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Does Rapid Auditory Stimulation Accelerate an Internal Pacemaker? Don't Bet on It

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Abstract

Several interesting studies in the literature have demonstrated that a temporal interval coinciding with or following a rapid sequence of auditory stimuli is subjectively lengthened relative to a baseline interval without such rapid auditory stimulation (RAS). It has also been found that an interval preceding RAS is subjectively shortened. These effects have been attributed to acceleration of an internal pacemaker by RAS. The present study used musically trained participants in two experiments, similar to some reported in the literature. In Experiment 1, rapid chromatic scales preceded, followed, or intervened between two empty intervals that had to be compared. In Experiment 2, a series of comparison intervals, each preceded by a series of rapidly repeated tones, had to be compared to a memorized standard interval. Neither experiment yielded any effects of RAS relative to a control condition without RAS. These negative results raise questions about the conditions under which RAS affects interval judgment, and whether pacemaker acceleration is the correct explanation for these effects when they do occur.

Keywords

Temporal discrimination, pacemaker, rapid auditory stimulation, arousal, internal clock

1. Introduction

The human ability to assess time is crucial to the manner in which we function in our everyday lives. Our capacity to judge intervals of time and to act accordingly is fundamental to how we interact with the world. What cognitive mechanisms are at play when we make such judgments? This question is addressed by a variety of research on human and nonhuman temporal perception. One hypothesis is

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that there is a dedicated biological mechanism, an ‘internal clock’ that is responsible for mediating our perception of time. In influential papers, Creelman (1962) and Treisman (1963) independently introduced the hypothesis of an *internal pacemaker* as the neural basis for the internal clock. According to Treisman, the pacemaker produces a series of pulses at a certain frequency that, however, can change with arousal or be entrained by external rhythms. A neural counter counts the pulses within an interval delimited by two sensory inputs. The count is recorded in short-term memory and can then be used as a standard against which subsequent time intervals are compared. These ideas eventually led to scalar expectancy theory (Gibbon, 1977, 1991; Gibbon, Church & Meck, 1984), which has been successful in accounting for a variety of results concerning nonhuman and human time perception and remains popular, despite recent challenges (e.g. Buhusi & Meck, 2005; Grondin, 2010).

In order to better understand the hypothesized pacemaker, researchers have attempted to influence its pulse emission frequency. For example, the administration of certain drugs to laboratory rats has led to behavior suggesting systematic changes in pacemaker speed (Meck, 1983, 1996). It has also been observed that an increase in body temperature seems to cause an increase in internal clock speed (Lockhart, 1967; Wearden & Penton-Voak, 1995). However, these types of manipulation are cumbersome and potentially hazardous for human participants. Therefore, apparent effects of harmless sensory stimuli on pacemaker frequency have aroused considerable interest. Early findings indicating that auditory stimuli are perceived to be longer than equally long visual stimuli (e.g. Goldstone & Goldfarb, 1964a, 1964b) could be viewed as being due to acceleration of the internal pacemaker by continuous auditory stimulation (Penney, Gibbon & Meck, 2000). Treisman, Cook, Naish & MacCrone (1990) presented clicks at various rates to influence the rate of the hypothesized internal pacemaker, which was assumed to be reflected in the judged duration of a simultaneously presented visual stimulus. Two independent effects of click rate were found: local decreases and increases of subjective duration near multiples of a certain frequency (12.4 Hz), and a monotonic increase of subjective duration with click rate up to about 16 Hz. Treisman et al. interpreted the local effects as being indicative of entrainment of an internal oscillator to click rates that are similar to its basic operating frequency, and the monotonic increase as being due to arousal, which was assumed to be mediated by a separate ‘calibration unit’ that intervenes between the oscillator and the pulse counter. Subsequent studies by Treisman and colleagues focused on the entrainment effect (Treisman & Brogan, 1992; Treisman, Cook, Naish & MacCrone, 1994; Treisman, Faulkner & Naish, 1992).

