
Article II

Temporal regularity effects on pre-attentive and attentive processing of deviance

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Keywords: ERP, oddball, attention, timing, regularity

Abstract

Temporal regularity allows predicting the temporal locus of future information thereby potentially facilitating cognitive processing. We applied event-related brain potentials (ERPs) to investigate how temporal regularity impacts pre-attentive and attentive processing of deviance in the auditory modality. Participants listened to sequences of sinusoidal tones differing exclusively in pitch. The inter-stimulus interval (ISI) in these sequences was manipulated to convey either isochronous or random temporal structure. In the pre-attentive session, deviance processing was unaffected by the regularity manipulation as evidenced in three event-related-potentials (ERPs): mismatch negativity (MMN), P3a, and reorienting negativity (RON). In the attentive session, the P3b was smaller for deviant tones embedded in irregular temporal structure, while the N2b component remained unaffected. These findings confirm that temporal regularity can reinforce cognitive mechanisms associated with the attentive processing of deviance. Furthermore, they provide evidence for the dynamic allocation of attention in time and dissociable pre-attentive and attention-dependent temporal processing mechanisms.

1. Introduction

Continuous change is a fundamental characteristic of life. Changes generate temporal structure or events in time, with effective behavior depending in part on the temporal coherence of cognition, action, and these events. The key to temporal coherence is adequate timing, i.e., the ability to be in the right place at the right time. Timing and temporal organization are not only crucial in overt behavior but also in cognitive processes and the allocation of cognitive resources (Fuster, 2001). How do neurocognitive processes cope with the temporal structure of the environment to achieve adequate timing in cognition and action? Adequate timing implies some internal representation of temporal structure. It is unclear though whether temporal structure is processed implicitly, or whether an explicit representation of temporal structure is generated by dedicated temporal processing systems (Buonomano, 2007; Ivry and Schlerf 2008). Some neurofunctional models suggest that dedicated temporal processing is a function of classical motor systems of which the cerebellum is involved in pre-attentive, short-range, event-based temporal processing, and the basal ganglia are engaged in attention-dependent, longer-range, interval-based temporal processing (Ivry, 1996; Lewis and Miall, 2003; Spencer et al., 2003; Buhusi and Meck, 2005). A benefit that may arise from the explicit processing and the evaluation of temporal structure is to recognize and prospectively use temporal regularity. This would allow to predict the temporal locus of future events and to allocate attention towards important aspects of information. Expectations and prior knowledge about upcoming information should entail optimized timing in cognition and action even if the use of temporal structure is subconscious and unintentional, i.e., if temporal processing is exogenous (Nobre et al., 2007; Coull and Nobre, 2008).

The proposed dissociation of pre-attentive and attention-dependent temporal processing systems offers a starting point to further characterize the underlying processes. In this context, important issues concern (1) the moment at which attention affects temporal processing, (2) whether temporal structure can be processed without adopting strategies for estimating time (Grondin, 2001), and (3) how attention is allocated and maintained in the presence of acoustic, and hence inherently temporal, signals. Early on, Bolton (1894) emphasized that attention appears discontinuous and intermittent, and that it manifests in a wave-like form or a series of pulses. Consequently, some form of adaptation deems necessary to align the internal fluctuation

of the attentional focus with the temporal structure of external events. With respect to the auditory domain, one important aspect in this interplay could be the bias of the auditory system to search for regularities in sensory input (Winkler et al., 2009). Although continuously changing, the temporal structure of the environment is not arbitrary. Any perceived regularity in temporal structure can indicate a pattern. Temporal patterns emerge in both the environment and in the allocation of attention (Jones and Boltz, 1989). This transient temporal stability in combination with predictive processing is fundamental for optimal anticipatory timing in cognition and action. This notion is expressed in Dynamic Attending Theory (DAT; Jones and Boltz 1989; Large and Jones, 1999). DAT proposes that internal attending rhythms synchronize with external event structure. This mechanism may be relevant to dissociate pre-attentive from attention-dependent temporal processing mechanisms. Ongoing processing of relatively stable temporal relations instantiates a repetitive process which can be conceived of as an instance of oscillatory activity. Oscillatory activity and interactions between different oscillations caused by appropriate external or internal stimulation constitute another fundamental characteristic of life (Glass, 2001). Their interplay represents an inherent property of both, living things and the activity of attending (Jones and Boltz, 1989). As such, oscillatory mechanisms provide a realistic computational basis to model the “adaptation to change by anticipation” (Fraisse, 1963, pp. 18). DAT proposes that one or more attention oscillations entrain to the rate and rhythm of external events (Large and Jones, 1999), i.e., adaptive oscillations lock into the temporal structure of the stimulation, thereby establishing synchronized processing. If confronted with a change in temporal structure, the oscillations adjust their phase and period in order to maintain or to reestablish synchronization. The result of this process is stimulus-driven attending (Barnes and Jones, 2000). DAT provides a framework capable of explaining how temporal structure guides attention on a moment-to-moment basis and temporal dependencies within a pattern, i.e. the possible influence of preceding temporal structure on subsequent temporal processing, and the influence of global temporal context (McAuley and Miller, 2007).

