Independent effects of temporal expectation and stimulus intensity in audition

Robert Schnuerch · Carina Kreitz · Kathrin Lange

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Abstract Temporal orienting—that is, selective attention to instants in time—has been shown to modulate performance in terms of faster responses in a variety of paradigms. Electrophysiological recordings have shown that temporal orienting modulates neural processing at early, probably perceptual, and late, probably decision- or response-related, stages. Recently, it was shown that the effect of temporal orienting on early auditory brain potentials is independent of the effect of the physical sound feature intensity. This indicates that temporal orienting might not affect stimulus processing by increasing the sensory gain of attended stimuli. In the present study, we investigated whether the independence of temporal-orienting and sound-intensity effects could be replicated behaviorally. Sequences were presented that were either rhythmic, most likely creating temporal expectations, or arrhythmic, presumably not creating such expectations. As hypothesized, the main effects of temporal expectation and sound intensity on reaction times were independent (Experiment 1). The exact pattern of results was replicated with a slightly altered paradigm (Experiment 2) and with a different kind of task (Experiment 3). In sum, these results corroborate the notion that the effect of temporal orienting might not rely on the same processes as the effect of sound intensity does.

Keywords Temporal orienting · Temporal expectation · Rhythmic sequences

Selective temporal attention, generally referred to as *temporal orienting* (Coull & Nobre, 1998), describes our ability to direct our attention to specific instants in time (for a review, see Nobre, Rohenkohl, & Stokes, 2012). Attention is often oriented in time on the basis of temporal expectations—that is, our expectation that a certain (response-relevant) event will happen at a specific point in time (see Nobre, 2004; Nobre et al., 2012). Similar to spatial orienting, such expectation-based temporal orienting of attention can be induced both endogenously, by predictive symbols (Correa, Lupiáñez, Milliken, & Tudela, 2004; Coull & Nobre, 1998), and exogenously, by regular stimulus sequences (Correa & Nobre, 2008; Doherty, Rao, Mesulam, & Nobre, 2005; Sanabria, Capizzi, & Correa, 2011; see also Rohenkohl, Coull, & Nobre, 2011; Triviño, Arnedo, Lupiáñez, Chirivella, & Correa, 2011). However, attention can also be oriented to specific instants in time by, among other techniques, manipulating the task relevance of time points. In relevance-based paradigms (e.g., Lange, Rösler, & Röder, 2003), participants are instructed to attend only to one point in time and to respond only to rare targets occurring at this particular time point, which is typically one of two (e.g., Lange, 2012; Lange & Röder, 2006) or three (e.g., Sanders & Astheimer, 2008) possible time points. Crucially, the neural processing of temporally attended, as compared to unattended, stimuli is analyzed for stimuli that do not require a response (i.e., for standards, not for targets). Due to the design of this paradigm, however, responses are only required to targets at attended points in time. Therefore, using such relevance-based temporal orienting, it is not possible to analyze the difference in reaction times (RTs) between attended and unattended time points (see also Lange, 2012), as compared with expectation-based temporal orienting, in which such comparisons can be made (e.g., Rohenkohl et al., 2011).

Temporal orienting modulates performance in terms of faster and more accurate responses to stimuli occurring at attended points in time (Nobre et al., 2012). Although the effect on response accuracy is subject to debate, and has

R. Schnuerch · C. Kreitz · K. Lange
Department of Experimental Psychology, Heinrich Heine
University Düsseldorf, Düsseldorf, Germany

R. Schnuerch (✉)
Department of Psychology, University of Bonn, Kaiser-Karl-Ring
9, 53111 Bonn, Germany
e-mail: robert.schnuerch@uni-bonn.de

been demonstrated when temporal orienting was combined with spatial orienting (e.g., Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Rohenkohl, Cravo, Wyart, & Nobre, 2012; see also Cravo, Rohenkohl, Wyart, & Nobre, 2013), the effect on RTs is robust and has been replicated in both vision and audition, as well as across various paradigms (e.g., Coull & Nobre, 1998; Lange, 2009; Sanabria et al., 2011; see also Nobre, 2001; Sanabria & Correa, 2013). At a physiological level, temporal orienting was repeatedly found to enhance late, probably decision- or response-related, brain potentials (e.g., Lange & Röder, 2006; Lange et al., 2003; Röder, Krämer, & Lange, 2007; see also Griffin, Miniussi, & Nobre, 2002; Miniussi, Wilding, Coull, & Nobre, 1999; Rohenkohl & Nobre, 2011). Moreover, at least for the auditory modality, early brain potentials were also shown to be affected by temporal orienting (enhancements, e.g., Lange et al., 2003; Rimmele, Jolsvai, & Sussman, 2011; Sanders & Astheimer, 2008; see also Lange, 2009, for a reduction of the N1 by temporal orienting). Hence, behavioral effects might be based on early (sensory) or later (decision- or response-related) processing stages.

An alternative approach to pinpoint the mechanisms underlying temporal orienting would be to simultaneously manipulate temporal attention and a second factor with similar behavioral effects. If these manipulations affect the same component process, this should be evident in interdependent effects (Sternberg, 1969, 2001). By contrast, if the two manipulations affect independent components (or “loci”; Sternberg, 2001) of processing, the effects would be additive. This approach would provide information regarding the functional overlap of different manipulations. Applying this logic to the investigation of event-related potential (ERP) effects of temporal orienting, Lange (2012) explored the enhancement of the early auditory brain potential N1 due to temporal orienting. Using a relevance-based paradigm, she manipulated temporal attention and, additionally, sound intensity. Sound intensity is known to affect sensory stimulus processing, as indexed by an enhanced N1 component to more intense sounds (Adler & Adler, 1991). Lange (2012) found that the enhancement of the N1 due to temporal orienting was independent of the sensory effect of sound intensity on the N1. On the basis of an additive-factors logic, the statistical independence of these particular effects indicated that they do not rely on a common mechanism. It should be noted that, in this context, two effects not relying on a common “mechanism” means that the influencing factors presumably do not affect the same component process or locus (Sternberg, 2001; see also Lange, 2012). This result does not allow for any inferences as to whether the effects are based on the same general physiological “mechanism” (or principle—e.g., a change in firing rate). Also, as was pointed out by Lange (2012), the findings do not rule out that both factors affect the same

overall stage of cognitive processing—for example, perceptual coding: It has been suggested that, even within what is pooled together as perceptual processing, multiple subprocesses are at work (Näätänen & Picton, 1987). However, the statistical independence of the effects does indicate that they do not rely on the same mechanism, in the sense that distinct component processes are presumably affected by temporal orienting and sound intensity (Lange, 2012).

