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1 ***The effect of regular rhythm on the perception of linguistic and non-***
2 ***linguistic auditory input***

3

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16

1 Abstract

2 Regular distribution of auditory stimuli over time can facilitate perception and attention.
3 However, such effects have to date only been observed in separate studies using either
4 linguistic or non-linguistic materials. This has made it difficult to compare the effects of
5 rhythmic regularity on attention across domains. The current study was designed to
6 provide an explicit within-subject comparison of reaction times and accuracy in an
7 auditory target-detection task using sequences of regularly and irregularly distributed
8 syllables (linguistic material) and environmental sounds (non-linguistic material). We
9 explored how reaction times and accuracy were modulated by regular and irregular
10 rhythms in a sound- (non-linguistic) and syllable-monitoring (linguistic) task performed
11 by native Spanish speakers (N=25). Surprisingly, we did not observe that regular rhythm
12 exerted a facilitatory effect on reaction times or accuracy. Further exploratory analysis
13 showed that targets that appear later in sequences of syllables and sounds are
14 identified more quickly. In late targets, reaction times in stimuli with a regular rhythm
15 were lower than in stimuli with irregular rhythm for linguistic material, but not for non-
16 linguistic material. The difference in reaction times on stimuli with regular and irregular
17 rhythm for late targets was also larger for linguistic than for non-linguistic material. This
18 suggests a modulatory effect of rhythm on linguistic stimuli only once the percept of
19 temporal isochrony has been established. We suggest that temporal isochrony
20 modulates attention to linguistic more than to non-linguistic stimuli because the human
21 auditory system is tuned to process speech. The results, however, need to be further
22 tested in confirmatory studies.

23 Introduction

24 The perceptual system does not process continuous sensory input equally at all times:
25 some elements of the input are more attended than others (Landau & Fries, 2012).
26 Attention samples the continuously changing environment in discrete chunks, which
27 correspond to the periods of neural oscillations in the 4-8Hz frequency band
28 (VanRullen, 2018). Perception thus operates on these chunks of sensory information,
29 while the phase of neural oscillations modulates attentional intensity, and thus the
30 probability of perceiving a certain element in the environment.

31 The central (Doelling, Arnal, Ghitza, et al., 2014; Ghitza, 2013) and peripheral
32 (Greenberg & Ainsworth, 2004) auditory neural systems are also sensitive to rhythmic
33 patterns in the environment. This sensitivity plays an important role in processing
34 auditory information, including both linguistic and non-linguistic auditory input. Some
35 segments in the input are better attended because their occurrence is predicted by a
36 repetitive rhythmic pattern. Several theories (e.g. Dynamic Attentional Theory, Jones,
37 1976; The Attentional Bounce Hypothesis, Shields, McHugh, & Martin, 1974, discussed
38 below) have been put forward to explain how these rhythmic patterns might modulate

1 attention allocated for processing sensory input. Attentional rhythms (most likely based
2 on neural oscillations; Fiebelkorn & Kastner, 2018; Haegens & Golombic, 2019; Hickok
3 et al., 2015; VanRullen, 2016) and environmental rhythms can become synchronized,
4 such that more attentional resources are allocated to the expectancy cues provided by
5 regularly occurring events in the environmental input (Obleser et al., 2017). Regular
6 metrical patterns in environmental input facilitate establishing and maintaining
7 synchronization between environmental and attentional oscillations, which may lead to
8 entraining even spontaneously occurring neural oscillations to environmental rhythms.
9 Neural rhythms sample the environment rhythmically, and the effect of environmental
10 rhythms, which entrain neural rhythms and thus lead to resampling the world based on
11 what the environment is like in particular circumstances, and drawing attention to more
12 relevant aspects of the world at a particular moment. This, in turn, allows for faster and
13 more accurate processing of continuous sensory inputs (Jones, 1976).

