Filled and empty motor reproductions of filled and empty intervals: Is there also a filled - reproduction illusion?

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Abstract Previous studies have demonstrated that filled intervals are perceived as being longer than empty intervals of the same duration (i.e., the filled - duration illusion). In the present study, we asked whether the motor actions involved in filled and empty reproductions (a single continuous key press vs. two discrete key presses) would affect time estimates in a similar way. We hypothesized that reproductions of intervals of the same duration should be shorter for filled than empty reproductions (i.e., a filled - reproduction illusion). In two experiments, participants reproduced filled and empty intervals (ranging from 400 to 1,600 ms) using filled and empty reproductions. The results provided evidence for both kinds of illusions, even though the evidence was clearer for the filled - duration than for the filled - reproduction illusion. The present study demonstrates that in a situation in which both illusions work in concert, reproductions of the same interval can vary dramatically depending on the combination of interval and reproduction type.

Keywords Filled - duration illusion · Time perception · Reproduction method

The perception of time is influenced by a variety of internal factors like body temperature (e.g., Hancock, 1993) and emotions (e.g., Droit-Volet & Meck, 2007) as well as external stimulus factors like modality (e.g., Bratzke, Seifried, &

Ulrich, 2012; Penney, Gibbon, & Meck, 2000; Wearden, Edwards, Fakhri, & Percival, 1998), intensity (e.g., Matthews, Stewart, & Wearden, 2011), and occurrence probability (e.g., Birngruber, Schröter, & Ulrich, 2014; Tse, Intriligator, Rivest, & Cavanagh, 2004). An important stimulus factor that influences our perception of time is the temporal structure of the stimulus, that is, whether it is filled with stimulation (filled intervals) or with silence (empty intervals). Numerous studies have demonstrated that filled intervals are perceived as being longer than empty intervals of the same duration (i.e., the filled-duration illusion; Adams, 1977; Buffardi, 1971; Craig, 1973; Goldstone & Goldfarb, 1963; Gomez & Robertson, 1979; Hasuo, Nakajima, Tomimatsu, Grondin, & Ueda, 2014; Wearden, Norton, Martin, & Montford-Bebb, 2007).

Internal clock models (Creelman, 1962; Gibbon, Church, & Meck, 1984; Treisman, 1963; Ulrich, Nitschke, & Rammsayer, 2006; Zakay & Block, 1997) provide a useful theoretical framework to explain such nontemporal influences on perceived time. Basically, these models assume an internal pacemaker that elicits pulses and an accumulator that counts these pulses. The rate of the pacemaker is often assumed to be modulated by arousal (e.g., Treisman, 1963). At the beginning of a to-be-timed interval, a switch connects the accumulator with the pacemaker, and the pulses are counted until the switch disconnects the accumulator from the pacemaker at the end of the interval. The counted number of pulses represents perceived time and can be compared with information stored in a reference memory. The attentional gate model by Zakay and Block (1997) extends this basic model by an attentional gate that modulates the throughput between the pacemaker and the accumulator. That is, the less attention is devoted to time the less pulses pass the attentional gate and the shorter the duration of an interval will be perceived.

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Within this theoretical framework, differences in the perceived duration of the same interval can be explained by variations in the switch latency, the pacemaker rate, and the attentional gate. Different switch latencies for filled and empty intervals might arise from the different on- and offset structures of the sensory markers defining the different intervals. For example, Grondin (1993) suggested that the switch immediately closes in case of a stimulus onset whereas the closing is somewhat delayed in case of a stimulus offset. For filled intervals, this would mean that the timing immediately starts with the onset of the stimulus and stops slightly delayed after the stimulus offset. For empty intervals, however, the timing would start slightly delayed after the offset of the first marker and stop immediately with the onset of the second marker. This would result in longer perceived duration for filled than for empty intervals.

As an alternative, a pacemaker account of the filled-duration illusion assumes that filled intervals induce a higher pacemaker rate than empty intervals, for example, due to higher arousal associated with the continuous stimulation of filled intervals as compared to the absence of external stimulation during empty intervals. In a previous study, Wearden and colleagues aimed to distinguish between switch and pacemaker accounts of the filled-duration illusion using a verbal estimation task (Wearden et al., 2007). They reasoned that if the illusion was caused by an effect on switch latency, the size of the illusion should be constant across a wide range of stimulus durations. In contrast, if the illusion was related to different pacemaker rates, the size of the illusion should increase with increasing stimulus duration. Their results were in line with the prediction of the pacemaker account. The authors thus concluded that the filled-duration illusion is probably due to a higher pacemaker rate for filled than for empty intervals.