Our study is concerned instead with the arousal effect, which was investigated further by Penton-Voak, Edwards, Percival & Wearden (1996). They used four different experimental paradigms: temporal generalization, pair comparison, verbal estimation, and interval production. In contrast to the studies by Treisman and colleagues, the test stimuli in the first three tasks were tones whose duration was to be judged, and click trains *preceded* (rather than coincided with) the tones. Nevertheless, the predicted effect of arousal was found in all experiments: tones were judged as longer when preceded by click trains than when preceded by silence, consistent with acceleration of an internal pacemaker that outlasts the *rapid auditory stimulation* (*RAS*) that causes it. Moreover, interval durations produced via button presses in response to millisecond values displayed on a screen were shorter following RAS than following silence, which is also consistent with persistent pacemaker acceleration. Click train duration and click frequency were varied in some of these experiments. In one experiment, larger effects were obtained with click train durations of 3 and 5 s than of 1 s. However, click frequency (ranging from 5 to 50 Hz) did not seem to be an important variable; effects were obtained even with the relatively slow stimulation rate of 5 Hz. Subsequent studies by Wearden and colleagues replicated some of these findings with Parkinson's patients (Wearden et al., 2009) and also showed that RAS can improve performance in various other cognitive tasks, presumably via acceleration of the internal pacemaker (Jones, Allely & Wearden, 2011).

Ono & Kitazawa (2010) recently introduced another variant of the RAS paradigm. Their task required comparison of two empty intervals delimited by brief tone bursts. A rapid series of short tones, presented at 5 or 25 Hz for a total duration of 1 s, occurred either before or after the second interval. When this RAS followed the second interval, the interval was judged to be relatively *shorter* than when no tones followed, which suggests a contrastive retroactive effect of pacemaker acceleration. The effect was larger with the faster stimulation and was found to disappear when a 500 ms silent interval intervened between the test interval and the RAS. When RAS preceded the test interval, the interval was judged as longer after 25 Hz than after 5 Hz stimulation; unfortunately, in that experiment there was no control condition without RAS. Ono & Kitazawa were primarily interested in the new retroactive effect, but it seems that they also replicated the proactive effect of RAS.

In the present study, we wanted to investigate whether this supposed pacemaker acceleration effect could also be demonstrated in musicians. If so, it might have some interesting implications for music perception and performance, as various forms of RAS (e.g. a roll on a snare drum) are quite common in real music. Musicians are likely to be more accurate in their temporal judgments than nonmusicians, but we thought their internal pacemaker should function in the same way and saw no obvious reason why it should be exempt from acceleration by RAS. Therefore, we expected to replicate the basic findings of the studies just reviewed. We report two experiments whose respective paradigms were similar to, though not identical with, those of Ono & Kitazawa (2010) and Experiment 1 of Penton-Voak et al. (1996).

2. Experiment 1

In this experiment, we asked participants to compare two empty intervals (I1, I2), as did Ono & Kitazawa (2010). However, we expanded the design to four conditions by presenting RAS (1) before I1, (2) between I1 and I2, (3) after I2, or (4) not at all. Relative to Condition 4, the control or baseline, we expected I1 to be judged as longer than I2 in Conditions 1 and 3, due to subjective lengthening of I1 in Condition 1 and subjective shortening of I2 in Condition 3. In Condition 2, we expected a reversed effect, due to simultaneous subjective shortening of I1 and subjective lengthening of I2. To give the experiment a slightly musical flavor, we used rapid chromatic scales as the RAS. Although previous studies had used repetitions of identical clicks or tones, we assumed that event rate was the important factor.

2.1. Method

2.1.1. Participants

The participants were nine graduate students from the Yale School of Music (3 men, 6 women, ages 21–27), who were paid for their efforts. They all played their primary instruments (piano (2), violin, viola (2), flute, trombone, harp, guitar) at a professional level, having studied them for 10–24 years.

2.1.2. Materials and Equipment

The experiment was programmed in Max/MSP 4.0.9 on an Intel iMac computer. Participants listened over Sennheiser HD280 pro headphones at a comfortable loudness and made their responses by clicking on virtual 'buttons' on the computer screen after each trial. All tones were produced by a Roland RD-250s digital piano and had a nominal duration of 40 ms. I1 was defined by the onsets of two successive tones with pitch C4 (262 Hz), and I2 by the onsets of two tones with pitch D4 (294 Hz). One of the two intervals (either I1 or I2) had a 'fixed' duration of either 600 or 800 ms while the 'variable' duration of the other interval differed from this standard by -20%, -10%, 0, $+10\%$, or $+20\%$. As these trials were randomly intermixed, this resulted in $2 \times 2 \times 5 - 2 = 18$ different trials (i.e. without duplication of the two trials with identical interval durations). As there were four RAS conditions (none, preceding I1, intervening, and following I2), a total of $18 \times 4 = 72$ different trials were presented in random order within a block.