In the current study we used ERPs to investigate the impact of regular and irregular temporal structure on the pre-attentive and attentive processing of change by means of auditory oddball sequences. An oddball sequence consists of more (standard) and less (deviant) frequent events, with the deviant event violating some rule established by the standard. Pre-attentive and attentive processing of this deviation is associated with distinct sets of endogenous ERPs. With

respect to the former we focus on mismatch negativity (MMN), P3a, and reorienting negativity (RON), and with respect to the latter on N2b and P3b.

In combination, MMN, P3a, and RON form the “distraction potential” (Escera and Corral, 2007). The MMN has a fronto-central scalp distribution and is elicited in response to a discriminable change in auditory stimulation compared to a repetitive aspect of preceding stimuli retained in short-term memory (Näätänen et al., 1978; Näätänen, 2007; Garrido et al., 2009). Usually the MMN peaks around 100 to 200 ms after the presentation of the deviant event. It reflects pre-attentive processing of sensory information as events in time, including auditory duration discrimination (Näätänen et al., 2004; Näätänen, 2007). The term MMN has largely replaced the classification of this component as a subcomponent of the N2 under the N2a label (Folstein and van Petten, 2008). The P3a is a fronto-centrally distributed positive deflection evoked by task-irrelevant salient events (Linden, 2005), whereas the later fronto-central RON reflects restoration of the task-optimal selective attention set following distraction by task-irrelevant events (Schröger and Wolff, 1998). However, although these components are related to the processing of deviant changes in the environment they can be elicited independent of each other (Horváth et al., 2008).

With respect to attention-dependent processing we concentrate on another fronto-central N2 subcomponent, the N2b, associated with the attentive detection of a deviant event, and the P3b, which typically peaks around 300 ms after the presentation of a deviant event. Like the P3a, the more centro-parietal P3b is part of the P300 complex (Polich and Criado, 2006; Volpe et al., 2007). However, each P3a is accompanied by a smaller P3b and vice versa (Linden, 2005). The P3b is commonly related to a task-relevant alteration of a mental model of the environment, a stimulus-driven attention mechanism, and memory processing (Linden, 2005; Polich, 2007). The goal of the current study was to investigate how the contrast between regular, and therefore highly predictable temporal structure, and irregular temporal structure would modulate the aforementioned ERP components associated with various aspects of the processing of deviance. In line with DAT, regular temporal structure was expected to narrow the attentional focus and to promote synchronization, whereas irregular structure should widen the attentional focus and promote reactive attending (Jones et al., 2002). We consider the ERP modulation as an index for the quality of stimulus-driven synchronization, the dynamic allocation of attention, and the quality of cognitive processes associated with the processing of deviant events. Specifically, we

hypothesize that attention-dependent recognition of temporal regularity and the subsequent use of this information to predict upcoming events results in an enhanced amplitude of the N2b and P3b components in response to deviants embedded in regular temporal structure relative to those embedded in irregular temporal structure. This enhancement should be similar for the pre-attentive processing of change, and the distraction potential, i.e., MMN, P3a, and RON, only if the underlying mechanism is also sensitive to temporal regularity. Alternatively, if attention-dependent temporal processing is necessary to exploit regularity, pre-attentive temporal processing should not benefit from temporal regularity. In this case the distraction potential should be resistant against the manipulation.

2. Materials and Methods

2.1 Participants

Twenty-four right-handed volunteers (12 females) participated in the study. Ages ranged from 19 to 30 years (mean: 24.4; SD: 2.8 years). All participants were students at the University of Leipzig and were recruited via the database of the Max-Planck Institute for Human Cognitive and Brain Sciences in Leipzig. None of the participants reported any neurological dysfunction or a hearing deficit at the time of testing. All participants gave their written informed consent and received a compensatory fee. The study was approved by the ethics committee of the University of Leipzig.

2.2 Stimulus presentation, EEG recording, and ERP analysis

The stimulus material consisted of two equidurational (300 ms; 10 ms rise and fall) sinusoidal tones. The tones were used to generate a temporally regular, i.e. isochronous, and a temporally irregular, i.e. random, auditory oddball sequence. The latter was created by varying the duration

of the inter-stimulus-interval (ISI) between individual tones. Whereas the ISI was 600 ms in the isochronous sequence, it was randomly assigned from a range between 200 and 1000 ms (normally distributed around an average 600 ms) in the random sequence. These specific parameters were chosen in order to take into consideration the privileged status of simple integer ratios and intervals lasting about 600 ms (Fraisse, 1982; Essens, 1986; Martin et al., 2007). An average SOA of 900 ms is still within the range of optimal tempo sensitivity (Drake and Botte, 1993), as well as the synchronization range (Fraisse, 1982). Thus, stimulus, ISI, and SOA intervals ranged from 300 to 1000 ms. The boundary between short-range and attention-dependent longer-range temporal processing mechanisms is commonly associated with values close to 1000 ms (Buhusi and Meck, 2005; Lewis and Miall, 2006). However, the mechanism underlying attention-dependent temporal processing is probably sensitive to intervals ranging from hundreds of milliseconds to seconds (Meck et al., 2008).