14 The coupling between neural and environmental rhythms can also enhance processing
15 of auditory linguistic information which contains more regularly distributed salient
16 acoustic events (stressed syllables, vowel onsets). Attention is drawn to stressed
17 syllables more than their unstressed counterparts (Cutler, 1977; Cutler & Foss, 1976),
18 and mispronounced phonemes are more likely to be perceived as deviant in stressed
19 positions (Bond & Garnes, 1980; Cole & Jakimik, 1980). Shields et al. (1974) asked
20 people to monitor a particular phoneme in connected speech. Target phonemes were
21 detected faster and more reliably in stressed syllables than in unstressed syllables.
22 Moreover, the facilitatory effect of stress was not observed when the same words
23 containing the target phoneme were embedded in nonsense sentences. The authors
24 suggested that stressed syllables in meaningful sentences are temporarily predictable
25 and thus attract more attentional resources and facilitate target detection. In
26 meaningless sentences, expectancy cues do not exist (participants cannot predict
27 upcoming words and stressed syllables). Thus, it is the expectancy cues rather than
28 acoustic correlates or the perceptual salience of stressed syllables that enhance
29 phoneme detection in speech. Their results led to the Attentional Bounce Hypothesis:
30 attention locks onto the quasi-isochronous distribution of stressed syllables and moves
31 from one stressed syllable to another (Shields et al., 1974). The longer the preceding
32 rhythmic pattern leading to the target, the better the percept of temporal isochrony is
33 established, and the stronger expectancy and its facilitatory effect (Pitt & Samuel,
34 1990). In line with this, Ordin et al. (2019) showed that in AX discrimination
35 experiments, regular rhythm in the A stimulus (first stimulus in a stimulus pair) led to
36 faster and more accurate responses, regardless of whether the X stimulus (second
37 stimulus in a stimulus pair) was rhythmically similar to or different from the A stimulus.
38 They suggested that rhythmic regularity in the first stimulus enhances attention and thus
39 results in better performance.

1 A succession of stressed syllables creates a metrical grid that is used to facilitate
2 speech processing. The perceptual system can rely on this grid to predict the
3 occurrence of the next stressed syllable, allocating more resources to these syllables so
4 as to process input more efficiently. In addition to metrical expectancy, which relies on
5 the metrical grid created by the occurrence and predictability of stressed syllables,
6 Quené and Port (2005) explored the effect of timing expectancy on the processing of
7 linguistic input. Participants performed a phoneme monitoring task while listening to a
8 sequence of isolated words. Timing expectancy was manipulated by variation in the
9 inter-word duration: regular inter-word intervals provided stronger expectancy cues for
10 word onsets than variable inter-word intervals. Metrical expectancy was achieved by
11 modifying the stress patterns in the preceding word sequence. A similar stress pattern
12 (iambic or trochaic) across all the words in a sequence allowed for expectancy cues to
13 emerge, whereas varying stress patterns within a sequence disrupted metrical
14 expectations. For timing expectancy, the resulting reaction times were shorter in the
15 regular than in the irregular condition, showing a clear timing expectancy effect when
16 inter-word durations were constant. On the other hand, metrical expectancy did not
17 exert an effect on reaction times. These results suggest that speech perception may be
18 more affected by timing than by metrical patterns.

19 Although the facilitatory effect of regularity and expectancy on auditory perception has
20 been observed on linguistic (Pitt & Samuel, 1990; Quené & Port, 2005; Shields et al.,
21 1974) and non-linguistic (Jones, 1976) materials, there are important differences in how
22 linguistic and non-linguistic sounds are processed (Warren, Obusek, Farmer et al.,
23 1969). Speech is segmented into phonemes which belong to classes defined by fine-
24 grained boundaries, while non-linguistic sounds are not (Hendrickson, Walenski, Friend,
25 et al., 2015). Humans engage in attentive processing of linguistic sounds in contrast to
26 non-linguistic sounds (Warren et al., 1969). Even if the latter are heard on a daily basis,
27 they are mostly processed unconsciously by the auditory system; humans tend to filter
28 out and ignore passive sounds they are accustomed to hearing constantly, but which
29 hold no significance for them (e.g., birds chirping outside the house).

