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RESEARCH ARTICLE

No temporal binding of action consequences to actions in a rhythmic context

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Abstract Temporal binding (TB) refers to a subjective contraction of the time that elapses between an action and a delayed sensory consequence of it. The TB effect has been demonstrated primarily in tasks in which a key press triggers a tone after a short delay and in which participants judge the timing of one or both of these events relative to a visual reference (e.g., a rotating clock hand). In the present Experiments 1 and 2, musicians listened instead to an auditory "clock" (a metronome) and occasionally made a tap that triggered a delayed tone. The task was to judge whether that test tone fell before, on, or after the midpoint of the interval between two metronome tones. In a passive control condition, participants judged test tones but did not tap. The hypothesis was that the test tone would be perceived as occurring earlier in the active than in the passive condition. However, there was no difference in perceptual judgments. Experiment 3 used a visual metronome as the reference but again obtained negative results, despite greater uncertainty of judgments. It is suggested that TB of action consequences to actions does not occur when the reference signal is rhythmic because such a context enables participants (musicians, at least) to perceive and judge the actual time of occurrence of the action-triggered tone.

Keywords Temporal binding · Intentional binding · Timing · Agency · Pacemaker

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Introduction

Actions and their perceptual consequences are tightly interconnected. It is the perceptual feedback (including proprioception) that informs us that we have actually carried out a movement, and there is now a large literature demonstrating the functional overlap of action and perception (for reviews see, e.g., Hommel et al. 2001; Schütz-Bosbach and Prinz 2007), bolstered by much research in neuroscience (e.g., Rizzolatti and Craighero 2004). Usually, perceptual feedback from an action is available almost immediately. However, sometimes the intended distal consequence of an action is delayed, especially when interacting with machinery. For example, a mouse click may cause a window to open after some fraction of a second. Nevertheless, we still have a strong feeling of causality linking such an action to its consequence.[1]

Taking advantage of this fact, Patrick Haggard and colleagues demonstrated a phenomenon originally dubbed "efferent binding" (Haggard et al. 2002a) and later called "intentional binding" (Haggard et al. 2002b), "causal binding" (Buehner and Humphreys 2009), or—the term preferred here—"temporal binding" (TB) (Humphreys and Buehner 2009). Haggard et al. (2002a) asked participants to press a key whenever they felt like it. Each key press was followed by a tone after a delay of 200 ms. Participants viewed a continuously rotating clock hand (a "Libet clock"; Libet et al. 1983) and reported its position at the time of the key press or at the time of the tone. Relative to this clock, they judged the tone as occurring earlier (by about 40 ms) than in a control condition in which the tone was not preceded

[1] In the literature, actions are usually said to produce "effects". The term "consequence" is preferred here, to avoid confusion with effects of experimental variables and with the temporal binding effect.

by a key press. When asked to judge the time of the key press, participants also showed a tendency to perceive it as occurring later than in a control condition where it was not followed by a tone. Both results imply that the temporal interval between an action and its consequence is shortened subjectively. This is the TB effect. To be precise, there are really three TB effects: an effect of the preceding action on the perceived time of the consequence (TB_C); an effect of the consequence on the perceived time (or, in some studies, on the actual time) of the action (TB_A); and an implied effect on the subjective duration of the temporal interval between the action and its consequence ($TB_I = TB_C - TB_A$, though this equality should not be taken for granted).

Haggard et al. (2002b) replicated their initial findings of TB_C and TB_A, now using a delay of 250 ms. They also showed that TB_C does not occur when the tone follows an involuntary movement caused by transcranial magnetic stimulation. Indeed, the tone seemed to occur *later* in that condition than in a no-movement control condition. Haggard et al. further explored the effect of delay duration on judgment of the tones. The initially very large TB_C effect decreased and almost disappeared as the delay was increased from 250 to 650 ms, and it was much reduced and present only with the shortest delay when the delay varied randomly from trial to trial. The authors concluded that the TB_C effect "is modulated by temporal contiguity and temporal predictability" (p. 384).

In a subsequent study, Haggard et al. (2003) showed that TB_C is particularly large in schizophrenics, though surprisingly a normal control group failed to show a significant effect. (This was attributed to two participants who showed a large effect in the opposite direction.) Strother et al. (2010) found TB_C in participants who passively watched another participant press a key to hear a tone (see also Obhi and Hall 2011a). However, when participants believed that a computer carried out the action, there was no TB_C (Obhi and Hall 2011b). All these studies used a Libet clock as the external temporal reference. Recently, however, Cravo et al. (2011) succeeded in demonstrating TB_C in a cross-modal simultaneity judgment task, using a single flash of light as the reference. Their task required participants to judge whether the flash did or did not coincide with a tone that was triggered by a finger lift. The action-consequence delay was either fixed or varied randomly, and there were also conditions in which no action was carried out. Cravo et al. found that the tone was perceived as occurring 20–30 ms earlier only with short (250 or 300 ms) delays in the fixed-delay action condition. No TB_C effect was found with a 600-ms delay or in a condition with randomly varying delays. The stringent psychophysical paradigm used by these authors seemed to reduce and constrain the TB_C effect.