The two tones differed in frequency (600 Hz for standards, and 660 Hz for deviants (Fig 1)). Each oddball sequence comprised 512 standard and 128 deviant tones, corresponding to a total of 640 tones and a standard-to-deviant ratio of 4:1.

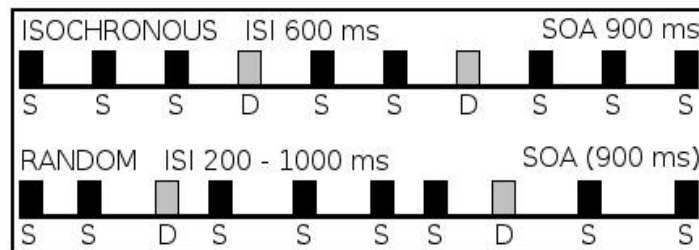


Fig.1. Stimulus sequences. Exemplary sections of isochronous and random stimulus sequences consisting of standard (S) and deviant (D) sinusoidal tones. SOA = stimulus onset asynchrony. The figure in parentheses indicates the global average across the random sequence.

Presentation 12.0 (Neurobehavioral Systems) running on a Windows PC was used to create the pseudorandomized oddball sequence and to present the stimuli via two loudspeakers. Pseudorandomization ensured that no more than two deviant events could appear in a row. The 600 ms ISI in the isochronous sequence resulted in a 1:2 ratio for the duration of the filled stimulus intervals and the empty ISI intervals. The order of these sequences was pseudo-

randomized across participants. After the presentation of the first sequence, participants were given a 5 min. break. The experiment was split into two sessions on two consecutive days. All participants started with the pre-attentive session followed by the attentive session to preclude familiarity effects.

The EEG procedure was identical in both sessions. During the EEG recording participants sat in a sound-attenuated booth in front of a monitor. Ag/AgCl electrodes mounted in an elastic cap according to the 10-20 International system were used to record the EEG from 59 scalp sites with a sampling rate of 500 Hz. An anti-aliasing filter of 135 Hz was applied. Online reference was placed on the left mastoid and the sternum served as ground. Besides the EEG, horizontal and vertical electrooculography were recorded. Electrode impedance was kept below 5 k Ω . EEP 3.2 (Max-Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany) was used to process the data. All data were re-referenced offline to averaged mastoids. Prior to subsequent analyses, EEG epochs lasting from 100 ms pre-stimulus onset to 450 ms post-stimulus onset were scanned by an automatic algorithm to reject eye movements, blinks, muscle artifacts, and electrode drifting. Trials exceeding 30 μ V (eye channels) or 40 μ V (CZ) were rejected. An additional manual rejection of trials containing artifacts or electrode drifting was performed after visual inspection. All epochs of events corresponding to the presentation of a standard after a deviant as well as a deviant following another deviant were generally rejected. Remaining epochs were averaged for each participant and for the whole group.

Statistical analyses were performed using SAS 8.20.20 (SAS Institute Inc., Cary, USA) for subsets of electrodes in six regions of interest. These regions included left-anterior (AF7, AF3, F9, F7, F5, F3), left-central (T7, C5, C3, TP7, CP5, CP3), left-posterior (P7, P5, P3, PO7, PO3, O1), right-anterior (AF8, AF4, F10, F8, F6, F4), right-central (T8, C6, C4, TP8, CP6, CP4), and right-posterior (P8, P6, P4, PO8, PO4, O2) electrode sites. Based on visual inspection and preparatory timeline analyses on mean amplitudes for consecutive windows of 25 ms from stimulus onset up to 450 ms post-stimulus onset, 100 – 200 ms MMN, 225 – 325 ms P3a, and 325 – 450 ms RON windows were selected for the subsequent statistical main analyses for the pre-attentive session, while 125 – 225 ms N2b and 250 – 450 ms P3b windows were selected for the attentive session. Timeline analyses consisted of separate 2 x 2 x 2 x 3 ANOVAs with factors type (isochronous vs. random), condition (standard vs. deviant), hemisphere (left vs. right) and region (anterior vs. central vs. parietal) for each 25 ms window.

