, Szeląg et al. 2002) or 300 ms range (Loveless et al. 1996, Wittmann et al. 2001).

The crucial problem to be considered here concerns cross-modal comparisons in TOJ. It should be noted that 75% level of correct responses often applied in literature as the theoretical level of correctness constitutes rather an approximate level (Tallal et al. 1998). For longer ISIs (Fig. 2), the results of particular subjects oscillate around this level because of the individual differences, typically observed in the visual and auditory tests. However, the significant within-modal improvement of correctness between ISIs of 40 and 80 ms (vision: $P < 0.01$ vs. audition: $P < 0.05$) as well as the lack of significant between-modal differences for ISIs of 40 and 80 ms, suggest the similar OT mechanism underlying sequencing abilities for both vision and audition. In the light of the foregoing, there is rather a weak probability that smaller ISI steps in the critical time range (from 40 to 80 ms) could show significant modality differences (extrapolation of lines drawn in Fig. 2). However, one could anticipate that the theoretical 75% level of correct responses may be reached a bit earlier in auditory than in visual test.

Although the intensity of the visual stimuli was comparable to that of the auditory ones (nonsignificant "modality" main effect), the significant interaction "modality" by "ISI" may be caused by peripheral influences. Referring to papers cited in the Introduction, the auditory system is characterised by much shorter transduction time than the visual system. Such

an influence was pronounced by the significant between-modal difference ($P < 0.01$, Fig. 2) at the shortest applied ISI, moreover, by a tendency for the ISIs of 10, 20 and 40 ms, where the MPCR for the visual test still remains at the chance level (Fig. 2).

According to the general threshold model (Ulrich 1987, Stelmach and Herdman 1991), TOJs depend on the arrival time of the sensory information at a hypothetical "temporal comparator". Such an arrival time depends on different parameters, e.g., transduction time or transmission latencies of the information from the receptor to a comparator (Pöppel 1988, Stelmach and Herdman 1991). Given equal onset times, the visual stimulus usually appeared to arrive after the auditory one (Chocholle 1940-1941, Pöppel 1988) because of the longer transduction time. Thus, in the visual system, the second stimulus probably arrives at the receptor while the transduction of the first one is still not completed. As a consequence, it may result in a lower MPCR for visual than auditory tasks. These peripheral influences seem especially pronounced for the shortest ISI applied here (Fig. 2). Similar kind of influences are reported for temporal resolution i.e. perception of simultaneity vs. nonsimultaneity. Usually the ISI required to perceived two events as presented nonsimultaneously is longer for vision than audition (Pöppel 1978, 1994).

The other question is why this difference is significant only for the shortest ISI. It may be hypothesised that same subjects may use another strategy to indicate temporal order by integrating two auditory stimuli for short ISIs such, that an apparent complex pattern consisted of low and high frequency or from high and low one is perceptually constructed, suggesting to the subject which stimulus must have come first or second. The shorter transduction time for auditory than visual modality may foster such a strategy for shorter ISIs.

The relatively long OT values reported here (above 40 ms) are in accordance with the results of previous studies in which subjects performed best when the presented stimuli varied in both quality and spatial location and poorest when two stimuli achieved the same place. It should be noted that, in the present experiment, the stimuli were presented without any spatial separation (tones exposed binaurally, diode lamps located in one place). These conditions of stimulus exposure may predict relatively higher OT values.

It remains still an open question whether the rapid temporal processing deficits observed in dysphasic children or in aphasic adults are restricted to audition only,

or are also present for other sensory systems. The present experiment cannot answer this question; further empirical studies in different language pathologies are necessary.

It should also be noted that the determination of the nature of sequencing abilities is a fundamental issue in neuroscience because it may have important practical implications. In previous reports, it was shown that the highly prolonged OT associated with language deficits can be ameliorated by the specific temporal training (von Steinbüchel 1991, Merzenich et al. 1996, Tallal et al. 1996). It is also remarkable that the cross-modal transfer of improvements in temporal discrimination between a trained somatosensory condition to untrained auditory condition was reported by Nagarajan et al. (1998), as well as between audition and vision, attributable to training in audition (Rousseau et al. 1983). These results confirm that discrimination of temporal information across different sensory systems may operate *via* a similar central temporal mechanism within a specific "temporal window".

CONCLUSIONS

Distinct events require a temporal separation longer than 40 ms to be perceived as successive, independently of the sensory modality. The significant between-modal difference at shorter ISIs may be caused by different transduction times in the visual and auditory system or by using different response strategies in the visual and auditory tests.