Wenke and Haggard (2009) tested the hypothesis that the rate of an internal pacemaker slows down in the interval between a voluntary action and its consequence. They inserted a temporal discrimination task into the delay interval, which varied randomly between 600 and 1,000 ms. A slowing of subjective time was predicted to increase the temporal discrimination threshold and that is indeed what they found early in the interval, but not late in the interval, compared to a condition in which a passive movement was followed by a tone. They also obtained direct subjective estimates of interval duration, which were substantially shorter in the active than in the passive movement condition. This TB_I effect did not depend on interval duration, which is consistent with pacemaker slowing during an early fixed period of the interval. Such a pacemaker slowing could also account for the TB_C effect obtained in other studies, but not for the finding that TB_C decreases and even vanishes as the delay between action and consequence increases (Cravo et al. 2011; Haggard et al. 2002b). Also, the finding of a large TB_I effect in the 600–1,000 ms range of delays contrasts with the apparent absence of a TB_C effect in this range.

Some studies were specifically concerned with the TB_I effect. Engbert et al. (2008) found that the action-consequence interval was estimated to be 80–100 ms shorter in active than in passive movement conditions, and this effect did not decrease as delay duration was increased from 200 to 300 ms. In contrast to Strother et al. (2010), they did not find any TB when the action was merely observed, possibly because they focused on TB_I rather than TB_C. The TB_I effect has also been used to show that TB requires a causal connection between an action and its designated consequence (Buehner and Humphreys 2009; Cravo et al. 2009; Eagleman and Holcombe 2002; Ebert and Wegner 2010). Humphreys and Buehner (2009) assessed TB_I using a wide range of randomly varying delays (up to 4 s). Surprisingly, the TB_I effect *increased* with interval duration across the whole range, which was considered indicative of a slowing in the rate of an internal pacemaker throughout the interval. (See Wearden et al. 2007 for a similar argument.) In a subsequent study, Humphreys and Buehner (2010) demonstrated TB_I using an interval reproduction task with delays in the 1,200–1,600 ms range. It is difficult to reconcile these findings with the rapid decline in the TB_C effect as interval duration increases or is randomized (Cravo et al. 2011; Haggard et al. 2002b). TB_I and TB_C may not be the same kind of TB phenomenon.

Other studies have focused on the TB_A effect, using the Libet clock paradigm (Engbert and Wohlschläger 2007; Moore and Haggard 2008; Moore et al. 2009). The TB_A effect is usually smaller than the TB_C effect, and some studies have failed to find it (Engbert and Wohlschläger 2007; Strother et al. 2010). There is a second kind of TB_A effect, where the dependent variable is not the judged time, but the actual time of the action relative to an external reference:

Actions tend to occur later when they have an expected consequence than when they do not (Buehner and Humphreys 2009; Keller et al. 2006; Mueller et al. 2007; Waszak et al. 2005).

The present study

The present study focused on the TB_C effect, specifically on the finding that a tone is perceived as occurring earlier when it is an expected consequence of a preceding action than when it occurs without a preceding action (Cravo et al. 2011; Haggard et al. 2002a, b; Strother et al. 2010). It is well known that temporal judgments are more accurate in the auditory than in the visual modality (e.g., Grondin 1993; Hartcher-O'Brien and Alais 2011; Repp and Penel 2002). Therefore, it is surprising that only one of the TB studies conducted so far has used an external auditory temporal reference, even though the action consequence was usually auditory. This single exception is the study of Buehner and Humphreys (2009), but it used action timing, not temporal judgment, as the dependent variable. Indeed, it assessed not only TB_A but also TB_C via action timing: A key press intended to coincide with a tone occurred sooner when the tone was the presumed consequence of an earlier key press than when it was not, which suggests anticipation of an action consequence.

The present study used a temporal judgment paradigm to investigate whether TB_C occurs when the action consequence is embedded in an external rhythm, particularly an auditory rhythm. Instead of a visual reference such as a Libet clock, an auditory "clock" was provided in the form of a metronome (an isochronous sequence of tones). Participants, who were highly trained musicians, had to judge the timing of a test tone against this auditory temporal reference (Experiments 1 and 2) or against a rhythmic visual reference (Experiment 3). A condition in which the test tone followed a tap at a delay (active condition) was compared to a condition without tapping (passive condition). TB_C would be evident if the test tone were judged as occurring earlier in the active than in the passive condition.

If TB_C is caused by the transient slowing of an internal pacemaker (Wenke and Haggard 2009), then it should also occur in a rhythmic context. Even if the cause is not an internal pacemaker but some other cognitive mechanism that subjectively advances an action consequence in time and/or shortens the subjective interval between an action and its consequence, it is not obvious why this should not occur in a rhythmic paradigm. Perhaps it seems somewhat counterintuitive that producing an auditory consequence through action, which is what musicians do all the time when playing their instruments, should affect their perception of the resulting rhythm, compared to a pure listening condition. The critical aspect of TB, however, is that the action consequence is artificially delayed, whereas in music performance, auditory feedback is usually (almost) immediate. Therefore, musicians might well show TB_C in a delayed feedback situation.

An alternative hypothesis is that no TB_C will be observed in a rhythmic context. The rationale for this prediction is that a rhythmic temporal reference may enable participants (and musicians especially) to accurately judge the true time of occurrence of the action consequence. According to this hypothesis, a test tone, even when it has been triggered by an action, will be perceived in the correct temporal relation to its surrounding "clock" tones, which provide firm temporal anchors.

Experiment 1

In this experiment, the delay between an action (a tap) and a consequent test tone was varied in order to vary the temporal position of the test tone within a metronome interval, which had to be judged. In order to investigate the effect of mean delay duration, several metronome tempi were used, each requiring a different range of test tone delays. One recognized drawback of this design was that the test tone delay varied considerably from trial to trial, which has been found in previous studies to attenuate or even eliminate TB_C. However, it was thought that a TB_C effect should be evident at least at the shortest delays if it occurs in a rhythmic context. The precision of the temporal judgments made possible by the rhythmic context and by participants' musical training was expected to reveal even small TB_C effects. (An alternative design was used subsequently in Experiment 2.)