In the study by Lange (2012), though, behavioral data could not be assessed, since the relevance-based approach to temporal orienting was used and responses were not given to unattended stimuli. Interestingly, related behavioral findings were provided in a recent visual study by Rohenkohl et al. (2012), who manipulated temporal orienting by varying the temporal regularity of stimulus sequences. Additionally, the contrast of visual masked target stimuli within the sequences was varied. Notably, Rohenkohl et al. (2012) provided psychometric and computational evidence that the effective contrast (the perceived signal-to-noise gain) of visual stimuli was enhanced when they occurred at regular—that is, expected—points in time. However, the behavioral effects of temporal orienting on response speed and accuracy were independent of the actual target contrast—which is in line with the ERP findings of Lange (2012). Thus, data from relevance-based (Lange, 2012) and expectation-based (Rohenkohl et al., 2012) temporal orienting have failed to provide support for the hypothesis that the effects of physical stimulus intensity and temporal attention are interdependent. Crucially, the data provided by Rohenkohl et al. (2012) may be seen as being indirect behavioral support of Lange’s (2012) findings from ERP recordings. However, it should be noted that the study by Rohenkohl and colleagues had a somewhat different focus, relying on psychometric and computational estimations. More importantly, their data were obtained in a visual paradigm. It seems appropriate to test more directly whether Lange’s (2012) auditory ERP findings could be replicated with behavioral measures.

In the present study, we therefore investigated whether additional evidence for the independence of temporal orienting and sound intensity can be found: Investigating effects in the auditory domain, as Lange (2012) did, we used stimulus-driven, expectation-based temporal orienting, as Rohenkohl et al. (2012) did, which allowed for the assessment of behavioral effects. Previous research has shown that the effects of temporal orienting on RTs are particularly robust (see, e.g., Rohenkohl & Nobre, 2011). Moreover, an additive-factors logic is especially suited for and applicable to RTs (see Posner, 2005). Therefore, we put a special focus on the possible independence of the effects on RTs. Most importantly, we hypothesized that the effect of temporal orienting should be independent of the effect of stimulus intensity. Such results would be well in line with Lange’s (2012) findings from ERPs and would expand the behavioral results of Rohenkohl et al.

(2012) to the auditory modality. Crucially, this independence would provide further evidence against the notion that the effects of temporal orienting and sound intensity are based on a common underlying mechanism, in terms of relying on a modulation of the same component process.

Experiment 1

In Experiment 1, we employed an auditory version of the visual procedure established by Rohenkohl et al. (2012), manipulating temporal orienting of attention by creating temporal expectations in stimulus sequences (see also, e.g., Doherty et al., 2005; Lange, 2009, 2010). Sequences were either rhythmic, inducing temporal expectations about upcoming stimuli, or arrhythmic, inducing no such expectations. Embedded into the sequences were imperative-to-be-discriminated targets whose sound intensity was manipulated. We had the following hypotheses: (1) Temporal orienting in rhythmic sequences should lead to lowered RTs to imperative targets within the sequence. (2) RTs should be lower for more intense target sounds. (3) The effects of temporal regularity and intensity on RTs should not interact, indicating independent mechanisms—that is, a modulation of distinct component processes. (4) Accuracy should be higher for more intense targets. (5) Similar to what was predicted for RTs, the effect of stimulus intensity on accuracy should be independent of temporal regularity, as was found by Rohenkohl et al. (2012). Whether response accuracy would increase with rhythmic sequences was rather unclear. Although temporal expectation has been found to increase response accuracy (e.g., Rohenkohl et al., 2012), it was shown not to affect accuracy in similar studies (e.g., Doherty et al., 2005; Lange, 2009).

Method

Participants The original sample consisted of 39 participants. Of these, one participant had to be excluded due to incomplete data. The final sample comprised 38 subjects (26 female, 12 male; $M = 23.89$ years, $SD = 4.77$). Since we assumed that the susceptibility to auditory rhythmic stimulation might vary with extensive practical musical experience, we did not include professional musicians (i.e., uncommonly experienced persons) in the sample. Rather, we ran a random sample of students, mostly psychology undergraduates. We assessed their mean musical education, which was 5.13 years ($SD = 5.98$) and represented a moderate level (see, e.g., Lange, 2009, 2010, 2012). All of the participants reported normal hearing, gave written informed consent, and received either course credit or monetary compensation.