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REFERENCES

- Chocholle R. (1940-1941) Variation de temps de reaction auditifs en fonction de l'intensité à diverses frequences. L'Année Psychologique 41/42: 65-124.
- Doehring D.G. (1960) Visual spatial memory in aphasic children. J. Speech Hear. Res. 3: 138-149.
- Efron R. (1963a) The effect of handedness on the perception of simultaneity and temporal order. Brain 86: 261-284.
- Efron R. (1963b) Temporal perception, aphasia and déjà vu. Brain 86: 403-423.
- Eggermont J.J. (1979) Narrow band AP latencies in normal and recruiting human ears. J. Acoust. Soc. Am. 65: 463-470.
- Galambos R., Makeig S., Talmachoff P.J. (1981) A 40-Hz auditory potential recorded from the human scalp. Proc. Natl. Acad. Sci. U S A 78: 2643-2647.
- Gibson B.S., Egeth H. (1994) Inhibition and disinhibition of return: Evidence from temporal order judgements. Percept. Psychophys. 56: 669-680.
- Heffner H.H., Heffner R.S. (1992) Auditory perception. In: Farm animals and the environment (Eds. P. Clive and D. Piggins). CAB International, Walingford, UK, p. 139-184.
- Hirsh I.J., Sherrick C.E. (1961) Perceived order in different sense modalities. J. Exp. Psych. 62: 423-432.
- Jaśkowski P. (1993) Temporal-order judgment and reaction time to stimuli of different rise times. Perception 22: 963-970.
- Jaśkowski P. (1996) Simple reaction time and perception of temporal order: dissociations and hypotheses. Percept. Mot. Skills 82: 707-730.
- Jaśkowski P., Verleger R. (2000) Attentional bias toward low-intensity stimuli: an explanation for the intensity dissociation between reaction time and temporal order judgement? Conscious Cogn. 9: 435-456.
- Jokeit H. (1990) Analysis of periodicities in human reaction times. Naturwissenschaften 77: 289-291.
- Kagerer F., Wittmann M., Szélag E., von Steinbüchel N. (2002) Cortical involvement in temporal reproduction: evidence for differential roles of the hemispheres. Neuropsychologia 40: 357-366.
- Lackner J.R., Teuber H.-L. (1973) Alterations in auditory fusion thresholds after cerebral injury in man. Neuropsychologia 11: 409-415.
- Loveless N., Levänen S., Josumäki V., Sams M., Hari R. (1996) Temporal integration in auditory sensory memory: neuromagnetic evidence. Electroencephalogr. Clin. Neurophysiol. 100: 220-228.
- Mates J., Müller U., Radil T., Pöppel E. (1994) Temporal integration in sensorimotor synchronization. J. Cogn. Neurosci. 6: 332-340.
- McFarland D.J., Cacace A.T., Setzen G. (1998) Temporal-order discrimination for selected auditory and visual stimulus dimensions. J. Speech Lang. Hear. Res. 41: 300-314.
- Merzenich M.M., Jenkins W.M., Johnston P., Schreiner C., Miller S.L., Tallal P. (1996) Temporal processing deficits of language-learning impaired children ameliorated by training. Science 271: 77-81.
- Mills L., Rollman G.B. (1980) Hemispheric asymmetry for auditory perception of temporal order. Neuropsychologia 18: 41-47.