One of the standard methods for studying temporal phenomena like the filled-duration illusion is the method of reproduction (see, e.g., Grondin, 2008). There are essentially three different variants of this method that have been used since the pioneering studies of Vierordt (1868). In all these variants a sample interval is presented, and participants are required to subsequently reproduce this interval by a specific motor action that differs between the variants. In one variant, participants continuously press a key for the perceived duration (i.e., filled reproduction; e.g., Bausenhardt, Dyjas, & Ulrich, 2014; Bryce & Bratzke, 2015; Tse et al., 2004). In a second variant, participants start and stop the reproduction with two brief key presses (i.e., empty reproduction; e.g., Bangert, Reuter-Lorenz, & Seidler, 2011; Grondin, 2012; Woodrow, 1930). In a third variant, participants only terminate the reproduction interval with a single key press (i.e., termination; e.g., Jazayeri & Shadlen, 2010; Riemer, Trojan, Kleinböhl, & Hölzl, 2012; Ulbrich, Churan, Fink, & Wittmann, 2007; Vierordt, 1868). In contrast to other widely

used timing methods (as, e.g., verbal estimation), a specific characteristic of reproduction is that during the reproduction phase timing of the interval is again required. Obviously, the motor activities required for filled and empty reproductions have properties very similar to the characteristics of the stimuli in the filled-duration illusion. It is reasonable to assume that the continuous motor activity of a filled reproduction leads to higher arousal and consequently also to a higher pacemaker rate than the two brief key presses involved in an empty reproduction. Accordingly, not only the stimulus type but also the reproduction type might affect reproduced duration.

Until today, only a few studies have investigated potential influences of the different variants of the reproduction method on temporal estimates (e.g., Buetti & Walsh, 2010; Mioni, Stablum, McClintock, & Grondin, 2014). In one of these studies, Mioni et al. (2014) employed all three variants, that is, filled reproduction, empty reproduction, and termination. In line with our consideration that filled reproduction might accelerate the pacemaker, they observed that across a wide range of sample durations (1–18 s), reproductions were on average shorter with filled than with empty reproductions. Their study thus provides the first evidence for what we will refer to as filled-reproduction illusion. It is important to note that such a filled-reproduction illusion works in the opposite direction of the filled-duration illusion. That is, filled reproductions lead to shorter time estimates than empty reproductions, whereas filled intervals lead to longer time estimates than empty intervals. These opposed directions of the two illusions are consistent with the view that both filled sample intervals and filled reproductions increase the rate of the pacemaker compared with empty intervals and empty reproductions, respectively (see Fig. 1 for a schematic illustration). In case of the filled-duration illusion, a higher pacemaker rate leads to longer estimates because more pulses are accumulated during the same interval. In case of the filled-reproduction illusion, however, a higher pacemaker rate leads to shorter estimates because the same number of pulses is accumulated earlier in time. Additionally, as can be seen in Fig. 1, the filled-reproduction illusion should be larger for filled than for empty sample intervals. Analogously, the filled-duration illusion should be larger for empty than for filled reproductions.

In the present study, we further investigated the filled-reproduction illusion employing filled and empty reproductions in combination with filled and empty sample intervals. Besides the aim to replicate both kinds of illusions (i.e., filled-duration and filled-reproduction illusion) in this combined paradigm, we considered two additional aspects. First, Mioni et al. (2014) included in their study only sample durations in the suprasecond range. It has been suggested that different mechanisms are involved in timing of very brief intervals (i.e., in the subsecond range) and intervals in the suprasecond range (Lewis & Miall, 2003; Rammsayer & Ulrich, 2011). To investigate whether a similar illusion also occurs in the

Fig. 1 Schematic illustration of how variations in pacemaker rate due to interval type (filled vs. empty) and reproduction type (filled vs. empty) should affect temporal reproductions. If both filled intervals and reproductions are associated with a higher pacemaker rate, filled intervals should lead to longer reproductions than empty intervals (filled - duration illusion), and filled reproductions should lead to shorter reproductions than empty reproductions (filled - reproduction illusion: FRI). Additionally, the filled - reproduction illusion should be stronger for filled than empty intervals

subsecond range, we employed four sample durations ranging from 400 to 1,600 ms. Second, we asked whether a filled-reproduction illusion can also be attributed to variations in pacemaker rate, as has been proposed for the filled-duration illusion. Accordingly, the filled-reproduction illusion should also increase with increasing sample duration. First evidence for such a scaling of the illusion with sample duration can be found in Mioni et al.'s study.