Methods

Participants

The participants were 9 graduate students from the Yale School of Music (5 female, 4 male, age 21–27) and the author (age 66). The students were regular paid participants in rhythm and timing experiments in the author's laboratory and played various primary instruments (piano(2), violin, viola(2), trombone, harp, and guitar(2)) at a professional level. The author is a life-long amateur pianist.

Materials and equipment

Tone sequences were generated online by a program written in Max/MSP 4.0.9, running on an Intel iMac computer. The tones (piano timbre) were produced by a Roland RD-250s digital piano according to musical-instrument-digital-interface (MIDI) instructions from the Max/MSP program and were presented over Sennheiser HD280 pro headphones. Metronome tones all had the same pitch (C4, 262 Hz), the same nominal duration (40 ms), and the same intensity (MIDI velocity of 60). Test tones differed from metronome tones in pitch (E4, 330 Hz) and intensity (MIDI velocity of 80), a difference of about 5 dB (Repp 1997). Participants tapped on a Roland SPD-6 electronic percussion pad, held on the lap. Finger impacts created thuds whose loudness depended on individual tapping force but was attenuated considerably by the circumaural headphones.

Procedure

The active and passive conditions were conducted in separate sessions on different days, in that order. Their order was not counterbalanced because it was thought that prior experience with the passive condition, where the test tones are clearly controlled by the computer, might diminish participants' feeling of agency in the superficially very similar active condition (see "General discussion"). The participant started each trial by pressing the space bar on the computer keyboard. The metronome started playing 2 s later at one of four tempi, corresponding to tone inter-onset intervals (IOIs) of 500, 600, 700, or 800 ms.

In the active condition, the participant was instructed to make a single tap from time to time with the left hand, such that the tap coincided with one of the metronome tones. Participants were told that each tap should feel spontaneous and that successive taps in the same trial (a total of 11) should not follow any regular pattern. Each tap triggered a test tone at one of 11 possible delays for a given IOI. The delay was timed from the tone with which the tap was synchronized (this was done to equate the delays in the active and passive conditions) and was one of 11 possible delays ranging from 40 to 60% of the IOI in steps of 2%. For example, the delays ranged from 200 to 300 ms in steps of 10 ms when the IOI was 500 ms. The participant had to judge whether the test tone preceded the midpoint of the IOI ("early"), occurred exactly at the midpoint ("on time"), or followed the midpoint ("late") by pressing one of three "arrow" keys on the keyboard with the right hand. After giving that response, the participant made another tap with the left hand at a self-selected moment, though always in synchrony with a metronome tone. A schematic diagram of a portion of a trial is shown in Fig. 1. The metronome stopped after 11 taps and test tone judgments had been made; this constituted one trial. Each of the 11 test tone delays for a given IOI occurred once in a trial, with the order of delays being random.

In the passive condition, the computer inserted the test tones and participants merely pressed the response keys to give their judgments. From 4 to 7 empty IOIs (randomly chosen) intervened between test tones in that condition. In each session, participants completed 10 blocks of 4 trials each, with the trials within each block representing the four metronome IOI durations.

Fig. 1 Schematic stimulus diagram showing a portion of a trial in the active condition of Experiment 1. Tones should be imagined preceding as well as following the sequence extract shown. Test tones follow taps after a variable delay. *IOI* tone inter-onset interval, *LH* left hand, *RH* right hand

Results and discussion

Figure 2 shows the mean response percentages in the four IOI conditions as a function of test tone delay, with the delay being expressed as a percentage deviation from the IOI midpoint. If there had been TB_C in the active condition, the response functions for that condition (filled symbols, solid lines) should have been shifted to the right (implying more "early" and fewer "late" responses) relative to the response functions for the passive condition (open symbols, dashed lines). This was not the case. The results for the two conditions were very similar. If anything, there was a tendency to give more "late" responses in the active than in the passive condition, especially at the slowest tempo (IOI = 800 ms).

Estimates of the subjective IOI midpoint were calculated in two ways: (1) as the weighted mean of the frequency distribution of "on time" responses and (2) as the 50% point on a regression line fitted to a cumulative response function representing the sum of "late" responses and half of "on time" responses. The results are shown in Fig. 3 as deviations from the actual IOI midpoint. Each set of estimates was subjected to a 2 (conditions) × 4 (IOIs) repeated-measures ANOVA, with Greenhouse-Geisser correction. There were no significant effects in the first ANOVA. In the second ANOVA, only the main effect of IOI was close to significance, $F(3, 27) = 3.68$, $P = .058$. Clearly, the second measure of the subjective midpoint was much more variable than the first, and its apparent increase with IOI duration was due to a few participants who showed very large effects of IOI.