2.3 Tasks

In the pre-attentive session, participants were asked to watch a silent video clip (Deep Blue, 2003) and to fill out a short questionnaire about the video after the session. Prior to testing, participants were told that they should concentrate on the video and to ignore any auditory input. In contrast, participants were asked to concentrate on the tonal sequences and to silently count the deviants embedded in each sequence while fixating an asterisk displayed on the monitor during the attentive session. Participants reported the result of counting after each sequence. Thus, while the sequences themselves were attended to, explicit attention to temporal structure was not task-relevant. Rather, temporal structure served as an implicit attractor for attention-dependent temporal processing. An additional sequence of eight tones, including five deviants, was appended to each random sequence in order to avoid identical numbers of deviants in each sequence. These additional tone sequences were excluded from all ERP analyses.

3. Results

3.1 Pre-attentive session

The percentage of correct answers given in the questionnaire after the pre-attentive session was 84.38 (SD 16.17), indicating that participants did indeed pay attention to the content of the video clip. Both isochronous and random oddball sequences evoked reliable MMN, P3a, and RON ERPs (Fig. 2 A and B).

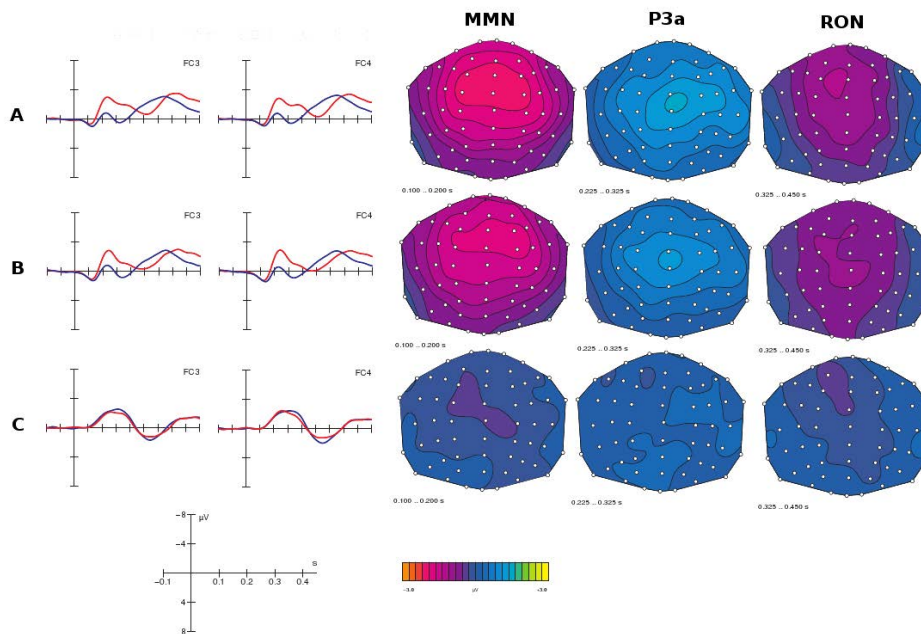


Fig 2. Pre-attentive session. Averaged EEG responses for standards (blue) and deviants (red) at two fronto-central electrodes in the pre-attentive session complemented by MMN, P3a, and RON scalp distributions for isochronous (A) and random (B) temporal structure. Differences waves and difference distributions contrast ERP effects for isochronous (blue) and random (red) temporal structure (C).

To ensure that each sequence elicited the desired components, all ERPs of interest were analyzed in separate $2 \times 2 \times 3$ ANOVAs with the factors condition (standard vs. deviant), hemisphere (left vs. right), and region (anterior vs. central vs. posterior). Where required, Greenhouse-Geisser correction was applied to the results reported in the following. In the isochronous sequences, there was a main effect of condition in the MMN ($F(1,23) = 53.51, p < .01$), the P3a ($F(1,23) = 10.20, p < .01$), and the RON ($F(1,23) = 6.12, p < .03$) time-window. In the MMN time-window we observed a significant two-way interaction of condition and region ($F(2,46) = 14.22, p < .01$), indicating that the condition effect was strongest at anterior sites ($F(1,23) = 60.76, p < .01$). In the random sequences we observed a similar pattern for condition in the MMN ($F(1,23) = 55.52, p < .01$), the P3a ($F(1,23) = 6.34, p < .02$), and the RON ($F(1,23) = 13.19, p < .01$) time-window. Again, there was a significant interaction in the MMN window of condition and region

($F(2,46) = 14.22, p < .01$), revealing that the effect was strongest at anterior sites ($F(1,23) = 49.40, p < .01$).

For the direct comparison of the effects obtained with isochronous and random temporal structure, we calculated difference waves by subtracting standard from deviant ERP responses. All subsequent analyses were performed on these difference waves. In contrast to random temporal structure, visual inspection suggested slightly more negative and positive effects as a function of isochronous temporal structure for the MMN and the P3a, respectively (Fig. 2 C). However, contrasting the effects by means of $2 \times 2 \times 2$ ANOVAs with factors type (isochronous vs. random), hemisphere (left vs. right), and region (anterior vs. central vs. posterior) only conformed an effect of region ($F(2,46) = 15.23, p < .01$), but not of type ($F(1,23) = .31, p = .58$) and no significant interaction. To further validate this finding, we narrowed the critical time window down to 50 ms and centered it in the optimal range (125 – 175 ms). However, this procedure did not change the initial result, type ($F(1,23) = 1.37, p = .25$). The same type of ANOVA was conducted for the P3a and the RON time-window, none of which yielded significant results. Narrowing the critical range for the P3a time-window to 250 – 300 ms did not change this outcome. Thus, we did not observe a significant influence of temporal regularity on the cognitive mechanisms underlying the pre-attentive processing of the deviant events.