Experiment 1

In Experiment 1, participants had to reproduce filled and empty sample intervals with filled and empty reproductions. The two interval types were presented randomly interleaved within experimental blocks, whereas the two reproduction types were employed in different halves of the experiment.

Method

Participants Twelve females and eight males, between 19 and 41 years of age ($M = 25.5$ years) participated in Experiment 1. One participant was left-handed, and all participants reported normal vision and hearing.

Apparatus and stimuli The experiment was run in a sound-attenuated, dimly illuminated experimental booth. Stimuli were presented and responses recorded by a Mac under the control of MATLAB using the Psychophysics Toolbox 3 extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). A 21-in. monitor with a resolution of 1024×768 pixels and a refresh rate of 150 Hz was used for stimulus presentation. Participants sat in front of the screen at a distance

of about 60 cm. The space bar of a standard German keyboard served as response key.

Visual stimuli were a fixation cross ($1.6^\circ \times 1.6^\circ$ of visual angle) and a question mark ($1.2^\circ \times 2.4^\circ$ of visual angle), which were presented in white against a black background. Auditory stimuli were sine tones of 500 Hz presented via headphones (Sennheiser HD 212 Pro) at an intensity of 70 dB(A) SPL. The intervals were either presented as filled (one continuous tone) or empty intervals (two successive tones). The markers for the empty intervals lasted for 20 ms. Filled intervals were bounded by the onset and the offset of each tone, while empty intervals were bounded by the onset of the first and the onset of the second marker. All tones and markers had 5-ms rise and fall times to avoid clicking noises.

Procedure and design Each trial started with the presentation of a fixation cross for 500 ms at the center of the screen. After the offset of the fixation cross, a filled or empty sample interval was presented with a variable duration (400; 800; 1,200; or 1,600 ms). Then, a question mark appeared at the center of the screen, prompting participants to start reproducing the sample by pressing the space bar as soon as possible. The question mark disappeared with the start of the reproduction. During the reproduction, no external sensory feedback was provided. Immediately after reproduction was finished, the fixation cross was presented again and the next trial started. Participants did not receive any feedback concerning their reproduction performance.

Participants were instructed to reproduce the sample intervals either with filled (a single continuous key press) or with empty (two distinct key presses) reproductions. For filled reproductions, participants were asked to press the space bar and hold it down for as long as the sample had lasted. In this case, the onset of the key press indicated the onset of the reproduction and the offset of the key press indicated the offset of the reproduction. For empty reproductions, participants had to start reproducing the sample by a short press of the space bar and to end the reproduction by pressing the space bar again. In this case, the onset of the first key press indicated the onset of the reproduction, and the onset of the second key press indicated the offset of the reproduction.

The interval type (filled vs. empty) was varied randomly within blocks, whereas the reproduction type was manipulated between halves of the experiment. The order of the reproduction types was counterbalanced between participants. One half of participants started with filled reproductions, and the other half of participants started with empty reproductions. An experimental session comprised two practice blocks (one for each reproduction method) and 20 experimental blocks (10 for each reproduction method). Practice blocks and experimental blocks consisted of 16 trials each (two trials for each

combination of sample duration and interval type). The experimental session lasted for about 35 minutes.

Results and discussion

The main dependent variable was mean reproduction. As in Mioni et al. (2014), we also analyzed reproduction variability (coefficient of variation; CV) and report the results here for the sake of comparison. The CV was calculated by dividing the standard deviation by the mean reproduction separately for each participant, reproduction type, interval type, and sample duration. Additionally, mean response time (RT) was analyzed to examine potential differences in processing the temporal information between different stimulus and reproduction conditions (see Bangert et al., 2011). Response time was measured from the onset of the question mark until the space bar was pressed.

Data from practice blocks as well as trials including outliers defined as reproductions deviating more than 2.5 standard deviations from the individual cell mean were excluded from data analysis (1.34% of all trials).¹ Separate $2 \times 2 \times 4$ repeated-measures ANOVAs, with the factors interval type (filled vs. empty), reproduction type (filled vs. empty), and sample duration (400; 800; 1,200; and 1,600 ms) were computed on mean reproduction, CV, and mean RT. Greenhouse–Geisser corrections were applied to adjust p values where appropriate. Within-subjects standard errors were computed according to Morey (2008).