30 The human auditory system may be better honed for processing linguistic than non-
31 linguistic acoustic material. Thus, the magnitude of the expectancy effect on attentional
32 rhythms might vary for linguistic and non-linguistic material. The current study provides
33 an explicit within-subject comparison of reaction times and accuracy in an auditory
34 target-detection task in a sequence of regularly and irregularly distributed syllables
35 (linguistic material) and environmental sounds (non-linguistic material). We
36 hypothesized that rhythmic expectancy modulates attention to linguistic more than to
37 non-linguistic stimuli. To test this hypothesis, we set up a syllable-monitoring (linguistic
38 sounds) and sound-monitoring (non-linguistic sounds) task for 25 native Spanish

1 participants. They were instructed to listen for auditory targets within a series of auditory
2 sequences, characterized by either regular or irregular inter-stimulus intervals.

3 Methodology

4 Participants

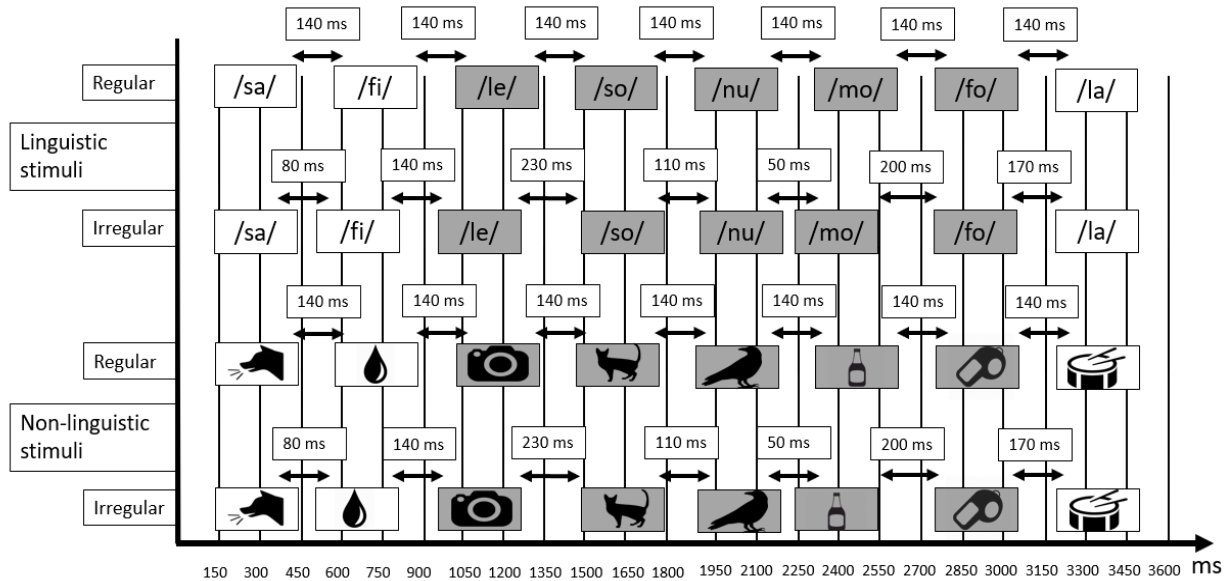
5 Twenty-five native Spanish speakers (mean age = 22.72 years, median age = 22 years;
6 17 women) were recruited. None of them reported any speech or hearing problems. The
7 experiment was approved by the BCBL ethical review board. All subjects signed written
8 consent in accordance with the Declaration of Helsinki and received €8 as financial
9 compensation.

10 Material

11 The linguistic material included 25 distinct consonant-vowel syllables recorded by a
12 native Spanish speaker. The syllables were composed of 5 consonants (l, m, n, s, f) and
13 5 vowels (a, o, i, e, u), all of which exist in Spanish. We avoided plosive consonants
14 because their durations cannot be manipulated without compromising naturalness.
15 Each syllable was recorded in a separate audio file. The durations of consonants and
16 vowels were manipulated such that all consonants lasted 100ms and all vowels lasted
17 200ms (300ms per syllable). All of the audio files were equalized in terms of their
18 average level of intensity (with the upper threshold set to 80dB), to ensure that none of
19 the syllables in *relatively* louder (i.e., has relatively higher intensity level) than other
20 syllables.

21 The non-linguistic stimuli comprised 25 distinct transient sounds (e.g. a drop of water).
22 These sounds were carefully picked to differ in terms of spectral characteristics and to
23 be clearly and easily discriminated by the participants. These sounds were equalized in
24 terms of duration (300ms) and average intensity (with an upper threshold of 80dB).