Both measures in Fig. 3 show the deviation of the subjective IOI midpoint to be negative, which implies that a test tone was judged most often to be "on time" when it occurred slightly early (by about 10 ms on average), as can also be seen in Fig. 2. This could mean that the subjective midpoint was indeed early or that there was an independent bias to perceive the test tone as occurring late. The second

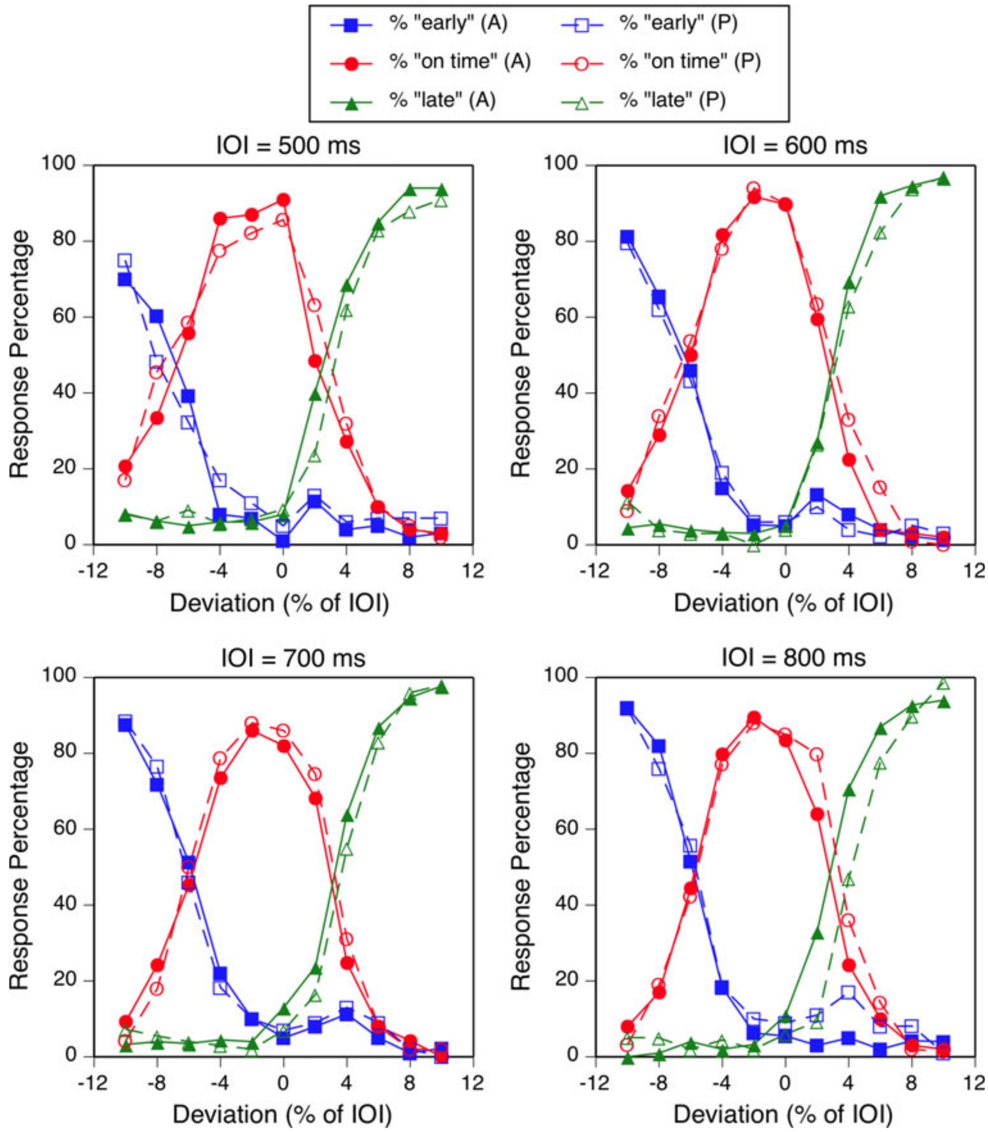

Fig. 2 Mean response percentages as a function of test tone deviation from the inter-onset interval (IOI) midpoint in the active (A) and passive (P) conditions of Experiment 1, for each of four IOI durations

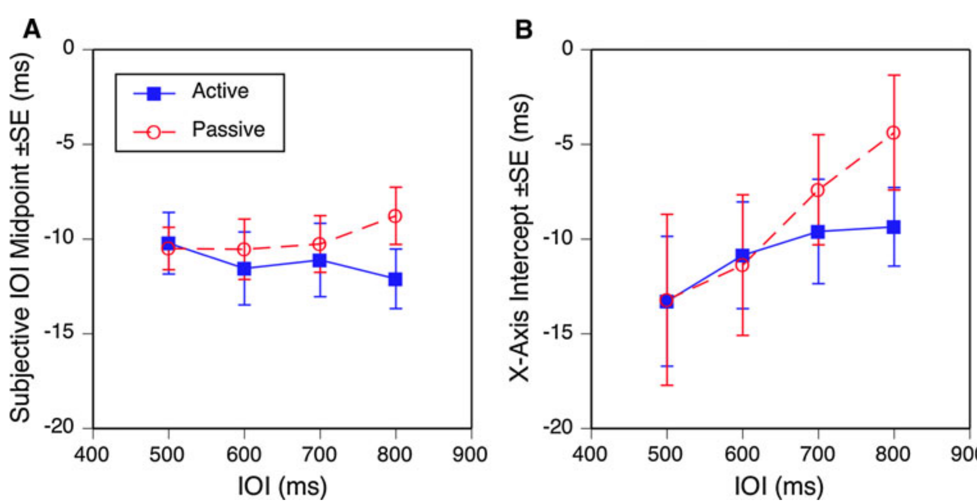

Fig. 3 Mean estimates of the subjective IOI midpoint, expressed as a deviation (in ms) from the actual midpoint, (**a**) derived from the distribution of “on time” responses and (**b**) representing the 50% intercept of the “late” response function in the active and passive conditions of Experiment 1. *Error bars* represent ±1 standard error (SE)

interpretation is more plausible in view of the higher pitch and intensity of the test tone relative to the metronome tones. It is known that relative intensity, in particular, affects perceived timing in exactly this way: The interval preceding an accented tone tends to be perceived as lengthened (Tekman 1995, 1997, 2001; Woodrow 1909). This effect is therefore not surprising, and it is irrelevant to the comparison between active and passive conditions. It is worth noting, though, that perception of test tone timing was not immune to a bias due to relative accentuation within the auditory sequence, while at the same time it seemed to be immune to TB_C.