To test for potential scaling of the two illusions (filled-duration and filled-reproduction illusion) with sample duration, we fitted simple linear regressions to the individual mean reproductions with sample duration as predictor and the size of the illusion as outcome variable. T tests were conducted in order to test whether the mean slopes of these regressions differed from zero.²

Mean reproduction As can be seen in the left panel of Fig. 2, mean reproduction increased with sample duration, $F(3, 57) = 809.58$, $p < .001$, $\eta_p^2 = .98$. As expected, the results showed the classic filled - duration illusion (see also the middle panel of Fig. 2). Reproductions of filled intervals (1,273 ms) were on average 243 ms longer than reproductions of empty intervals (1,030 ms), $F(1, 19) = 30.70$, $p < .001$, $\eta_p^2 = .62$. There was also a significant main effect of reproduction method, $F(1, 19) = 7.53$, $p = .013$, $\eta_p^2 = .28$. Reproductions were on average 77 ms longer for empty (1,190 ms) than for filled

(1,113 ms) reproductions, demonstrating a filled-reproduction illusion (see also the right panel of Fig. 2).

Additionally, the ANOVA yielded a significant interaction of interval type and sample duration, $F(3, 57) = 8.01$, $p = .002$, $\eta_p^2 = .30$, indicating that the filled-duration illusion increased with increasing sample duration (170, 216, 276, 313 ms), with a mean slope of 0.12, $t(19) = 3.42$, $p = .003$. A similar interaction was observed between reproduction type and sample duration, $F(3, 57) = 7.76$, $p = .002$, $\eta_p^2 = .29$, indicating that the filled-reproduction illusion also increased with sample duration (−20, −55, −94, −136 ms), with a mean slope of −0.10, $t(19) = -3.39$, $p = .003$. The ANOVA also yielded a significant interaction between interval type and reproduction type, $F(1, 19) = 8.03$, $p = .011$, $\eta_p^2 = .30$. Averaged across sample durations, there was a stronger filled - duration illusion for empty (295 ms) than for filled (192 ms) reproductions (see the middle panel of Fig. 2), and a stronger filled - reproduction illusion for filled (−128 ms) than for empty (−25 ms) intervals (see the right panel of Fig. 2).

Furthermore, the ANOVA revealed a significant three-way interaction between interval type, reproduction type, and sample duration, $F(3, 57) = 8.64$, $p < .001$, $\eta_p^2 = .31$. As can be seen in the right panel of Fig. 2, the effect of reproduction type for filled intervals was relatively constant across sample durations (−134, −91, −131, −155 ms), with a mean slope of −0.03, $t(19) = -0.69$, $p = .501$. For empty intervals, however, the effect was strongly modulated by sample duration, with an even reversed pattern at the shortest sample duration (95, −20, −57, −118 ms) and a mean slope of −0.17, $t(19) = -5.90$, $p < .001$. Furthermore, the three-way interaction indicated that even for the filled-duration illusion the expected scaling of the illusion with sample duration was not independent of reproduction type (see the middle panel of Fig. 2). Accordingly, the filled-duration illusion significantly increased with sample duration for filled reproductions (mean slope: 0.19), $t(19) = 5.22$, $p < .001$, but not for empty reproductions (mean slope: 0.05), $t(19) = 1.21$, $p = .243$.

Coefficient of variation (CV) The ANOVA revealed a significant main effect of sample duration, with larger CV for short than for long sample durations (see Fig. 3), $F(3, 57) = 28.14$, $p < .001$, $\eta_p^2 = .60$. This replicates the CV results by Mioni et al. (2014), although these authors used a very different range of sample durations (1–18 s). There was also a significant main effect of reproduction type on CV, $F(1, 19) = 7.35$, $p = .014$, $\eta_p^2 = .28$, with larger CV for the filled (0.20) than for the empty (0.18) reproduction type. This is in contrast to the results of Mioni et al., who did not observe a difference in CV between the two reproduction types. The interaction between interval and reproduction type was also significant, $F(1, 19) = 19.63$, $p < .001$, $\eta_p^2 = .51$. The effect of reproduction type was larger for empty (0.05) than for filled (−0.01) intervals. All other effects on CV were not significant (all $ps > .200$).