25 We created sequences of 8 syllables or sounds to be used as experimental trials. Each
26 sequence started and finished with a 140ms period of silence. We counterbalanced
27 sounds/syllables across sequences. The inter-syllable/sound intervals were
28 manipulated to generate rhythmic differences: constant inter-syllable/sound durations
29 for regular rhythm and jittered inter-syllable/sound durations for irregular rhythm stimuli.
30 In the regular rhythm condition, all 7 inter-syllable/sound intervals were constant at 140
31 ms. For the irregular condition, we used seven interval values: 50ms, 80ms, 110ms,
32 140ms, 170ms, 200ms, 230ms. Within each stimulus, these values occurred in
33 randomized order, with each value used only once, such that the total duration of each
34 trial sequence was 3660ms. In total, 300 stimuli were created, 75 per each of the 4
35 conditions defined by rhythm type (regular and irregular) and stimulus type (linguistic
36 and non-linguistic).



1
 2 **Figure 1:** Schematic overview of stimuli in the regular and irregular rhythm stimuli. Each box
 3 represents a syllable/sound. Possible positions of target syllables/sounds are marked by a
 4 darker colour.

5 Procedure

6 The experiment consisted of a syllable- (for linguistic stimuli) and sound- (for non-
 7 linguistic stimuli) monitoring task. The participants were seated in front of a screen in a
 8 soundproof room. The stimuli were presented via headphones in PsychoPy.

9 On each trial, participants heard the sentence “Now listen for X” (where X stands for the
 10 specific target sound or syllable used); after a 1-second pause a sequence of syllables
 11 or sounds was played. On each trial, a target was embedded in the presented
 12 sequence. The target positions varied between the third, fourth, fifth, sixth, and seventh
 13 positions within the sequence. (**Figure 1**). Syllables/sounds were counterbalanced to
 14 appear as targets the same number of times in each position. The targets and their
 15 positions within the sequences were counterbalanced across trials, with every single
 16 syllable/sound and position being selected three and fifteen times respectively in each
 17 condition.

18 Participants were instructed to press the button on a response box as soon as they
 19 heard the specified target sound/syllable. The trial was interrupted when the button was
 20 pressed. The participants manually initiated every trial at their own discretion. Nothing
 21 was presented on the screen when the sounds were being played. The order of trials
 22 with linguistic and non-linguistic material and with regular and irregular rhythms, was
 23 randomized for each participant. Prior to the experiment, 4 practice trials were initiated
 24 as a training session, in order to familiarize participants with the task and to allow them
 25 to adjust the volume to a comfortable level. Volume adjustment changed the loudness

1 of the stream overall, but due to the intensity normalization procedure the *relative*
 2 loudness of the sounds/syllables in sequences was kept constant.

3

4 Results

5 Reaction time was calculated as the delay between the onset of the target
 6 syllable/sound and the time when the participant pressed the button to signal that the
 7 target had been detected. Listeners failed to detect the targets 72 times (0.96% of all
 8 trials lacked responses; a response was considered to be missing if it was not given
 9 within 1000ms after the end of a sequence). On 212 trials (2.82% of all trials), a
 10 response was given before the target was presented. Missing responses and premature
 11 responses amounted to a total of 284 errors (3.7%) trials in the entire experiment. The
 12 number of errors across rhythm types was the same. In the linguistic stimuli, there were
 13 exactly 43 errors for both the regular and irregular rhythms, while in the non-linguistic
 14 stimuli, there were exactly 99 errors for both the regular and irregular rhythms (**Table 1**).

15 **Table 1.** Errors categorized by type, rhythm, and stimuli

Errors in linguistic stimuli				Errors in non-linguistic stimuli			
Regular		Irregular		Regular		Irregular	
43		43		99		99	
Early Response	No Response	Early Response	No Response	Early Response	No Response	Early Response	No Response
31	12	36	7	75	24	70	29