3.2 Attentive session

One-sample t-tests yielded no significant differences between the individual values reported by the participants in the counting task and the actual number of deviants embedded in the isochronous (actual number: 128; mean result: 128.21, SD: 4.35; $t(1,23) = .23, p = .81$) and in the random (actual number: 133; mean result: 133.25, SD: 4.48; $t(1,23) = .27, p = .79$) sequence. These results confirmed that participants indeed paid attention to the tonal sequences. The same type of $2 \times 2 \times 3$ ANOVA as for the pre-attentive session was conducted to test for the presence of the ERPs of interest in the attentive session (Fig. 3 A and B).

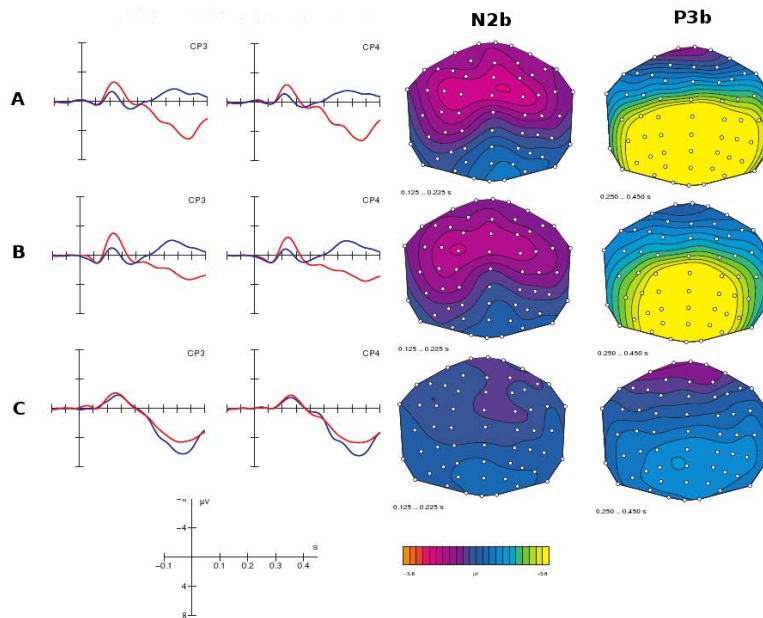


Fig 3. Attentive session. Averaged EEG responses for standards (blue) and deviants (red) at two centro-parietal electrodes in the attentive session complemented by N2b and P3b scalp distributions for isochronous (A) and random (B) temporal structure. Differences waves and difference distributions contrast ERP effects for isochronous (blue) and random (red) temporal structure (C).

Both the isochronous and the random oddball sequence elicited significant N2b and P3b components. In the N2b time-window we obtained significant effects of condition in the isochronous ($F(1,23) = 4.29, p < .05$) and in the random ($F(1,23) = 6.32, p < .02$) sequence. In both sequence types interactions of condition and region ($F(2,46) = 14.90, p < .01$; $F(2,46) = 13.14, p < .01$) indicated that the effect was present at anterior ($F(1,23) = 7.17, p < .02$; $F(1,23) = 8.75, p < .01$) and at central sites ($F(1,23) = 8.80, p < .01$; $F(1,23) = 12.26, p < .01$). The effect of condition emerged also in the P3b window in isochronous ($F(1,23) = 58.14, p < .01$) and random sequences ($F(1,23) = 42.77, p < .01$). An interaction of the factors condition and region in both sequences ($F(2,46) = 79.10, p < .01$; $F(2,46) = 63.48, p < .01$) indicated that the effect of condition was present at central sites ($F(1,23) = 78.77, p < .01$; $F(1,23) = 48.35, p < .01$), but that it was stronger at posterior sites for isochronous ($F(1,23) = 98.07, p < .01$) and random sequences ($F(1,23) = 67.17, p < .01$).

Again, difference waves were calculated for the subsequent comparison of the isochronous and the random sequence. In the N2b time-window, direct comparison of the ERP effects obtained with isochronous and random stimulation (Fig. 3 C) yielded neither a significant effect of type ($F(1,23) = .38, p = .55$) nor a significant interaction involving this factor. Narrowing the critical window to 175 – 225 ms did not change this result, type ($F(1,23) = .08, p = .78$).