Stimuli and apparatus The sequences in the present study consisted of repeated standard sounds and targets. As

repetitive standards preceding the targets, diotic 50-ms pure tones of 150 Hz were used (rise/fall time 3 ms). They were presented at approximately 70 dB_{SPL}. As the target, a 50-ms triangular-wave tone at 1200 Hz was presented monaurally. Its sound level was varied as a manipulation of target intensity. The target was masked by a diotic 50-ms white-noise burst that was always presented at approximately 70 dB_{SPL}. Target and masker were presented simultaneously, with no temporal offset. The white-noise burst, which always masked the target, was noticeably different from the repetitive standard tones. Hence, the white-noise burst always indicated that the actual target (the monaural tone) was presented, even when the target itself was not clearly audible. The target was presented at seven logarithmic steps of sound level that were adjusted for each participant individually on the basis of an adaptive staircase procedure prior to the experiment. The steps were adjusted relative to an estimated threshold. Each sound-level step was calculated as follows: $L_S = T * 1.08^S$, where L is the sound level, S is the step (ranging from -3 to 3 in seven integer steps), and T is the previously determined target sound level at which the task was performed at about 71 % correct (i.e., the threshold). All sound-level values were computed in arbitrary units ranging from 0 to 1, with 1 corresponding to an actual loudness of about 95 dB_{SPL}. The base of 1.08 was found to yield psychometrically fitting performance in pilot studies when stimuli were presented at steps differing in sound level by this factor. All of the sounds were stereo wave files (sampling rate of 44.10 kHz, bit depth of 16 bits).

Figure 1 shows a schematic of the task. Each sequence contained 140 stimuli, of which 14 were masked targets and 126 were standards. The number of standards preceding each target ranged from five to 14. Target sounds at all seven intensity levels occurred twice in each sequence, once to the left and once to the right ear. The order of all targets within each sequence was pseudorandomized. Rhythmicity (i.e., the regularity of the temporal intervals between the stimuli of a sequence) was varied in order to manipulate temporal expectations, and the sequences were isochronous (rhythmic condition) or anisochronous (arrhythmic condition). In rhythmic sequences, the stimulus onset asynchrony (SOA) between successive stimuli was held constant at 400 ms for all 140 stimuli. In arrhythmic sequences, the SOA could be 200, 300, 500, or 600 ms. All SOAs in the arrhythmic condition were presented equally often and were drawn randomly. To avoid any difference in masking or foreperiod between the rhythmic and arrhythmic sequences, the SOA before and after each target was 400 ms in both rhythmic and arrhythmic sequences.

The experiment was programmed and conducted using Presentation software (Neurobehavioral Systems, Albany, NY). All stimuli were created, processed, and RMS-normalized using Wavelab 7 software (Steinberg, Hamburg, Germany). Sounds were presented via headphones

Fig. 1 Schematic illustration of the sequence structure (excerpt). Each sequence contained stimuli presented with either a fixed stimulus onset asynchrony (rhythmic condition; SOA = 400 ms) or a variable SOA

(arrhythmic condition; SOA = 200, 300, 500, or 600 ms). The SOAs before and after the target were fixed at 400 ms in both conditions (see shading)

(Beyerdynamic, DT 770 M, Beyerdynamic, Heilbronn, Germany), and instructions were presented on CFT monitors. Responses were given on a USB response box (BB-10 Full Speed USB Button Box; Empirisoft, New York). All of the data were processed and analyzed on MATLAB 7.12 (The MathWorks, Natick, MA).

Procedure The participants sat in front of a monitor with a response pad placed in front of them. The session was started with extensive instructions. Participants were instructed to listen to sound sequences and to respond via corresponding button press with the corresponding hand whether a masked high-pitch “beep” (the triangular-wave tone; i.e., the target) was presented to the left or to the right ear. Since the white-noise masker, which always accompanied the actual target tone, markedly stood out from the repetitive standards, participants were explicitly instructed to respond whenever they heard the characteristic sound of the white-noise masker. Also, they were encouraged to guess whenever they were unsure whether the target within the masking noise had been presented to the left or the right ear. It should be noted that, because of the constant stream of repeated standards, responses to targets had to be given at least partly while the standards preceding the next target were already being presented. Participants were familiarized with the task and the sounds by means of repeated exemplary sounds and two practice sequences, containing a total of 28 easily discriminable targets.

Subsequently, participants underwent a threshold-determination procedure in which the target sound level was assessed at which performance in the discrimination task was at about 71 % accuracy. Only arrhythmic sequences were presented during this procedure, so as to assess participants’ threshold in the discrimination task in a neutral condition—that is, without temporal expectation. To estimate the threshold, participants simply performed the previously practiced task. However, the target sound level varied depending on their performance. A simple 2–1 algorithm was

implemented (Levitt, 1971), and the threshold value was computed as the mean sound level at reversals as soon as 25 reversals had occurred during the thresholding. Participants did not receive any feedback about their performance.

In the actual experiment, participants continued performing the side-discrimination task. However, half of all sequences were now rhythmic. Each participant listened to 50 sequences (25 rhythmic, 25 arrhythmic) in randomized order. Since each sequence contained 14 targets, 700 targets were presented to each participant. In total, targets were presented at each of the seven intensities 100 times (50 times in the rhythmic condition, 50 times in the arrhythmic condition). Targets were presented equally often to the left and the right ear. After each sequence, participants could rest for as long as they pleased and continue the experiment by buttonpress. During the breaks, participants received visual feedback about the number of targets that they had not responded to during the previous sequence. If the number was above zero, they were reminded to respond whenever they heard the white-noise masker bursts and to guess whenever they did not consciously hear the high-pitch tone. No feedback about the correctness of the responses was given. The whole session—including practice sequences, the thresholding, and the actual experiment—took approximately 1 h. Upon completion of the experiment, participants filled in brief questionnaires about their demographic and musical background.

Design A 2×7 repeated measures design was used. The independent variables were the temporal regularity of the sequences (rhythmic condition vs. arrhythmic condition) and the target intensity (−3, −2, −1, 0, 1, 2, or 3). RTs of correct responses and response accuracy—that is, target discriminability as measured by the sensitivity index d' (Green & Swets, 1974)—were the dependent variables.