¹ We also performed all analyses including outliers. For Experiment 1, these ANOVAs revealed only one qualitatively different result. The main effect of reproduction type on CV did not reach significance, $F(1, 19) = 1.83$, $p = .192$, $\eta_p^2 = .09$.

² The additional regression analyses were suggested by an anonymous reviewer.

Fig. 2 Reproduction results in Experiment 1. *Left panel:* Mean reproduction as a function of interval type, reproduction type, and sample duration. *Middle panel:* Filled - duration illusion (filled interval minus empty interval) as a function of reproduction type. *Right panel:*

Filled - reproduction illusion (filled reproduction minus empty reproduction) as a function of interval type. Note that for the filled - reproduction illusion negative values are plotted upwards. Error bars represent ± 1 within-subjects *SE* according to Morey (2008)

Mean response time (RT) Mean RT is depicted in Fig. 4. The ANOVA yielded a significant main effect of interval type, with shorter RT for filled (687 ms) than for empty (962 ms) intervals, $F(1, 19) = 71.51$, $p < .001$, $\eta_p^2 = .79$. The main effects of reproduction type and sample duration were not significant, $ps > .128$. There was a significant interaction of interval and reproduction type, $F(1, 19) = 12.28$, $p = .002$, $\eta_p^2 = .39$, reflecting that the effect of interval type was larger for filled (321 ms) than for empty (229 ms) reproductions. Furthermore, a significant interaction effect of interval type and sample duration was observed, $F(3, 57) = 19.08$, $p < .001$, $\eta_p^2 = .50$. As can be seen in Fig. 4, RT decreased with increasing sample duration for filled interval whereas RT increased with increasing sample duration for empty intervals (a similar RT increase for empty reproductions of empty intervals was observed by Bangert et al., 2011). Linear regression analyses of individual RTs with sample duration as predictor confirmed this pattern, with a mean slope of -0.10 for filled intervals, $t(19) = -2.83$, $p = .011$, and a mean slope of 0.20 for empty intervals, $t(19) =$

4.31, $p < .001$. This suggests that participants might have employed different modes of processing for empty and filled intervals. For example, empty intervals might have induced an internal rhythm that participants tended to follow in order to start and stop their reproductions. This idea is supported by the observation that empty reproductions of empty intervals were the least variable reproductions. All other interactions were not significant, all $ps > .316$.

Taken together, Experiment 1 yielded a rather mixed pattern of results. Overall, there was evidence for both the classic filled-duration illusion and a filled-reproduction illusion. Nevertheless, the filled-reproduction illusion only occurred for filled intervals and was even reversed for empty intervals

Fig. 3 Coefficient of variation as a function of interval type and reproduction type in Experiment 1. Error bars represent ± 1 within-subjects *SE* according to Morey (2008)

Fig. 4 Mean response time as a function of interval type and reproduction type in Experiment 1. Error bars represent ± 1 within-subjects *SE* according to Morey (2008)

⁰ ANOVAs including outliers revealed two qualitatively different results in Experiment 2. First, the main effect of reproduction type on mean reproduction was significant, $F(1, 19) = 5.07$, $p = .036$, $\eta_p^2 = .21$. Second, the interaction between reproduction type and sample duration on RT did not reach significance, $F(3, 57) = 2.55$, $p = .064$, $\eta_p^2 = .12$.

when the sample duration was rather short. Additionally, the interaction pattern expected under the assumption of a pace-maker account (i.e., an increasing size of the illusion with increasing sample duration) was also modulated by the specific combination of reproduction and interval type, and this was the case for both the filled-duration and the filled-reproduction illusion. Furthermore, RT analysis suggested that the different interval types might have induced different modes of processing.

Experiment 2

In Experiment 2, we investigated whether potential differences between processing of empty and filled intervals might have contributed to the result pattern of Experiment 1. To prevent participants from employing a rhythmical timing strategy for the reproduction of empty intervals, we inserted an additional variable interval between the offset of the sample interval and the response prompt.

Method

Participants A new sample consisting of 15 females and five males, between 18 and 42 years of age ($M = 24.5$ years), participated in Experiment 2. Five participants were left-handed, and all participants reported normal vision and hearing.

Apparatus and stimuli The apparatus and stimuli were identical to Experiment 1.