RAS consisted of a series of 25 tones (each of 40 ms nominal duration) ascending from C3 (131 Hz) to C5 (523 Hz) in semitone steps with inter-onset intervals (IOIs) of 40 ms (i.e. at a rate of 25 Hz). This chromatic scale thus lasted 960 ms from the onset of the first tone to the onset of the last tone. IOIs of 300 ms preceded and/or followed the scale, to prevent interference or confusion of scale tones with the tones delimiting I1 or I2. Regardless of RAS presence and placement, there was always an IOI of 1560 ms between the second tone of I1 and the first tone of I2.

2.1.3. Procedure

Participants started each trial by clicking on a 'next trial' button on the screen. After each trial they indicated whether they judged I2 to be shorter, equal to, or longer than I1. They completed four blocks of trials in a session of about 50 min duration and received no feedback at any point in the experiment. There were short breaks between blocks during which the data were saved.

2.2. Results and Discussion

We expressed the responses as percentages of '$I2 > I1$' responses, in which we included half of the 'equal' responses. Figure 1 shows average response functions for the four RAS conditions, with separate panels for the two fixed durations assigned to either I1 or I2. The x-axis represents the percentage deviation of the variable interval from the fixed interval. It can be seen that the results for the four RAS conditions are very similar in each panel.

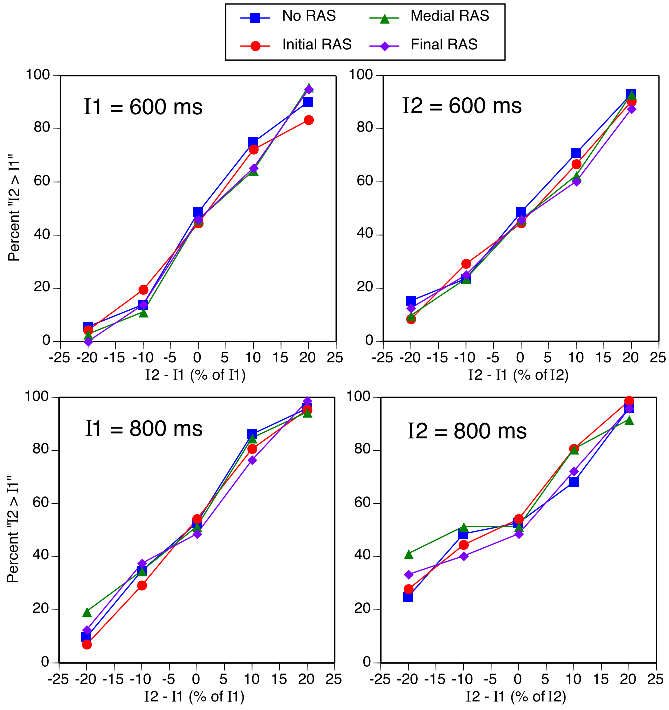

Figure 1. Percentage of 'I2 > I1' responses (with half of 'I2 = I1' responses included) as a function of I2 − I1 (expressed as a percentage of the fixed duration) in the four experimental conditions of Experiment 1, for four subsets of stimuli (separate panels). I1 = first interval, I2 = second interval, RAS = rapid auditory stimulation. This figure is published in color in the online version.

A 4 (RAS condition) × 2 (order: fixed duration first or second) × 2 (fixed duration: 600 or 800 ms) × 5 (interval difference: I2 − I1 in %) repeated-measures ANOVA on the I2 > I1 response percentages (with Greenhouse–Geisser correction to p levels) showed no main effect of RAS condition ($F(3, 24) = 1.09$, $p = 0.367$), nor any significant interaction involving RAS condition. Obviously there was a significant main effect of interval difference. In addition there were significant main effects of order, $F(1, 8) = 20.93$, $p = 0.002$, and fixed duration, $F(1, 8) = 39.75$, $p < 0.001$, as well as significant interactions of order with interval difference, $F(4, 32) = 17.67$, $p < 0.001$, and of fixed duration with interval difference, $F(4, 32) = 5.57$, $p = 0.008$. Overall, the response function was steeper when I1 was fixed than when I2 was fixed, and also steeper for shorter than for longer fixed interval durations. Although order and fixed duration did not interact significantly, the main reason for the significant effects can be seen in the lower right panel of Fig. 1: when I2 was 800 ms long and I1 was even longer (880 or 960 ms), participants found it difficult to detect that difference. This unexpected asymmetry suggests a shift of the memory for a long I1 towards the mean of the range of interval durations.