16

17 For premature responses, the effect of *stimulus type* (linguistic vs. non-linguistic) on the
 18 number of errors was significant and strong, $F(1,24)=8.977$, $p=.006$, $\eta_p^2=.272$, while the
 19 effect of *rhythm* (regular vs. irregular), $F(1,24)<.0005$, $p=1.0$, $\eta_p^2<.0005$, and the
 20 interaction between *rhythm* and *stimulus type*, $F(1,24)=.623$, $p=.438$, $\eta_p^2=.025$ were not
 21 significant. For missing responses, the effect of *stimulus type* was significant and
 22 strong, $F(1,24)=11.352$, $p=.003$, $\eta_p^2=.321$, while the effect of *rhythm*, $F(1,24)<.0005$,
 23 $p=1.0$, $\eta_p^2<.0005$, and the interaction between *rhythm* and *stimulus type*, $F(1,24)=1.263$,
 24 $p=.272$, $\eta_p^2=.05$ were not significant. This reveals a significantly and substantially larger
 25 number of errors on non-linguistic than on linguistic material, and this pattern is not
 26 modulated by the rhythm implemented in the stimuli.

27 Data screening was performed on remaining trials to detect the outlying RT values
 28 defined as the values exceeding 2SD from the mean in each rhythm*stimuli combination
 29 (22 trials or 0.3% of all trials). Including trials discarded due to errors, this brings the
 30 total percentage of discarded trials to 4% (306 out of 7.500 trials).

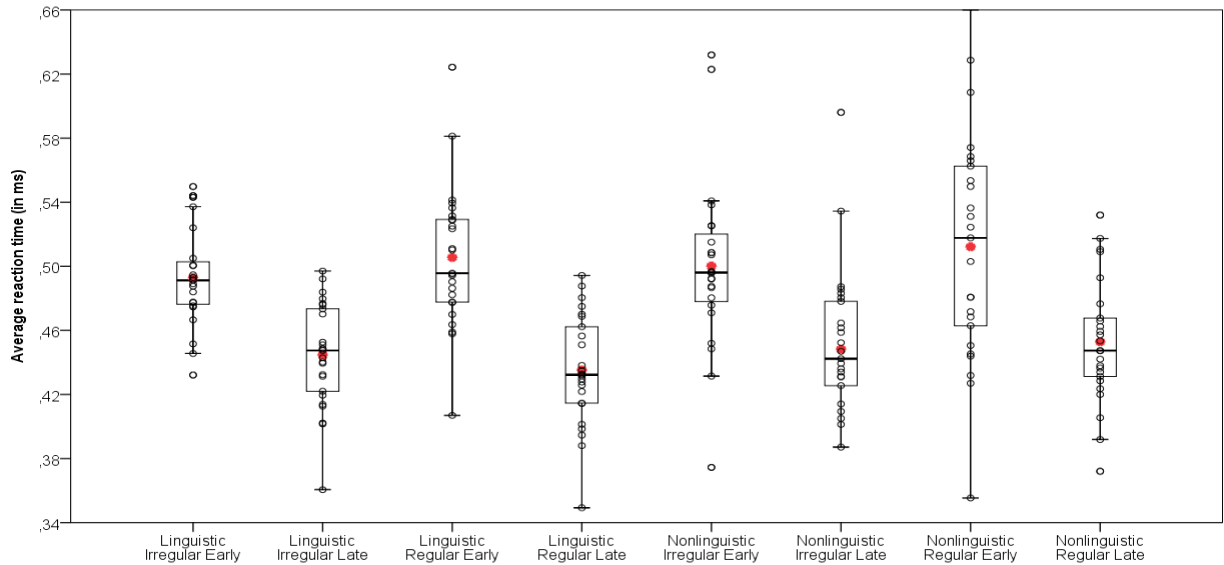
1 The remaining reaction time values were averaged for each participant per rhythm
 2 (regular/irregular) and stimulus type (linguistic/non-linguistic) and included in the
 3 statistical analysis. A repeated measures ANOVA with *rhythm* (regular vs. irregular) and
 4 *stimulus type* (linguistic vs. non-linguistic) as factors did not reveal a significant effect of
 5 *rhythm*, $F(1,24)=.542$, $p=.508$, $\eta_p^2=.018$ or *stimulus type*, $F(1,24)=3.577$, $p=.071$,
 6 $\eta_p^2=.13$. The interaction between *rhythm* and *stimulus type* was also not significant,
 7 $F(1,24)=.386$, $p=.368$, $\eta_p^2=.015$. Thus, the data does not confirm the original hypothesis:
 8 we did not find evidence that regular rhythm modulates performance more on linguistic
 9 than non-linguistic stimuli. Moreover, to our surprise, we did not observe any effect of
 10 rhythm type: the data did not provide evidence that metrical regularity facilitated
 11 performance on monitoring tasks. Therefore, we decided to explore the data further in
 12 an exploratory study.