Procedure and design The procedure and design were identical to Experiment 1, with the exception that an additional random interval (1–3 s) was included between the sample interval and the response prompt.

Results and discussion

Data analysis followed the procedure of Experiment 1. One hundred and twenty-seven trials (1.98% of all trials) were identified as outliers and discarded from analyses.³³

Mean reproduction As can be seen in the left panel of Fig. 5, the pattern of mean reproductions resembled the one of Experiment 1 in many respects. Overall, mean reproductions were somewhat longer (1,242 ms) than in Experiment 1

(1,151 ms). There were again significant main effects of sample duration, $F(3, 57) = 522.16$, $p < .001$, $\eta_p^2 = .96$, and interval type, $F(1, 19) = 45.06$, $p < .001$, $\eta_p^2 = .70$. The size of the filled duration illusion was 300 ms. Even though the difference between filled (1,196 ms) and empty (1,287 ms) reproductions was slightly larger than in Experiment 1 (−91 vs. −77 ms in Experiment 1), the main effect of reproduction type did not reach significance, $F(1, 19) = 2.44$, $p = .134$, $\eta_p^2 = .11$.

As in Experiment 1, the filled-duration illusion increased with increasing sample duration (217, 314, 320, 353 ms; see the middle panel of Fig. 5), $F(3, 57) = 6.02$, $p = .005$, $\eta_p^2 = .24$, with a mean slope of 0.10, $t(19) = 3.16$, $p = .005$. A significant interaction between reproduction type and sample duration indicated that the difference between filled and empty reproductions also increased with sample duration (−18, −62, −124, −159 ms; see the right panel of Fig. 5), $F(3, 57) = 7.76$, $p = .002$, $\eta_p^2 = .29$, with a mean slope of −0.12, $t(19) = -3.36$, $p = .003$. The interaction between interval and reproduction type was again significant, $F(1, 19) = 8.03$, $p = .011$, $\eta_p^2 = .30$. The interaction pattern resembled the pattern of Experiment 1. The filled-duration illusion was stronger for empty (434 ms) than for filled (168 ms) reproductions (see the middle panel of Fig. 5), and there was a substantial filled-reproduction illusion for filled intervals (−224 ms) but a reversed illusion for empty intervals (42 ms; see the right panel of Fig. 5).

Even though the pattern of the three-way interaction was similar to Experiment 1, the interaction did not reach significance, $F(3, 57) = 2.08$, $p = .112$, $\eta_p^2 = .10$. Nevertheless, regression analyses indicated that the filled-duration illusion significantly increased with sample duration for filled reproductions (mean slope: 0.14), $t(19) = 3.93$, $p < .001$, but not for empty reproductions (mean slope: 0.06), $t(19) = 1.26$, $p = .222$, and that the filled-reproduction illusion significantly increased for empty intervals (mean slope: −0.16), $t(19) = -3.96$, $p < .001$, but not for filled intervals (mean slope: −0.08), $t(19) = -1.58$, $p = .130$.

Coefficient of variation (CV) Overall, CVs were slightly higher (0.21) than in Experiment 1 (0.19). As can be seen in Fig. 6, CV was mainly affected by sample duration. Accordingly, only the effect of sample duration was significant, $F(3, 57) = 35.78$, $p < .001$, $\eta_p^2 = .65$, indicating that CV decreased from the shortest to the longest sample duration. All other main effects and interactions were not significant, all $ps > .066$.

Mean response time (RT) In contrast to Experiment 1, RT performance did not indicate that participants employed different processing modes for filled and empty intervals (see Fig. 7). Overall, the RT differences between different conditions were much smaller than in Experiment 1. Nevertheless, there was a significant main effect of sample duration, $F(3, 57) = 3.74$, $p = .036$, $\eta_p^2 = .16$, and a significant interaction

³³ ANOVAs including outliers revealed two qualitatively different results in Experiment 2. First, the main effect of reproduction type on mean reproduction was significant, $F(1, 19) = 5.07$, $p = .036$, $\eta_p^2 = .21$. Second, the interaction between reproduction type and sample duration on RT did not reach significance, $F(3, 57) = 2.55$, $p = .064$, $\eta_p^2 = .12$.