While the main effect of type was not significant in the P3b time-window ($F(1,23) = 1.92, p = .18$), there was a significant interaction of type and region ($F(2,46) = 7.94, p < .01$). Type approached significance at central sites ($F(1,23) = 3.99, p = .058$), but was significant at posterior sites ($F(1,23) = 4.76, p < .04$) confirming a larger P3b effect in isochronous than in random sequences.

4. Discussion

In the current study we investigated the impact of temporal regularity on ERPs associated with pre-attentive and attentive processing of auditory deviant events. The applied experimental paradigms reliably elicited MMN, P3a, RON, N2b, and P3b components. Regular temporal structure resulted in a larger attention-dependent P3b effect relative to irregular temporal structure. The results support the dissociation of pre-attentive and attention-dependent temporal processing mechanisms. Furthermore, they confirm concepts of a dynamic allocation of attention put forward in DAT (Large and Jones, 1999).

In the pre-attentive session, we did not observe a substantial impact of temporal regularity on three ERP components reflecting different aspects of deviant event processing. Unlike previous studies which used a limited number of SOAs (two or three) and report an effect of temporal regularity on MMN amplitude (Imada et al., 1993; Takegata and Morotomi, 1999; Moberget et al., 2008), the current study used online randomization, i.e. no predefined set of SOAs, to generate irregular temporal structure. Takegata and Morotomi (1999) conclude that increasing the number of SOAs in a sequence, not irregular timing, is the reason for the observed influence, as different SOAs may strengthen different memory traces. This hints at a qualitative difference between previous studies and the current study. Whereas continuous presentation of many stimulus repetitions with a limited number of predefined and well distinguishable SOAs

may evoke different, albeit weaker, memory traces, online randomization in the current study was only limited by temporal range, which in turn may prove temporal structure unreliable and dispensable. Crucially, in this latter case successive stimuli may still strengthen the same memory trace. However, even the random sequence conveys some regularity, as the sequential presentation of similar events in a specific time-window constitutes a form of regularity in itself. Thus, the question arises, how repetitive presentation of predefined temporal structure (“the SOA is either short or long”) compares to relative temporal structure (“the SOA is 900 ms on average”) in generating a random sequence, and how this difference affects deviance processing. With independently varied ISIs and SOAs, Takegata et al. (2001) found a larger MMN for constant temporal structure in comparison to either constant ISI, constant SOA, or neither constant conditions, but no difference between the latter. However, deviant events in this study were tones being presented “too early”, thereby merging temporal structure and deviance levels. By using frequency deviants we separated deviance from temporal structure. Nevertheless, for the MMN and the P3a, but not the RON, visual inspection suggested slightly more pronounced effects for deviants embedded in the isochronous sequence. However, this difference was not statistically significant. Morphological differences and the presence of a significant RON for regular and irregular contexts may indicate short episodes of attention-dependent temporal processing in the pre-attentive session following distraction by a task-irrelevant deviant event. Correspondingly, one can not completely rule out episodes of divided attention between the tonal stimuli and the silent video clip. Yet, processing of the deviant events in the pre-attentive session was neither significantly facilitated nor hindered by the temporal manipulation employed in this study. When contrasted with the results from the attentive session, this indifference bears implications for temporal processing and the allocation of attentional resources. When task instructions required to not attend to the auditory stimuli, an internal representation of temporal structure may still be encoded via pre-attentive temporal processing. Correspondingly, we did not find an indication of stimulus-driven synchronization in the pre-attentive session. Decoding of such internal representation of temporal structure and the recognition of temporal regularity likely require additional attention-dependent temporal processing routines such as duration discrimination of successive intervals (Meck et al., 2008). Once a pattern has been recognized, subsequent processing should be facilitated as it allows predicting the temporal locus of future events, to focus attention on specific information, and to initiate behavior anticipatorily.

During the early stages of auditory processing it is probably more relevant to rapidly detect events and to generate precise internal representations of temporal structure. This may be necessary to encode temporal detail before this information becomes erratic due to long neural transmission lines and numerous synapses (Adams, 2006). This function may involve the cerebellar temporal processing system and its connections to the earliest stages of auditory processing (Petacchi et al., 2005). The auditory cortex may keep reference to the immediate auditory past and future (Nääätänen et al., 2001), probably processing temporal regularity without depending on it. This would explain the robustness of the pre-attentive ERPs against the temporal manipulation. Furthermore, given that temporal irregularity or deviation from a temporal pattern may represent important information in itself, the initial processing should be comparable, independent of whether the input indeed conveys regularity or whether it is irregular. In contrast, we observed an influence of temporal regularity in the attentive session. Whereas the earlier N2b effect remained unaffected, the later P3b effect was significantly larger for deviant events embedded in isochronous context. In line with DAT, this may reflect stimulus-driven synchronization of attention that leads to facilitation in cognitive processing. Furthermore, this dissociation hints at a difference in the time-course of the underlying processes. With respect to the moment at which attention affects temporal processing, these results speak for an impact of attention on later mechanisms relative to those represented in the earlier N2b. The influence of attention-dependent temporal processing is hence not reflected in the detection of deviant events. It becomes apparent in subsequent memory processing and model updating, possibly referring to successful memory storage in order to facilitate retrieval and recognition (Polich, 2007). These processes may involve the ongoing evaluation of an interval-based representation of temporal inter-event relations in order to track regularity. Interestingly, the cortical generators of the P3b include the temporo-parietal junction and the inferior parietal lobe (Linden, 2005), an area that is also associated with implicit temporal processing (Coull and Nobre, 2008; Wiener et al., 2010). Furthermore, at this stage, temporal and memory processing may draw upon the same prefrontal capacities (Lustig et al., 2005; Lewis and Miall, 2006).