Data analysis Prior to all analyses, for each participant separately in each of the 14 conditions (Temporal

Regularity $\times$ Target Intensity), RTs shorter than two standard deviations below the respective mean of the specific condition or longer than two standard deviations above this mean were interpreted as outliers and excluded from further analysis. On the basis of this criterion, 5.06 % of all responses were excluded. Additional analyses revealed that neither conditions nor participants were differentially affected by this exclusion. That is, the number of trial rejections did not differ significantly between conditions or between participants. RT and accuracy were analyzed by means of repeated measures analyses of variance (ANOVAs). Whenever Mauchly's (1940) test of sphericity led to the assumption that variances were not homogeneous, degrees of freedom were corrected by means of the procedure proposed by Greenhouse and Geisser (1959). When degrees of freedom were adjusted, uncorrected values and the correction factor ε are reported.

Results

Figure 2 shows the descriptive results of Experiment 1. As can be seen in the left panel, participants responded faster to targets in rhythmic sequences than to those in arrhythmic sequences [main effect of temporal regularity: $F(1, 37) = 17.74$, $p < .001$, $\eta_p^2 = .32$]. Moreover, responses were faster to more intense target sounds [main effect of target intensity: $F(6, 222) = 28.17$, $p < .001$, $\eta_p^2 = .43$, $\varepsilon = .61$], but no interaction between temporal regularity and target intensity was apparent, $F(6, 222) = 0.95$, $p = .44$, $\eta_p^2 = .03$, $\varepsilon = .64$.

The right panel of Fig. 2 shows participants' accuracy at the different target intensities for the rhythmic and arrhythmic conditions. Temporal regularity did not influence accuracy, $F(1, 37) = 0.02$, $p = .91$, $\eta_p^2 < .01$. However, responses

were more accurate for more intense target sounds [main effect of target intensity: $F(6, 222) = 257.53$, $p < .001$, $\eta_p^2 = .87$, $\varepsilon = .55$]. We found no significant interaction between temporal regularity and target intensity, $F(6, 222) = 0.99$, $p = .43$, $\eta_p^2 = .03$, $\varepsilon = .86$.

Discussion

We investigated whether the effects of temporal orienting and sound intensity on RTs are independent when combined in one experimental paradigm. By this investigation, we aimed to find out whether the two effects are based on a common process, thereby narrowing down possible mechanisms underlying temporal orienting. Participants listened to rhythmic and arrhythmic stimulus sequences and performed a simple side-discrimination task to occasional targets within the sequences. The results showed that our hypotheses were supported: (1) In rhythmic sequences, which most likely entailed temporal expectations and orienting of attention, responses were faster than in arrhythmic sequences (see Lange, 2009). (2) Moreover, responses were faster to more intense targets (see Lange, 2012). (3) The effects of temporal regularity and sound intensity did not interact, providing little evidence for a common locus. (4) Response accuracy varied as a function of intensity, being higher for higher intensities. (5) The effect of stimulus intensity on accuracy was not further modulated by temporal regularity. Moreover, responses were not more accurate in rhythmic than in arrhythmic sequences. This result is well in line with previous studies that have reported that RT is highly sensitive to manipulations of temporal orienting, whereas accuracy is less prone to its influence, unless combined with spatial attention (Rohenkohl & Nobre, 2011; see also Doherty et al., 2005).

Fig. 2 Descriptive results of Experiment 1. White dots depict the means from the rhythmic condition, and black dots display the means from the arrhythmic condition. All error bars indicate standard errors.

The left panel shows reaction times (in milliseconds), the right panel shows accuracy (sensitivity, as measured by d')

We showed that stimulus-driven effects of temporal orienting were independent of the effects of stimulus intensity in audition. To assure that this null effect was not simply due to insufficient power, we conducted a post-hoc power analysis (see Hoenig & Heisey, 2001; Prajapati, Dunne, & Armstrong, 2010). The analysis was performed using G*Power 3 software (Faul, Erdfelder, Lang, & Buchner, 2007) and revealed that the power ($1 - \beta$) of Experiment 1 was .94, even for small effects (hypothesized effect size $f = .1$), which represents high power. However, an effective way to test more carefully and with even higher overall power whether the behavioral effects of temporal orienting and sound intensity are truly independent would be to replicate the experiment.

Experiment 2

In a second experiment, we aimed to replicate the pattern of results obtained from Experiment 1 with a different random sample. Moreover, we wanted to find out whether the pattern of results from Experiment 1 could be replicated in a design more closely resembling previous investigations of stimulus-driven attention. In previous studies (e.g., Doherty et al., 2005; Lange, 2009, 2010; Rimmele et al., 2011; Rohenkohl & Nobre, 2011), single, separate induction sequences were employed. At the end of each induction sequence, which was either rhythmic or arrhythmic, one target had to be evaluated. After a short break, the next sequence was started. In the task of Rohenkohl et al. (2012) and in Experiment 1 of the present study, the sequences continued directly after the target, and the RT data from Experiment 1 revealed that at least part of the responses were given while the first standard succeeding the target was already being presented. In Experiment 2, we therefore applied a very slight change to the paradigm: The sequences stopped after each target, such that responses were given after the target without the concurrent continuation of the sequence of standards. Thus, we implemented separate induction sequences, similar to those previously used (e.g., Lange, 2010). Such a paradigm seems particularly worthwhile to investigate, given its ecological validity: In naturalistic settings, regular sequences provide implicit information about the timing of upcoming events (Doherty et al., 2005; Rohenkohl et al., 2012). However, naturalistic sequences are indeed often separate streams of stimuli that end with a task-relevant event. Long, continuous streams embedding multiple imperative stimuli (as in Exp. 1), although they strongly manipulate temporal expectation (Rohenkohl et al., 2012), seem slightly less naturalistic. Real-life examples of separate induction sequences preceding a response-relevant event might be a soccer player running toward the ball during a penalty or the countdown before the starting signal in a race (Correa, 2010). Also, when there is no concurrent stimulation during the response period (see, e.g.,

Doherty et al., 2005), the task is presumably less demanding, and participants' capacity for the actual task increases. This should be evident in a lower overall level of RTs. However, we hypothesized that should the same general pattern of results be found as in Experiment 1, this would corroborate the notion that temporal orienting and sound intensity might not affect the same component processes.