The main result, however, is that Experiment 1 failed to obtain the predicted effect of RAS. Some possible reasons are that the RAS was too brief (just 1 s long), that the changing pitch in the chromatic scale made it ineffective, and that the interval comparison task was somehow not ideal for demonstrating the effect. In Experiment 2 we adopted a different experimental paradigm, more similar to that of Experiment 1 in Penton-Voak et al. (1996).

3. Experiment 2

In this experiment we used a ‘temporal generalization’ task that required holding a standard interval duration in memory and to compare it to a series of comparison interval durations. Each comparison interval was preceded by RAS, or none was. The RAS was here a repeated tone and had one of two durations.

3.1. Methods

3.1.1. Participants

The participants were the same as in Experiment 1, except for the flutist (female) who was replaced by a guitarist (male). About 7 months elapsed between experiments.

3.1.2. Materials and Equipment

The equipment was the same as in Experiment 1. Each trial started with an empty standard interval that was presented three times in succession. This interval was delimited by the onsets of two 40 ms tones (pitch C4) and could have one of three durations: 600, 800, or 1000 ms. The IOI between repetitions of the standard interval was 2 s. The third presentation was followed by an IOI of 4 s. Then either the first comparison interval or the RAS preceding it was presented. Comparison intervals were delimited by the onsets of two 40 ms tones of pitch D4, the first of which followed the last RAS tone (if there was any RAS) after an IOI of 200 ms. RAS consisted of a 20 ms tone of pitch C6 (1047 Hz) presented at a rate of 25 Hz either 24 or 72 times, resulting in cumulative IOIs of 920 and 2840 ms, respectively. This stimulus sounded somewhat like the ringtone of an old telephone. The next comparison interval or the RAS that preceded it occurred 2 s after the participant’s response. There were 9 comparison intervals in each trial whose durations relative to the standard interval ranged from -20% to 20% in steps of 5%. Each of these durations occurred once in a trial, in random order. The factorial combination of three RAS conditions (none, short, or long) and three standard durations resulted in 9 randomly ordered trials, and as there were 9 comparison durations per trial, participants made 81 judgments per block.

3.1.3. Procedure

Participants started each trial by pressing the spacebar on the keyboard following a prompt on the screen and gave their responses by clicking ‘shorter’, ‘same’, or ‘longer’ on the screen in response to the printed question “Is the comparison interval shorter, the same, or longer than the standard interval?” They completed 5 blocks of 9 trials each. There were short breaks between blocks during which the data were saved in a file.

3.2. Results and Discussion

The results are shown in Fig. 2. The percentage of ‘$C > S$’ (comparison longer than standard) judgments (with half of ‘$C = S$’ judgments included) is shown as a function of the $S - C$ difference (in %) for the three experimental conditions and the three standard interval durations. It is clear that RAS had no effect.

A 3 (standard duration) × 3 (RAS condition) × 9 (interval difference) repeated-measures ANOVA on the response percentages revealed no significant effect in-

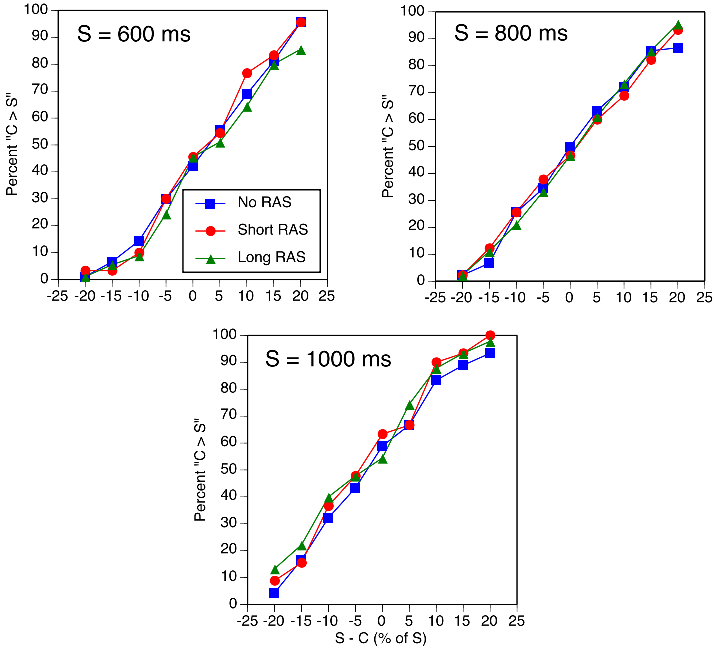

Figure 2. Percentage of 'C > S' responses (with half of 'C = S' responses included) as a function of S − C (expressed as a percentage of the standard duration) in the three experimental conditions of Experiment 2, for three standard durations (separate panels). S = standard interval, C = comparison interval, RAS = rapid auditory stimulation. This figure is published in color in the online version.