The observed influence of temporal regularity in the attentive session was independent of explicit attention to time or an explicit estimation of time. As long as attention was directed towards the auditory stimuli, temporal structure was processed and exploited without estimating time. The current results thereby offer an example for the interplay of top-down, task-specific

attention and stimulus-driven attending in order to guide attention along a sequential stimulation. In line with previous findings (Schmidt-Kassow et al., 2009) the P3b should hence be considered as an index for the quality of stimulus-driven synchronization. The specific pattern of results suggests that the attentive detection of a deviant event functions independent of temporal regularity, whereas subsequent processes benefit from temporal predictability of the stimulus sequence. We were able to show that temporally regular stimulus presentation (the “when” aspect of sensory input) supports the attentive processing of formal stimulus characteristics (the “what” aspect of sensory input). Although the current experiment restricted the formal aspect to a single difference in pitch, we expect this principle to be effective in other modalities and in complex settings such as music and speech processing (Kotz and Schwartz, 2010). This in turn may hint at a predisposition for constant attempts to synchronize cognition and action to perceived regularity in the succession of changes in the environment.

5. References

- Adams, J.C., 2006. Neuroanatomical considerations of speech processing. In S. Greenberg, W. Ainsworth (Eds.). *Listening to speech: an auditory perspective* (pp 79 – 90). Lawrence Erlbaum Associates, Mahwah.
- Barnes, R., Jones, M.R., 2000. Expectancy, attention, and time. *Cognitive Psychology* 41, 254-311.
- Bolton, T.L., 1894. Rhythm. *Journal of Psychology* 6, 145-238.
- Buhusi, C.V., Meck, W.H., 2005. What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews Neuroscience* 6, 755-765.
- Buonomano, D.V., 2007. The biology of time across different scales. *Nature Chemical Biology* 3, 594-597.
- Coull, J.T., Nobre, A.C., 2008. Dissociating explicit timing from temporal expectation with fMRI. *Current Opinion in Neurobiology* 18, 137-144.
- Drake, C., Botte, M.C., 1993. Tempo sensitivity in auditory sequences: evidence for a multiple-look model. *Perception & Psychophysics* 54, 277-286.

- Escera, C., Corral, M.J., 2007. Role of mismatch negativity and novelty-P3 in involuntary auditory attention. *Journal of Psychophysiology* 21, 251-264.
- Essens, P.J., 1986. Hierarchical organization of temporal patterns. *Perception & Psychophysics* 40, 69 – 73.
- Folstein, J.R., van Petten, C., 2008. Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology* 45, 152-170.
- Fraisse, P., 1982. Rhythm and tempo. In D. Deutsch (Ed.). *The psychology of music* (pp. 149 – 180). Academic Press, New York.
- Fraisse, P., 1963. *The psychology of time*. Harper & Row, New York.
- Fuster, J.M., 2001. The prefrontal cortex – an update: time is of the essence. *Neuron* 30, 319-333.
- Garrido, M.I., Kilner, J.M., Stephan, K.E., Friston, K.J., 2009. The mismatch negativity: a review of underlying mechanisms. *Clinical Neurophysiology* 120, 453-463.
- Glass, L., 2001. Synchronization and rhythmic processes in physiology. *Nature* 410, 277-284.
- Grondin, S., 2001. From physical time to the first and second moments of psychological time. *Psychological Bulletin* 127, 22-44.
- Horváth, J., Winkler, I., Bendixen, A., 2008. Do N1/MMN, P3a, and RON form a strongly coupled chain reflecting the three stages of auditory distraction? *Biological Psychology* 79, 139-147.
- Imada, T., Loveless, H.N., McEvoy, L., Sams, M., 1993. Determinants of the auditory mismatch response. *Electroencephalography and Clinical Neurophysiology* 87, 144-153.
- Ivry, R.B., 1996. The representation of temporal information in perception and motor control. *Current Opinion in Neurobiology* 6, 851-857.
- Ivry, R.B., Schlerf, J.E., 2008. Dedicated and intrinsic models of time perception. *Trends in Cognitive Sciences* 12, 273-280.
- Jones, M.R., Boltz, M., 1989. Dynamic attending and responses to time. *Psychological Review* 96, 459-491.
- Jones, M.R., Moynihan, H., MacKenzie, N., Puente, J., 2002. Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychological Science* 13, 313-319.
- Kotz, S.A., Schwartz, M., 2010. Cortical speech processing unplugged: a timely subcortico-cortical framework. *Trends in Cognitive Sciences* 14, 392-399.