Method

Participants A total of 39 people participated in the experiment (34 female, five male; $M = 22.90$ years, $SD = 3.85$). These participants reported a mean musical education of 6.08 years ($SD = 6.67$), and none was a professional musician. All of the participants reported normal hearing, gave written informed consent, and received either course credit or monetary compensation.

Stimuli and apparatus The stimuli and apparatus were the same as in Experiment 1, except for the general structure of the sequences: After each target within the sequence, a short interruption was inserted during which participants could respond to the target. Thus, all of the phases of repeated standards and one successive target were discrete sequences, instead of a continuous stream as in Experiment 1. The interruption after each target lasted for 1,000 ms (fixed), plus a jitter of 100–500 ms (randomized).

Procedure, design, and data analysis The procedure, design, and data analysis of Experiment 2 were the same as in Experiment 1. On the basis of the criteria for exclusion, 5.83 % of all responses were rejected in Experiment 2. Again, additional analyses revealed that the rejection criteria did not affect different conditions or participants differently.

Results

Figure 3 shows the descriptive results of Experiment 2. The left panel shows RTs, with participants responding faster to targets in rhythmic sequences than to those in arrhythmic sequences [main effect of temporal regularity: $F(1, 38) = 9.00$, $p < .01$, $\eta_p^2 = .19$]. Responses were also faster to more intense target sounds [main effect of target intensity: $F(6, 228) = 49.569$, $p < .001$, $\eta_p^2 = .57$, $\varepsilon = .28$], but no interaction emerged between temporal regularity and target intensity, $F(6, 228) = 0.81$, $p = .54$, $\eta_p^2 = .02$, $\varepsilon = .75$.

As is shown in the right panel of Fig. 3, temporal regularity did not influence accuracy, $F(1, 38) = 0.48$, $p = .49$, $\eta_p^2 = .01$, and responses were more accurate for more intense target sounds [main effect of target intensity: $F(6, 228) = 193.74$, $p < .001$, $\eta_p^2 = .84$, $\varepsilon = .43$]. We again observed no significant interaction between temporal regularity and target intensity, $F(6, 228) = 0.49$, $p = .79$, $\eta_p^2 = .01$, $\varepsilon = .90$.

Fig. 3 Descriptive results of Experiment 2. White dots depict the means from the rhythmic condition, and black dots display the means from the arrhythmic condition. All error bars indicate standard errors.

Discussion

In Experiment 2, we used a paradigm very similar to the one implemented in Experiment 1, to investigate whether the effects of expectation-based temporal orienting and stimulus intensity on RTs are independent. We were able to replicate the pattern of results obtained from our first experiment: The significant effects of temporal regularity and sound intensity on RTs were independent. Moreover, accuracy was only affected by stimulus intensity, and this effect was independent of the influence of temporal regularity. Evidently, the slight change of the sequence structure into separate induction sequences did not affect the overall pattern of results. Responses were somewhat faster than in Experiment 1, which is highly plausible, since responses in the second experiment were given without concurrent stimulation. Most importantly, the main goal of Experiment 2 was to increase the overall power of our investigation, to diminish the probability that we failed to find an interaction of temporal orienting and intensity due to insufficient power. Having run another sample of 39 participants, we still did not find evidence for an interaction of the factors and, thus, for conjoint mechanisms.

However, it should be noted that the possibility of finding evidence for an effect of temporal orienting on sensory gain might bear on the choice of task. Using a spatial discrimination task, we failed to find an interaction of the two factors. In the study by Rohenkohl et al. (2012), participants had to decide whether a Gabor pattern was tilted to the left or the right side. Therefore, participants did not have to attend to two sides, but could focus on the foveally presented pattern to assess its orientation. Although their results were based on a somewhat different reasoning, Rohenkohl et al. (2012) found evidence for an increase in sensory quality using their orientation-discrimination task. Such a task might be regarded

The left panel shows reaction times (in milliseconds), the right panel shows accuracy (sensitivity, as measured by d')

as being considerably different from our task, due not only to the different modalities. In our task, spatial attention had to be divided between both ears so as to discriminate the two possible target locations. Such divided attention was not needed in the Rohenkohl task, as was acknowledged by those authors. In fact, Rohenkohl et al. (2012) pointed out that, in their study, the spatial location of all stimuli was fixed. Thus, their findings suggesting enhanced sensory information might bear on the possibility of temporally fine-tuning the effect of spatial attention on early perceptual processing, as attention could easily be oriented in space due to the absolute certainty of the spatial location of targets (Rohenkohl et al., 2012; see also Doherty et al., 2005). Thus, it seemed worthwhile to investigate whether the results from vision and audition would be more alike when this confound was eliminated. We therefore aimed to find out whether the pattern of results obtained in Experiments 1 and 2 could be predicated on the fact that a spatial discrimination task was used. It might be assumed that a task that does not involve spatial uncertainty might allow for precise timing and a boosting of the sensory effects of spatial attention through temporal orienting (Rohenkohl et al., 2012).