Experiment 2

Experiment 1 yielded a negative result with regard to TB_C. There could be several reasons for this. The most obvious candidate is the variability of action-consequence delay durations. Although the delay intervals were in a range (200–480 ms) where TB_C effects have previously been obtained, they varied from one tap to the next and also from one trial to the next. Although Haggard et al. (2002b) still found TB_C at short delays when delay durations were randomized, Cravo et al. (2011) did not. Experiment 2 therefore used a modified paradigm in which the delay was nearly constant. Instead, the metronome IOI was varied from tap to tap, so that participants could judge the relative position of the test tone within the IOI. Because of this change, trials were short and contained only a single test tone.

Methods

Participants

Eight of the participants of Experiment 1 participated again. About 4 months had elapsed since Experiment 1, with many other experiments intervening. One pianist was no longer available, and the author's data were not included here because it could be argued that his knowledge of the perfect correlation between metronome tempo and test tone placement within the metronome interval could have unwittingly biased his responses.

Materials and equipment

The equipment was the same as in Experiment 1, and metronome tones were the same as previously. Test tones now had a pitch one octave higher (C5, 523 Hz) than the metronome tones but were played at the same nominal intensity (MIDI velocity). Each trial contained only one test tone (triggered by a tap in the active condition and by the computer in the passive condition), which followed the preceding metronome tone by exactly 250 ms. The metronome had one of 11 IOI durations, chosen such that the test tone onset fell at a point ranging from 40 to 60% of the IOI in steps of 2%. The metronome IOIs thus ranged from 625 ms (40% of which is 250 ms) to 417 ms (60% of which is 250 ms).

Procedure

Participants completed the active condition before the passive condition in a single session. Each took less than 15 min and consisted of two blocks of 55 trials each. The 55 trials resulted from the concatenation of five randomizations of 11 trials, each with a different metronome tempo and hence a different test tone placement in the IOI. Participants started each trial by pressing the "enter" key. In the active condition, they were instructed to make a single tap with the left hand in synchrony with one of the tones and then to judge the position of the resulting test tone relative to the IOI midpoint by pressing one of the three arrow keys, as in Experiment 1. The metronome kept playing until one of the arrow keys was pressed. Participants were asked to tap in a spontaneous manner, not always at the same time in each trial. In the passive condition, the computer played the test tone in one of five possible IOIs of the sequence (4th to 8th, selected randomly). At the end of the session, participants were asked whether they had noticed that tones always occurred early when the metronome tempo was slow and late when the tempo was fast and whether they had ever adopted the strategy of responding "early" or "late" just on the basis of the metronome tempo, without trying to judge the position of the test tone directly. Although some said they had noticed the correlation, all firmly denied having used a strategy based on metronome tempo alone.

Results and discussion

Figure 4 shows the average percentages in the three response categories as a function of test tone position (percentage deviation from the IOI midpoint) for the active and passive conditions. Participants' overall accuracy was similar to that in Experiment 1. There was little difference between the active and passive conditions.

The subjective IOI midpoint was again calculated in two ways. When based on the weighted mean of "on time" responses, the average subjective midpoint was at −1.32% of the IOI (SE = 0.32) in the active condition and at −1.40% (SE = 0.45) in the passive condition, relative to the actual midpoint. The difference was not significant, $t(7) = 0.28$, $P = .788$. However, the mean deviation (both conditions combined) from zero was significant, $t(7) = -3.71$,

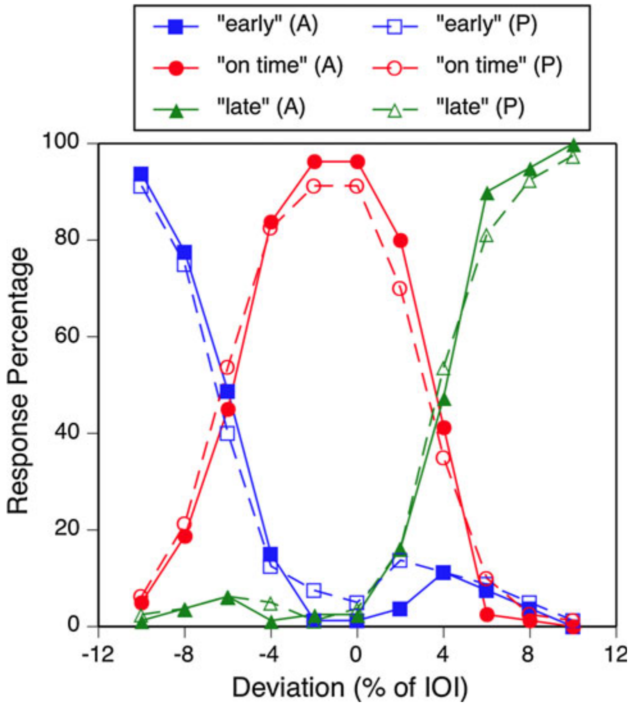

Fig. 4 Mean response percentages as a function of test tone deviation from the IOI midpoint in the active (A) and passive (P) conditions of Experiment 2

$P = .008$. The 50% point of a straight line fitted to the cumulative percentage of “late” responses (with half of “on time” responses included) was at −1.05% (SE = 0.39) and at −0.78% (SE = 0.46) of the IOI, respectively. This difference, too, was not significant, $t(7) = -0.56$, $P = .591$, although the difference from zero was significant, $t(7) = -2.62$, $P = .035$.