volving RAS condition. Apart from the obviously significant main effect of interval difference, the main effect of standard duration, $F(2, 16) = 24.83$, $p < 0.001$, and the interaction of standard duration and interval difference, $F(16, 128) = 3.27$, $p = 0.013$, were significant (with Greenhouse–Geisser correction to p levels). The main effect was due to an overall increase in 'C > S' responses as standard duration increased, which can be interpreted as a drift of the memory for the standard in the direction of the mean interval duration in the experiment (800 ms). Such global context effects are common in experiments on temporal judgment (e.g. McAuley & Miller, 2007). The interaction was mainly a consequence of this drift, which led to an early asymptote at negative values of S − C when S = 600 ms and an early asymptote at positive values when S = 1000 ms, whereas the response function for S = 800 ms was almost linear across the whole range. The slope of the response function changed little with standard duration, which is consistent with Weber's law holding (at least approximately) between 600 and 1000 ms.

4. General Discussion

Our two experiments were not successful in replicating the effect of RAS on temporal judgment, an effect that has been attributed to acceleration of an internal pacemaker. These findings indicate limitations to the conditions under which the RAS effect occurs, but it is difficult to pinpoint the experimental variables that were responsible for the negative results. Below we consider a number of possibilities.

One possibility is that RAS does not affect the perception of empty intervals, although this would be inconsistent with the pacemaker acceleration hypothesis. Treisman et al. (1990) used silent intervals defined by the duration of a visual stimulus, with RAS occurring during those intervals. Penton-Voak et al. (1996) found that RAS affects duration perception when it precedes the test stimulus, but the stimulus was a tone, hence a filled interval. (In one experiment, it was a visual stimulus.) Our point of departure was the study of Ono & Kitazawa (2010), who used empty intervals delimited by brief auditory stimuli. Their own replication of the effect of preceding RAS was only partial, lacking a baseline condition. Still, it seems unlikely to us that our use of unfilled intervals explains the absence of a RAS effect.

A more serious issue is the decay time of the effect RAS has on the pacemaker, about which little is known. It is quite plausible that an internal pacemaker might be accelerated during presentation of RAS, as in the study of Treisman et al. (1990), but how long does this acceleration persist after RAS is turned off? The persistence could be as short as a few hundred milliseconds or as long as a few seconds or more. Penton-Voak et al. (1996) in their Experiment 3b observed that the effect of preceding RAS increased with the duration of the judged interval up to 1200 ms (the longest duration they used), which is consistent with pacemaker acceleration persisting throughout the interval. Actually, however, their data show little evidence of a steady increase; rather, long intervals showed a larger effect of RAS than did short intervals, which suggests two quickly decaying bursts of pacemaker acceleration. In any case, it is possible that the effect of RAS is rather persistent, perhaps lasting many seconds. If so, the effect may carry over from one trial to the next, and this could wash out differences between different RAS conditions (including the baseline without RAS). However, our experiments were partially modeled on those of previous authors who did obtain effects of RAS. Using a design similar to our Experiment 1, Ono & Kitazawa (2010) did obtain significant effects of RAS preceding and (especially) following the second interval, and Penton-Voak et al. (1996) in their Experiment 1 obtained reliable effects using a design similar to our Experiment 2. If slow decay of pacemaker acceleration were a problem, these previous experiments should not have obtained significant effects of RAS.

A related variable is the duration of the interval between RAS and the following interval that is to be judged. This duration would be important only if pacemaker acceleration subsided very quickly after RAS, contrary to what Penton-Voak et al. (1996) claimed to have found in their Experiment 3b. Their test interval to be judged was a continuous tone that started immediately after RAS, without any intervening silence. Ono & Kitazawa (2010) inserted 100 ms of silence between RAS and a silent test interval, or vice versa. We inserted 300 ms (Experiment 1) or 200 ms (Experiment 2) because we were worried that a tone delimiting the test interval might be grouped with the preceding or following RAS tones. Could it be that this brief separation totally wiped out any effect of RAS? It does not seem very plausible to us.