Experiment 3

To find out whether our previous findings that temporal orienting and sound intensity affected RTs (and accuracy) independently rested on the spatial nature of the task, we now applied a change to the task presented in Experiment 1: Instead of having to discriminate the side on which the target tone was presented, participants now made a qualitative discrimination of the target stimuli. They were asked to decide whether a brief target tone presented within the continuous sequence of sounds was either human (a vocal

sound) or electronic (a triangular-wave tone). Crucially, the spatial position of all targets was fixed at center (diotic presentation), such that no spatial uncertainty emerged, as in Experiments 1 and 2. Moreover, we also avoided pitch uncertainty and matched the pitch of the two target sounds, as it has been proposed that pitch may be a concept in audition that resembles space in vision (Kubovy, 1981; see also Lange, 2009). Thus, we wanted to make sure that attention did not have to be divided between different sides or different pitches. It should be noted, though, that pitch had already been held constant in Experiments 1 and 2. However, with both pitch and space now being certain, we assumed that the nature of the task might be slightly more similar to the one used in the visual paradigm by Rohenkohl et al. (2012). Moreover, altering the task might broaden the scope of the investigation by replicating Experiment 1 with another new sample and with a different task.

On the basis of our previous results, as well as of prior studies (e.g., Lange, 2012; Rohenkohl et al., 2012), we again hypothesized that (1) temporal regularity and stimulus intensity should affect RTs, and that (2) these effects should be independent. (3) Accuracy should be higher for more intense target tones. Whether accuracy would now be affected by temporal regularity (or only by stimulus intensity) was unclear. However, we hypothesized that (4) the influences of both factors on accuracy should be independent.

Method

Participants A group of 29 participants took part in the experiment, from which one participant was excluded due to incomplete data. The final sample comprised 28 subjects (22 female, six male; $M = 23.04$ years, $SD = 4.08$), none of whom was a professional musician. The participants reported a mean musical education of 5.96 years ($SD = 4.58$). All of the participants reported normal hearing, gave written informed consent, and received course credit or monetary compensation.

Stimuli and apparatus The stimuli and apparatus in Experiment 3 were the same as in Experiment 1, except for the following: The target tone, which was always masked by a concurrent white-noise burst, was either the first 50 ms of a recording of a woman saying “ba” or a triangular-wave tone at 256 Hz. This pitch was chosen as it matched the pitch of the vocal sound. Both sounds had a rise/fall time of 3 ms, were RMS-normalized to be equally loud, and were always presented diotically. The assignment of responses (human vs. electronic) to sides (left or right response button) was counterbalanced across participants. Note that the separate-sequence structure of Experiment 2 was not repeated in Experiment 3, but that longer, continuous sequences including multiple targets were again used, as in Experiment 1.

Procedure, design, and data analysis The procedure, design, and data analysis of Experiment 3 were the same as in Experiment 1. However, participants’ task was no longer to detect a sound at the left or the right ear, but to classify a diotic sound as being either human or electronic via buttonpress. On the basis of the criteria for exclusion, 4.95 % of all responses were rejected. Trial rejection was distributed relatively equally across conditions and across participants, with no significant differences in rejection rates between different conditions and between different participants.

Results

The descriptive results of Experiment 3 can be seen in Fig. 4. As is displayed in the left panel, participants responded faster to targets in rhythmic sequences than to those in arrhythmic sequences [main effect of temporal regularity: $F(1, 27) = 13.85$, $p < .001$, $\eta_p^2 = .34$]. Moreover, responses were faster to more intense target sounds [main effect of target intensity: $F(6, 162) = 2.88$, $p < .05$, $\eta_p^2 = .10$, $\epsilon = .64$], but no interaction emerged between temporal regularity and target intensity, $F(6, 162) = 1.36$, $p = .26$, $\eta_p^2 = .05$, $\epsilon = .53$.

The right panel of Fig. 4 shows accuracy at the different target intensities for the rhythmic and the arrhythmic conditions. Temporal regularity did not influence accuracy, $F(1, 27) = 0.13$, $p = .72$, $\eta_p^2 < .01$, but responses were more accurate for more intense target sounds [main effect of target intensity: $F(6, 162) = 144.741$, $p < .001$, $\eta_p^2 = .84$, $\epsilon = .58$]. We found no interaction between temporal regularity and target intensity, $F(6, 162) = 1.66$, $p = .15$, $\eta_p^2 = .06$, $\epsilon = .85$.

Discussion

In Experiment 3, we again failed to find a statistical interaction of temporal orienting (based on temporal regularity) and sound intensity: (1) Temporal regularity and stimulus intensity had significant effects on RTs, with responses being faster in rhythmic than in arrhythmic sequences, and faster to intense than to less intense target tones. (2) The effects did not interact. (3) Accuracy was significantly influenced by stimulus intensity. However, accuracy was not significantly different between rhythmic and arrhythmic sequences. As hypothesized, (4) the effect of intensity on accuracy was not modulated further by temporal regularity. In sum, we once more did not find direct evidence for common underlying mechanisms. Interestingly, we replicated the patterns of results from Experiment 1 and from the slightly altered version in Experiment 2. This is especially notable, since we eliminated the previous difference between our task and the one employed by Rohenkohl et al. (2012) with regard to spatial certainty. It therefore seems unlikely that the lack of evidence for conjoint mechanisms of temporal orienting and sound intensity simply relied on a

Fig. 4 Descriptive results of Experiment 3. White dots depict the means from the rhythmic condition, and black dots display the means from the arrhythmic condition. All error bars indicate standard errors.

task that involved a spatial discrimination, like the one used in Experiments 1 and 2.