13 We expected to find a significant effect of rhythm based on earlier studies and
 14 theoretical assumptions. The absence of this effect might indicate that it takes time to
 15 establish the percept of isochrony between syllable or sound onsets. This would result
 16 in either a weak or non-existent effect on targets closer to the beginning of the trial
 17 sequences. Therefore, we decided to explore the effect of *rhythm* in early and late
 18 positions. The third and fourth positions were considered the *early target positions*,
 19 while the fifth, sixth, and seventh positions were considered *late target positions*. We
 20 calculated the average reaction time for each participant separately for *early* and *late*
 21 positions per stimulus type and rhythm (**Figure 2**), and introduced *position* (early vs.
 22 late) as a factor in the model (in addition to the effects of *stimulus type* and *rhythm*). The
 23 analysis revealed a significant and substantial effect of *position*, $F(1,24)=166.24$,
 24 $p<.0005$, $\eta_p^2=.874$. Targets in late positions were detected with shorter reaction times
 25 than targets in early positions (**Table 2**). However, the effect of *stimulus type*,
 26 $F(1,24)=2.994$, $p=.096$, $\eta_p^2=.111$, and the effect of *rhythm*, $F(1,24)=.919$, $p=.347$,
 27 $\eta_p^2=.037$ were not significant. None of the interactions were significant.

28 **Table 2.** Averaged reaction time per stimuli type, rhythm, and position

Condition	Mean (in ms)	SD	95% confidence interval around M
Linguistic Irregular Early Position	.4928	.044	.48:.51
Linguistic Irregular Late Position	.4446	.033	.43:.46
Linguistic Regular Early Position	.5054	.044	.49:.52
Linguistic Regular Late Position	.4353	.035	.42:.45
Non-Linguistic Irregular Early Position	.508	.065	.48:.54
Non-Linguistic Irregular Late Position	.4483	.052	.43:.47
Non-Linguistic Regular Early Position	.5122	.071	.48:.54
Non-Linguistic Regular Late Position	.4529	.039	.44:.47

29



1
2 **Figure 2.** Average reaction times categorized by stimulus type (linguistic or non-linguistic),
3 rhythm (regular or irregular), and position (early or late). Each circle stands for the data from an
4 individual participant, red dots represent the means and horizontal lines represent the medians.
5 Boxes contain 50% of the datapoints, downward and upward whiskers each span 25% of
6 datapoints.

7
8 Following the pattern, we compared the effect of *rhythm* on reaction times for linguistic
9 and non-linguistic stimuli, separately, using paired t-tests (two-tailed, assumption of
10 normality verified by the Kolmogorov-Smirnov tests, which showed no significant
11 deviations in the data distribution from the normal distribution in any sample, all p values
12 >.9). On linguistic material, targets in late positions were identified faster in the regular
13 than the irregular condition, $t(24)=2.49$, $p=.02$ (corrected by the Bonferroni method),
14 mean difference $M=.009(SD=0.19)$, $SE=.004$, 95%CI of the difference [.002: .017],
15 $d=.28$. On non-linguistic stimuli, however, the effect of rhythm in late positions was not
16 significant, $t(24)=.688$, $p=.498$, $M=.005(0.34)$, $SE=.007$, 95%CI of the difference [-.019:
17 .001], $d=.1$. To directly test the hypothesis that the difference in RTs in late position
18 between regular and irregular conditions was larger for linguistic than non-linguistic
19 material, we ran a paired t-test, $t(24)=1.958$, $p=.031$, $d=.506$. This pattern suggests that
20 the effect can only be observed on linguistic stimuli, and at least four inter-syllable
21 intervals are required for the effect of isochrony to emerge – possibly because it takes
22 this long for the percept of regularity to become established.