The bias to judge the test tone as late can again be attributed to its relative accentedness, now solely due to its different pitch. It is well known that a pitch deviation from a melodic contour in music conveys an accent, the so-called pitch or melodic accent (Huron and Royal 1996; Thomassen 1982), and Tekman (1997) has shown that tones carrying a melodic accent are also judged to be louder than other tones in a rhythmic sequence. As mentioned earlier, louder tones in a sequence tend to be perceived as relatively late.

Experiment 3

There are several possible explanations why no TB_C effect was obtained in Experiments 1 and 2 (see “General discussion”). One possibility is that the effect emerges only in cross-modal comparisons. All previous studies of TB_C used a visual reference (a Libet clock or a light flash) for judging the timing of an auditory action consequence, except for Buehner and Humphreys (2009), who looked at action timing relative to a tone. Perhaps high uncertainty in temporal judgment is a prerequisite for TB_C to emerge. Therefore, in Experiment 3, a visual metronome (a flashing light) was substituted for the auditory metronome.

When only the metronome was changed from auditory to visual while maintaining the design of Experiment 2, the task proved to be extremely difficult, as assessed by the author in a pilot run. In particular, it was difficult to judge the position of the test tone when the metronome tempo was fast, which is consistent with earlier findings showing that isochronous visual flash sequences with IOI <500 ms are difficult to track perceptually (Repp 2003). Therefore, a slower range of metronome tempi was used, which necessitated using a longer test tone delay. In addition, the deviations of the test tone from the IOI midpoint were doubled to facilitate judgments.

Methods

Participants

The participants were the same as in Experiment 2.

Materials and equipment

The equipment was the same as in Experiment 2. The test tones were the same also. Instead of an auditory metronome, a virtual LED on the computer screen (the LED object of Max/MSP) was used as a visual metronome. The LED was circular, 4 mm in diameter, blue in color, and had a nominal flash duration of 40 ms. The flashes were clearly visible. The temporal accuracy of the LED was not known (there may have been variable delays within the software and/or due to the screen refresh rate), but it was the same in the active and passive conditions. The test tone always occurred 350 ms after the nominal time of a flash, and its position in the IOI ranged from 30 to 70% of the IOI in steps of 4%. The visual metronome IOI durations consequently ranged from 1,167 ms (30% of which is 350 ms) to 500 ms (70% of which is 350 ms).

Procedure

Experiment 3 immediately followed upon Experiment 2 in the same session. Participants completed the active condition before the passive condition. Each took less than 15 min and consisted of two blocks of 55 trials each, structured as in Experiment 2. The procedure was also the same as in Experiment 2. In the active condition, participants were instructed to make a single tap with the left hand in synchrony with one of the LED flashes and then to judge the position of the resulting test tone relative to the IOI midpoint. They were warned that the task might be difficult,

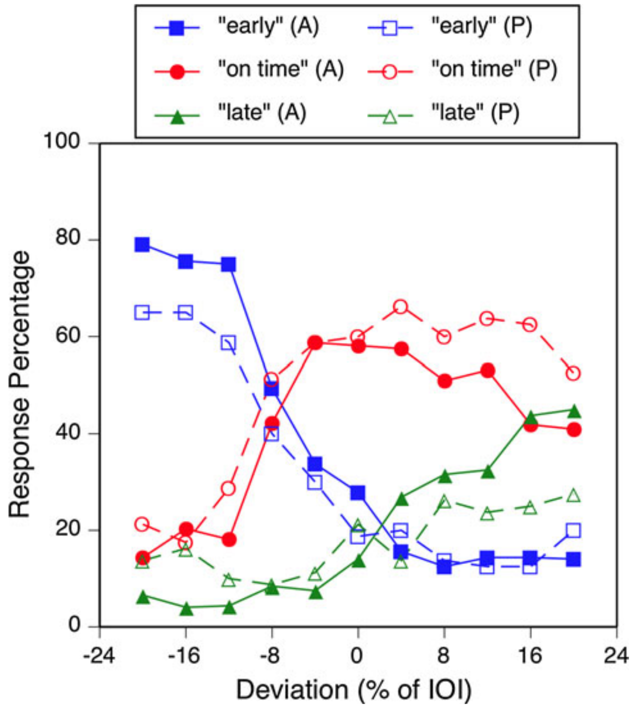

Fig. 5 Mean response percentages as a function of test tone deviation from the IOI midpoint in the active (A) and passive (P) conditions of Experiment 3

and they were encouraged to internalize the visual beat and move along with it (e.g., by swaying or tapping with their foot), as long as they did not make any sounds. The questions asked at the end of the session (see Procedure of "Experiment 2") applied to both Experiments 2 and 3. One participants' data from the second block of trials in the active condition were not saved by mistake, so her results in that condition were based on a single block.

Results and discussion

Figure 5 shows the average response percentages. Despite the measures taken to facilitate the task, judgments were still much harder to make than with the auditory metronome. In particular, it was difficult to judge correctly that the test tone was late because then the IOI was relatively short. This poor performance is consistent with participants' denial of having responded solely on the basis of metronome tempo, as is the somewhat poorer performance in the passive than in the active condition. (Given that some time was needed to discover the correlation between tempo and test tone placement, the passive condition should have benefited from an IOI-based strategy). Although participants did respond "early" more often in the active than in the passive condition, as predicted by the TB hypothesis, they also responded "late" more often in the active than in the passive condition when the test tone was really late. This latter tendency occurred when uncertainty was highest, and it is contrary to the TB_C effect.