Although the general pattern of results was the same as in Experiments 1 and 2, the descriptive results of Experiment 3 were less clear-cut than those of the previous two experiments. Especially, RTs were characterized by high variance and a less steady course of mean values across intensity levels (see Fig. 4, left panel). This might be explained by the considerably higher demands of the task used in Experiment 3: Whereas in Experiments 1 and 2 participants simply had to indicate at which ear they had detected a target sound, they had to determine the category of the target in Experiment 3. A semantic classification or recognition of the target as either human or electronic was needed, and the mere detection of a stimulus in one ear or the other did not suffice. Therefore, more and higher processing of target sounds was necessary, which presumably made the task more difficult and RTs more variable than in Experiments 1 and 2. The higher demands in this task than in the side-discrimination task is evident in the longer RTs in Experiment 3. Also, we tested slightly fewer participants in Experiment 3, which could explain the higher variance. Moreover, whereas the simple left–right discrimination in Experiments 1 and 2 entailed a high degree of stimulus–response compatibility, the mapping of categories (human vs. electronic) to manual responses in Experiment 3 was not based on such a well-established link between perception and action, but was somewhat arbitrary (see Eimer, 1995; Fitts & Seeger, 1953). Accordingly, it was to be expected that responses would be slower and more variable. Most importantly, however, the general pattern of results (which was of central interest for this replication) was the very same as in the previous two experiments, such that Experiment 3 corroborated the notion that temporal orienting and sound intensity

The left panel shows reaction times (in milliseconds), the right panel shows accuracy (sensitivity, as measured by d')

might not affect the same, presumably sensory, component process.

General discussion

We investigated whether the effects of stimulus-driven, expectation-based temporal orienting and sound intensity on RTs are independent. It had previously been shown by Lange (2012) using a different paradigm that the effects of temporal orienting and sound intensity on the auditory event-related N1 brain potential do not interact. Together with the fact that the two effects had different scalp topographies, this finding was interpreted as indicating that distinct component processes are affected by the two factors. Since it is assumed that sound intensity affects the sensory representation (e.g., Adler & Adler, 1991), failing to find a statistical interaction of temporal orienting and intensity could be seen as indirect evidence that auditory temporal orienting might not affect sensory processing in the same way that increasing physical intensity does (Lange, 2012).

To investigate this behaviorally, we presented sound sequences that consisted of repetitive standard sounds and occasional masked targets (see Rohenkohl et al., 2012). The intensity of the targets was manipulated, as well as the temporal regularity of the sequences. Regular stimulus sequences are assumed to create temporal expectations about upcoming stimuli and to lead to an entrainment of attentional oscillations (see, e.g., Jones, Moynihan, MacKenzie, & Puente, 2002). Crucially, we found independent effects of temporal regularity and stimulus intensity across three experiments. In Experiment 1, a simple side-discrimination task within continuous sound sequences was implemented. In Experiment 2, the same task

was used, but separate sequences preceding each target were used instead of long sequences containing multiple targets. In Experiment 3, continuous sequences were again used, but all of the targets were presented at the same spatial location, and the task was to categorize two possible target sounds as being either human or electronic. None of the experiments yielded an interaction of the significant effects of temporal expectation and stimulus intensity on RTs. Given the high power of this threefold investigation, it might be safe to presume that a sheer lack of power did not prevent us from detecting a small interaction effect. Moreover, we varied the task by employing both a spatial discrimination (Exps. 1 and 2) and a nonspatial category discrimination (Exp. 3). The patterns of results, though, were the same in both tasks.

The present results support the suggestion that temporal orienting does not affect stimulus processing in the same way that stimulus intensity does (see Lange, 2012). In fact, on the basis of the behavioral results of the present study, we cannot determine whether temporal orienting modulates early sensory or later decision- or response-related processes. However, our results are well in line with and expand Lange's (2012) findings on the independent effects of temporal orienting and sound intensity on the early N1 brain potential. It should be noted, though, that such results (as well as the present data) cannot fully rule out that temporal orienting affects sensory processing of stimuli, as was pointed out by Lange (2012). In all modalities, perceptual processing is highly parallel. Therefore, temporal orienting might affect early stages of processing by modulating perceptual (sub)processes that are independent of physical stimulus intensity. That is, if early, perceptual processing is composed of multiple parallel subprocesses, as was proposed for audition by Näätänen and Picton (1987), stimulus intensity might be processed in one of these subprocesses. Temporal attention might also enhance perceptual processing, but exert its effect on a different subprocess. Thus, temporal attention might indeed affect sensory processing (as was proposed recently by Cravo et al., 2013, and Rohenkohl et al., 2012), yet by enhancing perceptual processes that are independent of physical stimulus intensity. As was suggested by Lange (2012), temporal attention might influence the probability of conscious detection of stimuli rather than the perceptual analysis per se (see also Näätänen & Picton, 1987). Whatever the specific mechanisms, if the general notion of multiple parallel perceptual subprocesses is correct, the present data would have to be interpreted slightly differently. Even then, however, they would provide insight into the functional mechanisms involved in temporal orienting. That is, they would still indicate that temporal orienting does not affect stimulus processing via the same processes as physical stimulus intensity—even if both factors modulated what might be subsumed as perceptual processing (see Lange, 2012, for a related discussion). Thus, the apparent contradiction between the present and earlier

behavioral data, on the one hand (Lange, 2012; Rohenkohl et al., 2012), and recent psychometric and computational results, on the other (Cravo et al., 2013; Rohenkohl et al., 2012), might be explained. Although they did not find an interaction of temporal orienting and stimulus intensity, Rohenkohl et al. (2012) demonstrated that the perceived signal-to-noise ratio of visual stimuli increased due to the temporal orienting of attention. However, an increment in the perceived contrast might not rely on the exact same mechanism (i.e., an influence on the same component process) as an increase in (physical) gain. Temporal orienting might have somehow increased the percept (and, therefore, enhanced a perceptual process), but it might have operated on a process other than the one reflecting an increase in physical input gain.