Let us now consider the nature of RAS itself. First there is its frequency, which was 25 Hz in both of our experiments. In using this frequency we followed again the preceding studies. Although both Penton-Voak et al. (1996) and Ono & Kitazawa (2010) varied RAS frequency in some experiments, they always included a rate of 25 Hz and found reliable effects with it. Actually, it is curious that this frequency was chosen because it is related by a simple ratio to the frequency of the internal pacemaker that Treisman et al. (1990) inferred from entrainment effects. This means that, depending on the precise frequency of an individual participant's pacemaker, RAS at 25 Hz could either accelerate or decelerate the pacemaker frequency through entrainment, in addition to affecting the hypothetical calibration unit that is sensitive to arousal. RAS with, say, a frequency of 22 Hz would not be subject to that complication. Nevertheless, the success of the earlier studies using RAS at 25 Hz indicates that this is not a serious problem, and so our use of this rate can hardly be responsible for our negative results.

The sounds used to produce RAS have varied somewhat from study to study. Treisman et al. (1990) used very brief clicks with a broad frequency spectrum. Penton-Voak et al. (1996) used 1000 Hz pure tones 10 ms in duration, which they called clicks. Ono & Kitazawa (2010) used 500 Hz pure tones 10 ms in duration. No study specifically investigated whether the nature of the sounds matters, but all obtained effects of RAS. In our Experiment 1 we used a scale ascending from 131 to 523 Hz, composed of digital piano tones. The scale was played *legato*, which means each tone started while the preceding tone still sounded, resulting in some overlap. It is possible that the relative smoothness of this scale or its variation in pitch made it ineffective as RAS. In Experiment 2, however, we used constant tones of 20 ms nominal duration with a fundamental frequency close to 1000 Hz, which were rather similar to the tones used by Penton-Voak et al. (1996). Being digital piano tones, they did not stop abruptly after 20 ms but decayed gradually, so the onsets of successive tones were not as abrupt as those of pure tones with (presumably) rectangular amplitude envelopes. Nevertheless, their subjective impression (sounding like a ringtone) was similar to the 'buzz' mentioned by Penton-Voak et al.

Another factor is the relative loudness of the RAS. Treisman et al. (1990) mention that their RAS was presented at 75 dBA. Penton-Voak et al. (1996) and Ono & Kitazawa (2010) do not mention loudness levels, but it seems that they presented RAS at the same (comfortable) level as the auditory test stimuli, and so did we. Therefore, the cause of our negative results is not likely to lie in the relative loudness of RAS, although this variable deserves to be explored further.

One very obvious difference between our study and the previous ones is that our participants were highly trained musicians. The previous studies do not mention musical training, but clearly the participants were not professional musicians and had not been selected according to musical background. Musicians are likely to make more accurate temporal judgments than non-musicians. In that connection it should be noted that a significant effect of RAS in Experiment 1 of Penton-Voak et al. (1996), which resembled our Experiment 2, emerged only after the participants were divided into two subgroups, one that showed 'normally peaked' temporal generalization functions (i.e. a peak of 'same' responses when the comparison stimulus matched the standard duration) and another that had much broader and 'abnormally peaked' functions. Only the former group, which gave more consistent judgments, showed the predicted effect of RAS. Because that group included the better listeners, perhaps some with musical training, our use of musician participants may not seem a likely cause of our negative findings. However, our musicians' judgments were much more accurate than even those of the better group in Penton-Voak et al. The latter gave 50% 'same' judgments when the comparison stimulus differed by about ±25% from the standard, whereas our musicians gave this level of 'same' responses to differences of about ±10%. It is possible, therefore, that the reported effect of RAS depends on relatively high uncertainty in participants' temporal judgment. If so, this seems problematic for the pacemaker acceleration hypothesis, for if ordinary people have a pacemaker in their brain, musicians presumably have one too, and its acceleration should be seen even more clearly when temporal judgments are highly accurate. It could be that musicians' training protects their internal pacemaker from external influences. They may have learned not be aroused by strange sounds such as RAS. In the online Supplementary Material we report results from a group of non-musician participants in Experiment 2, which showed a marginally significant effect of RAS but are inconclusive with regard to group differences.

It is noteworthy that RAS did not interfere at all with temporal judgment in our experiments. This also seems to have been the case in the earlier studies. Apparently, memory for interval durations is immune to strange interpolated sounds, and the delays caused by the insertion of RAS in Experiment 2 did not affect performance either. (In Experiment 1, the delay between the two intervals to be compared was held constant.) As for the effect of RAS on the hypothetical internal pacemaker, further research is required to delineate the necessary and sufficient conditions for its occurrence. Such research can provide us with important insights regarding our abilities to judge intervals, and how manipulation of the internal pacemaker mechanism can alter time judgments in both nonmusical and musical settings.

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