The mean subjective IOI midpoint based on the distribution of "on time" responses was 3.08% (SE = 0.94) of the IOI in the active condition and 3.66% (SE = 0.84) in the passive condition, relative to the actual midpoint. This difference is not significant, $t(7) = -0.62$, $P = .556$, and in fact is contrary to a TB_C effect. The mean deviation from zero was significant, $t(7) = 4.91$, $P = .002$. Note that it was now in the positive direction, due to the difficulty of the task when the IOI was short and the absence of an auditory context that created a contrastive pitch accent on the test tone. The mean 50% points of the regression lines fitted to the "late" response functions were at 7.56% (SE = 2.44) and 4.49% (SE = 4.80) in the active and passive conditions, respectively. The direction of this difference is consistent with a TB_C effect, but it was not even close to significance, $t(7) = 0.80$, $P = .452$. The difference from zero also fell short of significance here, $t(7) = 2.01$, $P = .084$. The TB_C-like tendency probably reflects just poorer performance in the passive than in the active condition, perhaps due to fatigue. Consistent with that explanation, the slope of the "late" response function (including half of "on time" responses) was significantly shallower in the passive than in the active condition, $t(7) = 2.66$, $P = .033$. It does not seem that the difficulty of the cross-modal temporal judgments in this experiment led to emergence of a TB_C effect.

General discussion

The present study explored whether TB_C occurs when a tap triggers a delayed auditory action consequence (a tone) within a simple rhythmic context. The reference against which the timing of the test tone was judged was an isochronous auditory or visual "metronome" sequence. According to the TB_C hypothesis, a test tone triggered by a tap should have been perceived as occurring earlier relative to the metronome events than a test tone played by the computer in the absence of any immediately preceding action. However, no such effect was found in each of three experiments. These negative findings contrast with results of previous studies, reviewed in the Introduction, in which some form of TB_C was usually found. What may have caused the present negative results? A number of possibilities are considered below, with the most plausible explanations at the end.

One important variable is the delay between the action and its consequence. Both the absolute duration and the variability of the delay are important, at least for TB_C (Cravo et al. 2011; Haggard et al. 2002b). In Experiment 1, the delay varied considerably from trial to trial. Not only were there four nominal mean delays (i.e., between preceding tone and test tone) ranging from 250 to 400 ms (associated with different metronome tempi), but the nominal delay also varied by ±10% for each metronome IOI. Additional variability of the actual delay between tap and test tone was caused by variability in tap timing, which may have amounted to about ±5% of the IOI. It was not actually measured in this study but could be inferred from many previous synchronization studies with these and similar participants. The delay thus varied roughly between 200 and 500 ms, which could explain the absence of any TB_C effect, although Haggard et al. (2002b) still found TB_C at the shortest delay when delays varied randomly between 250 and 650 ms. In Experiment 2, however, the nominal delay was fixed at 250 ms, a duration for which even Cravo et al. (2011) found TB_C in their cross-modal simultaneity judgment paradigm, and the only variability stemmed from the timing of the tap, which, being relatively small, should not have prevented TB_C from occurring. In Experiment 3, the nominal delay was 350 ms, which, judging from previous research, also seems within the range where TB_C should be observed. So the delay is probably not the cause of the negative results.

A second important variable is the feeling of agency. TB clearly presupposes that participants believe that the "consequence" is caused by their action. The experimental situation is somewhat artificial because in real life, auditory action consequences are usually the immediate result of some physical interaction, such as knocking on wood, kicking a ball, or depressing a piano key. In TB experiments, the auditory consequence of the action is not only delayed but also clearly produced by a computer, not by the participant. Nevertheless, there is evidence that participants do retain some feeling of agency in this situation (e.g., Sato and Yasuda 2005), and this has been an assumption underlying all the TB research. Several additional factors in the present experiments could have reduced the feeling of agency further. First, a tap did produce an immediate auditory consequence, a thud on the percussion pad, which may have diverted feelings of agency from the delayed test tone. In Experiments 1 and 2, however, the thud closely coincided with one of the metronome tones and was probably largely masked; only in Experiment 3, it was clearly audible. Moreover, the fact that the action produced a sound immediately should not totally eliminate the feeling of agency for a second, delayed auditory consequence (cf. Buehner and Humphreys 2009, where the action made a click). Second, the fact that the tap coincided with a metronome event could have attenuated the feeling of agency because the metronome tone or flash could have been mistaken for an immediate action consequence (cf. Repp and Knoblich 2007). An argument against this possibility is that the metronome tones or flashes formed a coherent stream that clearly was controlled by the computer and did not depend on the participant's action, whereas the test tone did not belong to that stream because of its singularity, different pitch, and contingency on a tap. A third possibility is that the test tone was attributed to computer agency because it occurred in the context of an auditory rhythm that was controlled by the computer (cf. Obhi and Hall 2011b). If that was the case, the paradigms of Experiments 1 and 2 would seem invalid as tests of TB_C. The argument does not seem very plausible, however, and does not apply to Experiment 3. There, the visual metronome was not unlike a Libet clock, which is also computer controlled. Therefore, it does not seem very likely that elimination of the feeling of agency was the critical factor that led to negative results in the present experiments.