A certain limitation to the present study is that the general reasoning was based on an additive-factors logic (Sternberg, 1969, 2001). That is, the interpretation of our data as evidence against the notion that temporal orienting and stimulus intensity rely on the same mechanism is based on a missing interaction between the two effects. Although this approach has been widely accepted and frequently used (see, e.g., Dehaene, 1996; Posner, 2005; Sergeant & van der Meere, 1990; van den Wildenberg & van der Molen, 2004), it has also been criticized (Stafford & Gurney, 2011). Thus, there might be some concern as to how valid any interpretation based on this logic is. However, it should be noted that the present data bring forward additional evidence that might be seen as similarly contradictory to the idea that temporal orienting and physical gain affect the same component process: Not once did we find a main effect of temporal orienting on accuracy. If sensory gain did indeed increase due to temporal attention, one might assume that responses to attended targets should be more accurate (i.e., target discriminability should have increased). This expectation seems highly appropriate, given the fact that accuracy in all three experiments of the present study was evidently sensitive to an increase in gain: Accuracy significantly increased when the actual physical stimulus intensity was higher. Therefore, not only might an interaction of temporal orienting and intensity be suggestive of increased sensory gain, but also a main effect of temporal orienting on sensitivity (see Rohenkohl et al., 2012). Fittingly, Rohenkohl et al. (2012) reported this main effect. We, however, did not find this effect using an auditory version of Rohenkohl et al.'s (2012) paradigm. This is in line with and convergent support for the fact that we did not find an interaction between the RT effects of temporal orienting and intensity.

It remains unclear, though, why sensitivity was not enhanced in any of the three experiments of the present study, whereas it was in Rohenkohl et al.'s (2012) study. This is particularly surprising because we created an auditory approximation of the design and task employed by Rohenkohl et al. (2012), and most experimental parameters were the same or very similar. Crucially, it has been suggested that temporal orienting might affect early visual processing by

timing neurons that directly code different features of the stimulus, such as its location (Doherty et al., 2005). Accordingly, Rohenkohl et al. (2012) assumed that their findings indicating perceptual effects of temporal orienting were based on the boosting of the effects of spatial attention, elicited by the spatial certainty of all of the target stimuli. Thus, it might be hypothesized that temporal orienting, when combined with spatial attention, enhances perceptual processing, which should surface as an increase in sensitivity (see Correa, Lupiáñez, & Tudela, 2005; Mathewson et al., 2010; Rohenkohl et al., 2012).

In the present study, however, a task including spatial certainty (Exp. 3) did not reveal an effect of temporal orienting on sensitivity. Moreover, pitch, which might be seen as an auditory analogue of space in vision (Kubovy, 1981) was held constant in all experiments, yet no effect on sensitivity was observed. Although the reasoning is somewhat speculative, one explanation for this result might be that the stimuli in the present study simply did not allow for the fine-tuning of early, perceptual coding through temporal attention. Unlike space in vision, auditory space and pitch are not directly represented (in terms of being directly mapped to specialized neurons with a simple topical organization) at the earliest stages of neural processing, but are computed in a relatively complex fashion along the auditory pathway on the basis of various neural signals (Schnupp, Nelken, & King, 2011). Thus, by default, the suggested temporal fine-tuning of neurons coding different features of the stimulus (see, e.g., Rohenkohl et al., 2012) might not apply to these particular stimulus features, such that perceptual processing was not enhanced. Instead, frequency might be a stimulus feature whose neural coding could be temporally fine-tuned by means of temporal expectation. Frequency, like spatial location in vision, is a dimension of auditory stimuli that is directly represented by neurons responding selectively to stimulation within their specific range, even at the earliest stages of the neural pathway (Schnupp et al., 2011). This selective-coding system is particularly evident in the tonotopic organization of frequency-specific neurons, for example, in the auditory cortex (Ottaviani, Di Girolamo, Briglia, De Rossi, Di Giuda, & Di Nardo, 1997; Wessinger, Buonocore, Kussmaul, & Mangun, 1997). Therefore, it might be interesting to implement constant frequencies instead of pitch in future studies. Although the constant pitch in Experiments 1 and 2 entailed constant frequencies as well, a complex pattern of harmonic frequencies is what was repeatedly activated. Temporal attention therefore would have had to fine-tune the timing of a vast variety of neurons spreading along the auditory cortex in order to enhance sensory information. It might thus be useful to employ a simple task with a pure tone, which consists of only one frequency instead of a complex pattern. Such experiments controlling specific auditory features will certainly be needed in order to clarify whether auditory and visual perceptual processing are modulated similarly by temporal orienting (but see Rimmele et al., 2011).

However, as a last note, we will add that the recent conclusive results underlining the notion that temporal orienting enhances perceptual processing (Cravo et al., 2013; Rohenkohl et al., 2012; see also Mathewson et al., 2010) were acquired in visual paradigms. Thus, it remains a possibility that the mechanisms of visual and auditory temporal orienting might differ in general. As various studies on the effects of temporal orienting on event-related brain potentials have shown, there is a considerable disparity in the results and interpretations pertaining to the two modalities (Correa, 2010; Lange, 2012; Nobre, 2010). Evidently, more studies will be needed to identify the neural and cognitive mechanisms underlying temporal orienting of attention. Among other things, future studies might address whether the differences in the results obtained in the different senses are mere artifacts, based on confounds, or can indeed be attributed to unequal underlying mechanisms.

Author Note R.S. is now at the Department of Psychology, University of Bonn, Bonn, Germany. C.K. is now at the Institute of Cognitive and Team/Racket Sport Research, German Sport University Cologne, Cologne, Germany. K.L. is now at the Federal Institute for Drugs and Medical Devices, Bonn, Germany. This research was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) through Grant No. LA 2486/1-2 to K.L. The authors thank Gustavo Rohenkohl, André M. Cravo, and Anna C. Nobre for their contributions to the experimental design and helpful comments on the manuscript.

Correspondence concerning this article should be addressed to Robert Schnuerch, Department of Psychology, University of Bonn, Kaiser-Karl-Ring 9, 53111 Bonn, Germany. E-mail: robert.schnuerch@uni-bonn.de

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