- Nagarajan S.S., Blake D.T., Wright B.A., Byl N., Merzenich M.M. (1998) Practice-related improvements in somatosensory interval discrimination are temporally specific but generalize across skin location, hemisphere and modality. *J. Neurosci.* 18: 1559-1570.
- Oldfield R.C. (1971) The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* 9: 97-113.
- Poppen R., Stark J., Eisenson J., Forrest T., Wertheim G. (1969) Visual sequencing performance of aphasic children. *J. Speech Hear. Res.* 12: 288-300.
- Pöppel E. (1970) Excitability cycles in central intermittency. *Psychol. Forschung* 34: 1-9.
- Pöppel E. (1971) Oscillations as possible basis for time perception. *Studium Generale* 24: 85-107.
- Pöppel E. (1978) Time perception. In: *Handbook of sensory physiology* (Eds. R. Held, H. Leibowitz and H.-L. Teuber). Berlin, Springer-Verlag, p. 713-729.
- Pöppel E. (1994) Temporal mechanisms in perception. *Int. Rev. Neurobiol.* 37: 185-202.
- Pöppel E. (1988) *Mindworks. Time and conscious experience.* Harcourt Brace Jovanovich, Boston.
- Pöppel E. (1997) A hierarchical model of temporal perception. *Trends Cogn. Sci.* 1: 56-61.
- Pöppel E., Logothetis N. (1986) Neuronal oscillations in the brain. Discontinuous initiations of pursuit eye movements indicate a 30-Hz temporal framework for visual information processing. *Naturwissenschaften* 73: 267-268.
- Robin D.A., Tomblin B., Kearney A., Hug L.N. (1989) Auditory temporal pattern learning in children with speech and language impairments. *Brain Lang.* 36: 604-613.
- Rousseau R., Poirier J., Lemyre L. (1983) Duration discrimination of empty time intervals marked by intermodal pulses. *Percept Psychophys.* 59: 119-128.
- Ryuggero M.A. (1992) Response to sound of the basilar membrane of the mammalian cochlea. *Curr. Opin. Neurobiol.* 2: 449-456.
- Ryuggero M.A. (1994) Cochlear delays and travelling waves, comments on experimental look at cochlear mechanisms. *Audiology* 33: 131-142.
- Schwender D., Madler C., Klasing S., Peter K., Pöppel E. (1994) Anaesthetic control of 40-Hz brain activity and implicit memory. *Conscious Cogn.* 3: 129-147.
- Sherwin I., Efron R. (1980) Temporal ordering deficits following anterior temporal lobectomy. *Brain Lang.* 11: 195-203.
- Stark J. (1966) Performance of aphasic children on the ITPA. *Except. Child.* 33: 153-158.
- Stelmach L.B., Herdman C.M. (1991) Directed attention and perception of temporal order. *J. Exp. Psych.* 17: 539-550.
- Swisher L., Hirsh I.J. (1972) Brain damage and the ordering of two temporally successive stimuli. *Neuropsychologia* 10: 137-152.
- Szelag E. (1997) Temporal integration of the brain as studied with the metronome paradigm. In: *Time, temporality, now.* (Eds. H. Atmanspacher and E. Ruhnau) Springer Verlag, Berlin Heidelberg, p. 121-131.
- Szelag E., Kowalska J., Rymarczyk K., Pöppel E. (2002) Duration processing in children as determined by time reproduction; implications for a few seconds temporal window. *Acta Psychol.* 110: 1-19.
- Tallal P., Piercy M. (1973) Developmental aphasia: impaired rate of non-verbal processing as a function of sensory modality. *Neuropsychologia* 11: 389-398.
- Tallal P., Stark R., Kallman C., Mellitis D. (1981) A reexamination of some nonverbal perceptual abilities of language-impaired and normal children as a function of age and sensory modality. *J. Acoust. Soc. Am.* 24: 351-357.
- Tallal P., Miller S.L., Bedi G., Byma G., Wang X., Nagarajan S.S., Schreiner C., Jenkins W.M., Merzenich M.M. (1996) Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science* 271: 81-84.
- Tallal P., Merzenich M.M., Miller S., Jenkins W. (1998) Language learning impairments: integrating basic science, technology, and remediation. *Exp. Brain Res.* 123: 210-219.
- Ulrich R. (1987) Threshold models of temporal-order judgments evaluated by a ternary response task. *Percept. Psychophys.* 42: 224-239.
- Velhagen K., Broschmann D. (1997) *Tafeln zur prüfung des farbennnes.* Georg Thieme Verlag, Stuttgart.
- von Steinbüchel N., Pöppel E. (1991) Temporal order threshold and language perception. In: *Frontiers in knowledge-based computing.* Narosa Publishing House, p. 81-90.
- von Steinbüchel N., Wittmann M., Szelag E. (1999a) Temporal constraints of perceiving, generating, and integrating information: Clinical indications. *Restor. Neurol. Neurosci.* 14: 167-182.
- von Steinbüchel N., Wittmann M., Strasburger H., Szelag E. (1999b) Auditory temporal order judgement is impaired in patients with cortical lesions in posterior regions of the left hemisphere. *Neurosci. Lett.* 264: 168-171.
- Wittmann M., von Steinbüchel N., Szelag E. (2001) Hemispheric specialisation for self-paced motor sequences. *Brain Res. Cogn. Brain Res.* 10: 341-344.
- Woodworth R.S., Schlosberg H. (1954) *Experimental Psychology.* London, Methuen.
- Zackon D.H., Casson E.J., Zafar A., Stelmach L., Racette L. (1999) The temporal order judgement paradigm: subcortical attentional contribution under exogenous and endogenous cueing conditions. *Neuropsychologia* 37: 511-520.