23 To further understand this relationship, we ran Spearman's correlations between the
24 positional order when the target was detected (all positions were considered, without
25 splitting them into bins) and reaction times, separately for linguistic regular ($\rho=-.635$),
26 linguistic irregular ($\rho=-.535$), non-linguistic regular ($\rho=-.489$) and non-linguistic irregular
27 ($\rho=-.459$) stimuli. The fact that all these correlations were negative shows that reaction

1 time decreases as ordinal position increases (people are faster towards the end of a
 2 sequence). However, the only significant difference between the correlation coefficients
 3 was between correlations for regular linguistic and regular non-linguistic stimuli, $z=1.7$,
 4 $p=.045$ (2-tailed). This shows that regularity is associated with a sharper decline in
 5 reaction times in linguistic stimuli than non-linguistic stimuli as a sequence progresses
 6 (and the ordinal number of the target position increases). This is in line with the earlier
 7 conclusion that regularity has a stronger effect on linguistic than on non-linguistic
 8 materials. We did not observe differences in correlation strengths in other tests (Table
 9 3).

10 **Table 3.** Comparing strengths of non-parametric correlations between the ordinal position of the
 11 target and reaction times in stimuli with isochronous (regular) and non-isochronous (irregular)
 12 distribution of speech-like syllables (linguistic stimuli) and non-linguistic sounds (non-linguistic
 13 stimuli).

Condition	z	p	Interpretation
Linguistic Regular vs. Linguistic Irregular	1.192	.117	Tests linguistic materials to ascertain if regular rhythm is associated with a sharper decline in reaction times than irregular rhythm
Non-Linguistic Regular vs. Non-Linguistic Irregular	.282	.389	Tests non-linguistic materials to ascertain if regular rhythm is associated with a sharper decline in reaction times than irregular rhythm
Linguistic Regular vs. Non-Linguistic Regular	1.7	.045	Tests whether regular rhythm is associated with a sharper decline in reaction times for linguistic compared to non-linguistic stimuli
Linguistic Irregular vs. Non-Linguistic Irregular	.79	.215	Tests if irregular rhythm is associated with a sharper decline in reaction times for linguistic compared to non-linguistic stimuli

14 Discussion

15 Surprisingly, we did not observe any effect of temporal regularity on performance
 16 (accuracy and reaction times) in the sound-monitoring task, which we used as a proxy
 17 for online attention. Our exploratory analysis showed that targets towards the end of the
 18 sequences were detected faster. The way we randomized inter-sound/syllable intervals
 19 might explain why we observed better performance both on regular and irregular stimuli
 20 in late positions. To create irregularity, we used a set of 7 possible values, ranging from
 21 50ms to 230ms (with 30-ms steps) as inter-syllable and inter-sound intervals, with each
 22 value used only once per sequence. Consequently, participants might have figured out
 23 that the inter-sound intervals were not completely random, since with each passing
 24 sound, the degrees of freedom for the remaining values reduced, increasing the

1 predictability of the duration of the next inter-sound interval. That is, at the beginning of
2 any sequence, there are seven possible interval durations, but for late positions, only
3 three possible durations remain; if participants kept track of durations that had already
4 occurred as the sequence progressed, they could better predict the onset of the
5 following sound/syllable, and prepare to make a behavioral response if a target was
6 detected. This predictive effect might mask any effect of rhythmic regularity, if the latter
7 only emerges in late positions. In early positions, a regularity effect has not yet been
8 established in the regular condition, nor has a predictability effect been established in
9 the irregular condition, thus explaining why no significant differences between
10 conditions or material types were observed. A similar phenomenon has also been
11 reported in the visual perceptual modality, when targets were embedded in a sequence
12 of isochronously and non-isochronously presented sequences of images (Coull, 2009).
13 Reaction times decreased over time because the conditional probability that a target
14 would appear given that it has not yet appeared increases over time, thus alerting
15 participants' attention towards the end of the sequence. In future experiments, the
16 position of the target could be kept constant, while manipulating the presence vs.
17 absence of the target. This would control for differences in attention at the beginning
18 and the end of the sequences due to the increase of the conditional probability that the
19 target will occur, given that it has not yet occurred.