A third potential factor was the spontaneity of the action. In TB experiments, participants are typically instructed to carry out the prescribed action whenever they feel like it. In the present experiments, there was a temporal constraint, namely the requirement to synchronize the tap with a metronome event. However, participants could freely choose which event to tap with, and they were encouraged by instructions to vary the serial position of the chosen event and make the tap feel spontaneous. Studies comparing the timing of intention-based and stimulus-based actions (Keller et al. 2006; Mueller et al. 2007; Waszak et al. 2005) also imposed a temporal constraint, namely to press a key at the midpoint of stimulus IOIs, and nevertheless obtained evidence of TB_A. Buehner and Humphreys (2009) had participants tap with tones and found both TB_A and TB_C. So, again, this aspect of the present task is not a compelling reason for the absence of a TB_C effect.

A fourth factor was the music training of the participants. The author works almost exclusively with musicians in his research on rhythm and synchronization because of their ready availability, high motivation, and accuracy. If music training were the reason for the absence of TB_C, the effect would seem less interesting because it would have been shown not be obligatory but rather contingent on inaccurate temporal judgment and response bias. In particular, the hypothesis that the rate of an internal pacemaker is changed during the interval between an action and its delayed consequence would be discredited if it did not apply to musicians (cf. Repp and Marcus 2010). Music training is probably not the correct explanation either.

A fifth factor, addressed in the present study, is the modality in which the external reference occurs. It was considered possible that TB_C is specific to situations in which an auditory action consequence is judged against a visual reference, as all studies to date (except for Buehner and Humphreys 2009) have used some variant of this procedure. However, Experiment 3, where the external reference was visual, did not yield TB_C, despite considerable uncertainty in the judgments that should have made participants susceptible to any kind of bias.

Finally, there is the rhythmic nature of the external temporal reference, and it is probably here that the crucial difference lies. Two possible scenarios come to mind: The rhythmic reference may enable participants to make veridical timing judgments (this is the hypothesis that led to the present research), or it may itself be distorted as a consequence of TB.[2] In either case, the result would be absence of a TB_C effect in the data.

Let us consider the second possibility first. If TB reflects the temporary slowing of an internal pacemaker immediately following the action (Wenke and Haggard 2009), then slowing might also affect an external temporal reference. In other words, not only the interval between the action and its consequence but also the simultaneous IOI of the metronome might have been shortened subjectively. Participants in this study were asked to judge when the test tone occurred relative to the IOI midpoint. This may have required internal prediction of the IOI midpoint, and slowing of the internal pacemaker may have made that prediction occur earlier. As a result, the TB_C effect may have been neutralized, because both the test tone and its internal reference were shifted in subjective time. One important difference between a metronome and a Libet clock is that the former is purely temporal, whereas the latter is spatiotemporal. When judging a test tone against a metronome, the question is *when the test tone occurred* relative to the metronome. When judging a test tone against a Libet clock, the question is *where the clock hand was* when the tone occurred. The Libet clock is not a very reliable reference, but it is likely to be immune to subjective temporal distortion by a pacemaker slowing because of its spatial component. An auditory metronome provides a much more accurate temporal reference, but its purely temporal nature makes it potentially vulnerable to modulation by the internal processes that underlie TB.

However, there are some possible counterarguments to this explanation. One is that comparison against a predicted IOI midpoint is not the only way to judge the timing of the test tone. Another way is to judge whether the test tone is closer to the preceding or the following metronome tone, which implies a comparison of the two sub-IOIs of the metronome IOI, created by the test tone. Because pacemaker slowing is assumed to occur only in the interval between the action and its consequence, perception of the second sub-IOI should be unaffected, and a TB_C effect should emerge. It is true that participants were not instructed to use this interval comparison strategy, but it seems likely that musicians would have both strategies available and use them in parallel. A second counterargument is that Cravo et al. (2011) did find a TB_C effect using a visual reference (a single flash). If internal pacemaker slowing had simply slowed the progress of subjective time, both the test tone and the flash should have been affected equally. However, Cravo et al. concluded “voluntary action does not indiscriminately affect temporal processing of all subsequent events, but only of those that are thought to result from that action” (p. 165). For a recent demonstration of timing specificity in another context, see Pariyadath and Eagleman (2007). This issue is far from resolved, however.

Now we return to our original hypothesis that, by defining a temporal grid within which actions and consequences are situated, the metronome may prevent the subjective contraction of time between action and consequence from occurring or manifesting itself. Consider this analogy: If the visual pattern that gives rise to the Müller-Lyer illusion was drawn alongside a ruler, participants would be able to see that the line segments are of equal length and presumably would not experience the illusion or at least would not reveal it in their judgments of line length, which they could read off the ruler. Similarly, an auditory rhythm may provide a “ruler” against which the temporal position of a test sound can be judged accurately. From that perspective, it is perhaps surprising that the visual rhythm, which was much less effective as a temporal reference, also seemed to prevent TB_C from occurring. However, the auditory and visual rhythms had in common that they were likely to engage the participants’ motor system through internal resonance (Large 2008). Even though visual rhythms are much less engaging than auditory rhythms in that regard (Patel et al. 2005), participants were encouraged to move along with the flashes and internalize the visual beat, and as musicians they may have been quite successful in doing this. These internal rhythmic references may have enabled them to overcome TB_C.

Further research is required to determine whether this explanation is correct and whether the change in temporal processing involved in TB reflects a general timing mechanism or is specific to the action-consequence relationship. It would also be useful to investigate whether TB_A occurs in the present paradigm. This requires recording the exact times at which the taps occur and comparing a condition in which the taps are followed by test tones with a condition in which the test tones are omitted. The present negative findings regarding TB_C do not rule out the possibility that TB_A might occur in rhythmic contexts (cf. Buehner and Humphreys 2009).

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[2] I am grateful to Yi-Huang (Jasmine) Su for alerting me to the second possibility.

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