- Large, E.W., Jones, M.R., 1999. The dynamics of attending: how people track time-varying events. *Psychological Review* 106, 119-159.
- Lewis, P.A., Miall, R.C., 2003. Distinct systems for automatic and cognitively controlled time measurement: evidence from neuroimaging. *Current Opinion in Neurobiology* 13, 250-255.
- Lewis, P.A., Miall, R.C., 2006. Remembering the time: a continuous clock. *Trends in Cognitive Sciences* 10, 401-406.
- Linden, D.E.J., 2005. The P300: where in the brain is it produced and what does it tell us? *The Neuroscientist* 11, 563-576.
- Lustig, C., Matell, M.S., Meck, W.H. Not “just” a coincidence: frontal-striatal interactions in working memory and interval timing. *Memory* 13, 441-448.
- Martin, X.P., Delterne, P., Hoonhorst, I., Markessis, E., Rossion, B., Colin, C., 2007. Perceptual biases for rhythm: the mismatch negativity latency indexes the privileged status of binary vs non-binary interval ratios. *Clinical Neuropsychology* 118, 2709-2715.
- McAuley, J.D., Miller, N.S., 2007. Picking up the pace: effects of global temporal context on sensitivity to the tempo of auditory sequences. *Perception & Psychophysics* 69, 709-718.
- Meck, W.H., Penney, T.B., Pouthas, V., 2008. Cortico-striatal representation of time in animals and humans. *Current Opinion in Neurobiology* 18, 145-152.
- Moberget, T., Karns, C.M., Deouell, L.Y., Lindgren, M., Knight, R.T., Ivry, R.B., 2008. Detecting violations of sensory expectancies following cerebellar degeneration: a mismatch negativity study. *Neuropsychologia* 46, 2569-2579.
- Näätänen, R., Gaillard, A.W.K., Mäntysalo, S., 1978. Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica* 42, 313-329.
- Näätänen, R., Tervaniemi, M., Sussmann, E., Paavilainen, P., Winkler, I., 2001. ‘Primitive intelligence’ in the auditory cortex. *Trends in Neurosciences* 24, 283-288.
- Näätänen, R., Syssoeva, O., Takegata, R., 2004. Automatic time perception in the human brain for intervals ranging from milliseconds to seconds. *Psychophysiology* 41, 660-663.
- Näätänen, R., Paavilainen, P., Rinne, T., Alho, K., 2007. The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology* 118, 2544-2590.

- Nobre, A.C., Correa, A., Coull, J.T., 2007. The hazards of time. *Current Opinion in Neurobiology* 17, 465-470.
- Petacchi, A., Laird, A.R., Fox, P.T., Bower, J.M., 2005. Cerebellum and auditory function: an ALE meta-analysis of functional neuroimaging studies. *Human Brain Mapping* 25, 118-128.
- Polich, J., Criado, J.R., 2006. Neuropsychology and neuropharmacology of P3a and P3b. *International Journal of Psychophysiology* 60, 172-185.
- Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology* 118, 2128-2148.
- Schröger, E., Wolff, C., 1998. Attentional orienting and reorienting is indicated by human event-related brain potentials. *Neuroreport* 9, 3355-3358.
- Schmidt-Kassow, M., Schubotz, R.I., Kotz, S.A., 2009. Attention and entrainment: P3b varies as a function of temporal predictability. *Neuroreport* 20, 31-36.
- Spencer, R.M.C., Zelaznik, H.N., Diedrichsen, J., Ivry, R.B., 2003. Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science* 300, 1437-1439.
- Takegata, R., Morotomi, T., 1999. Integrated neural representation of sound and temporal features in human auditory sensory memory: an event-related potential study. *Neuroscience Letters* 274, 207-210.
- Takegata, R., Syssoeva, O., Winkler, I., Paavilainen, P., Näätänen, R., 2001. Common neural mechanism for processing onset-to-onset intervals and silent gaps in sound sequences. *Neuroreport* 12, 1783-1787.
- Volpe, U., Mucci, A., Bucci, P., Merlotti, E., Galderisi, S., Maj, M., 2007. The cortical generators of P3a and P3b: a LORETA study. *Brain Research Bulletin* 73, 220-230.
- Wiener, M., Turkeltaub, P.E., Coslett, H.B., 2010. Implicit timing activates the left inferior parietal cortex. *Neuropsychologia* 48, 3967-3971.
- Winkler, I., Denham, S.L., Nelken, I., 2009. Modeling the auditory scene: predictive regularity representations and perceptual objects. *Trends in Cognitive Sciences* 13, 532-540.