20 Further tests showed that in late positions, targets were detected faster when syllables
21 – in linguistic stimuli – were distributed with isochronous inter-syllable intervals.
22 Importantly, significant differences in reaction times for detecting target sounds – in non-
23 linguistic material – were not observed. The difference in reaction times between regular
24 and irregular conditions for linguistic stimuli was significantly bigger than the difference
25 in reaction times between regular and irregular conditions for non-linguistic stimuli. This
26 suggests that a modulatory effect of regularity can only be observed on **linguistic**
27 material **later** in sequences (which is in line with Pitt & Samuel, 1990, who observed a
28 stronger facilitatory effect of regular rhythm in longer than in shorter sequences).
29 However, due to the exploratory nature of this analysis in our study, a confirmatory
30 study using a more targeted design should be conducted.

31 It is not clear why we found no effect of regularity on non-linguistic material even in late
32 positions. We can suggest several factors that could interfere with the modulatory effect
33 of rhythm on the sound monitoring task. Individual differences in familiarity with sounds
34 could be an interfering factor; some participants might have experienced more exposure
35 to certain sounds than others. Another factor might be the problem of classifying non-
36 linguistic sounds. Such sounds might not be concretely classified in the mental lexicon,
37 and thus make it more difficult to exactly determine their identity, resulting in semantic
38 misinterpretations (Hendrickson et al., 2015). Also, humans interact with linguistic and
39 non-linguistic sounds differently. They allocate more attention to sounds which are

1 deemed more important; linguistic sounds are likely to be accorded more importance as
2 they are a means for communication.

3 Spontaneous neural oscillations lead to rhythmic sampling of the world (VanRullen,
4 2016; Fiebelkorn & Kastner, 2018). However, acoustic rhythms in environmental input
5 can modulate excitability patterns in the auditory system, entraining neural rhythms to
6 environmental rhythms (Hickok et al., 2015; Lakatos et al., 2019; Obleser et al., 2017).
7 This entrainment could change how the world is sampled, and what aspects of the
8 environmental stimuli are zoomed in on and selected for attention. Because of the
9 functional importance of speech, it is also possible that speech-like stimuli lead to
10 stronger modulatory effects on neural oscillations, producing better entrainment of
11 neural oscillations than non-linguistic stimuli. If the initial non-linguistic sound in a
12 regular condition in our experiment was aligned with a phase of the perceptual cycle
13 where the probability for perception was low, the following sounds in the sequence,
14 which are distributed at equal temporal intervals, might also have been aligned with that
15 same phase, where they were unlikely to be perceived (VanRullen, 2016). By contrast,
16 syllables, which are quickly recognized as functionally important linguistic inputs, could
17 lead to a more rapid re-adjustment of the phase of neural oscillators. Even in cases
18 where initial syllables in a sequence were aligned with a phase in the perceptual cycle
19 that afforded only a low probability for perception, syllables later in the sequence could
20 become aligned with a phase with a higher probability of perception. Slower phase
21 resets for non-linguistic stimuli and faster phase resets for syllables might explain why
22 we found better task performance for linguistic than non-linguistic material towards the
23 end of the sequence. This interpretation, however, calls for additional empirical testing.

24 Whether the effect of linguistic stimuli would be observed in the visual modality presents
25 an interesting question for further investigation. As an evolutionarily ancient
26 phenomenon, spoken language might involve finely tuned perceptual and cognitive
27 mechanisms specifically adapted for speech processing and comprehension. Regular
28 rhythm (in the auditory modality) not only affects auditory processes related to speech
29 processing but also higher-level mechanisms involved in language comprehension,
30 including lexico-semantic integration (Rothermich, Schmidt-Kassow, & Kotz, 2012).
31 Writing is a relatively recent cultural innovation and, in the visual unlike the auditory
32 modality, linguistic stimuli might not exert a stronger effect on rhythmic attention than
33 non-linguistic stimuli. This hypothesis, if verified, might throw light on how the speech
34 and language faculty influence general cognitive processes in humans.

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3 Competing Interests

4 The authors have no competing interests to declare.

5 Authors contributions

6 OR and MO conceived the study, OR prepared and ran the experiment and analyzed
7 the data, OR and MO interpreted the results and wrote the manuscript.

8 Data accessibility

9 Data will be made available on the figshare repository.

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