Fig. 5 Reproduction results in Experiment 2. *Left panel:* Mean reproduction as a function of interval type, reproduction type, and sample duration. *Middle panel:* Filled-duration illusion (filled interval minus empty interval) as a function of reproduction type. *Right panel:*

Filled - reproduction illusion (filled reproduction minus empty reproduction) as a function of interval type. Note that for the filled - reproduction illusion negative values are plotted upwards. Error bars represent ± 1 within-subjects SE according to Morey (2008)

between reproduction type and sample duration, $F(3, 57) = 3.24$, $p = .046$, $\eta_p^2 = .15$. RT decreased from the shortest to the longest sample duration (658, 619, 598, 593 ms), and this pattern was slightly different for filled (609, 616, 569, 595 ms) than for empty (704, 623, 626, 591 ms) reproductions. All other main effects and interactions were not significant, all $ps > .094$.

In summary, it appears that the insertion of a variable delay between the offset of the sample interval and the response prompt sufficiently prevented participants from employing different reproduction modes for filled and empty intervals. As side effects of this procedural change, mean reproductions were overall somewhat longer and variability of reproductions was somewhat higher than in Experiment 1. Nevertheless, the mean reproduction results were not substantially changed compared to Experiment 1. Accordingly, the results still showed a complex interaction pattern between reproduction and interval type.

General discussion

In the present study, participants reproduced filled and empty intervals using two variants of the reproduction method, namely, filled and empty reproduction. Based on previous empirical evidence and the theoretical framework provided by pacemaker counter models, we expected to observe both a filled - duration illusion (i.e., longer reproductions for filled than for empty intervals) and a filled-reproduction illusion (i.e., shorter reproductions for empty than for filled reproductions). Indeed, the results provided evidence for both kinds of illusions, even though the evidence was clearer for the filled - duration than for the filled - reproduction illusion. The present study demonstrates that in a situation where both illusions work in concert, reproductions of the same interval can vary by up to 90% (averaged across all sample durations: 48%) of the duration of the to-be-reproduced interval depending on the combination of interval and reproduction type.

Fig. 6 Coefficient of variation as a function of interval type and reproduction type in Experiment 2. Error bars represent ± 1 within-subjects SE according to Morey (2008)

Fig. 7 Mean response time as a function of interval type and reproduction type in Experiment 2. Error bars represent ± 1 within-subjects SE according to Morey (2008)

In line with a pacemaker account of the two illusions, the filled-duration illusion was larger in combination with filled than with empty reproductions, and the filled-reproduction illusion was larger for empty than for filled intervals. However, a clear deviation from the predicted pattern was that the filled-reproduction illusion was even reversed for empty intervals of rather short durations. Also, the prediction of the pacemaker account that the two illusions would increase with sample duration was not confirmed in all cases. For example, in both experiments, even the filled-duration illusion did not show the predicted scaling of the illusion with sample duration in case of empty reproductions.

Mioni et al. (2014) already reported longer reproductions for empty than for filled reproductions of filled intervals across a wide range of sample durations in the suprasecond range. Our results replicate their finding for filled intervals and extend it to the subsecond range. The effect of reproduction type, however, was less clear for the reproduction of empty intervals. In Experiment 1, RT performance suggested that participants might have adopted different processing modes for empty and filled intervals, which could have contributed to the difference in the effect of reproduction type between the two interval types. Specifically, RT increased with increasing sample duration for empty intervals, whereas RT rather decreased with increasing sample duration for filled intervals. We hypothesized that participants' reproductions for empty intervals were influenced by the rhythm entrained by the brief markers of those intervals (see Large & Jones, 1999). An insertion of a variable delay between the sample interval and the reproduction in Experiment 2 clearly equalized the RT patterns of the two interval conditions but did not affect the difference between the two reproduction type effects. We thus suggest that the different effects of reproduction type were probably not due to different temporal processing modes for filled and empty intervals.

A lack or even a reversal of the filled - reproduction illusion for empty intervals mainly appeared for rather short intervals. This observation hints at the potential contribution of motor constraints for the present findings. Several authors have critically discussed the role of motor action in temporal reproduction (Droit-Volet, 2010; Mioni et al., 2014; Wearden, 2003). For example, Droit-Volet (2010) suggested that motor components play a crucial role in reproduction differences between children and adults. In her study, she adopted a model proposed by Wearden (2003), which takes into account the time demands to initiate and execute the motor action involved in temporal reproduction. This model assumes that temporal reproductions are generated in two consecutive phases—a waiting and a response phase. During the first phase, the participant waits until the elapsed time is “close enough” to the represented duration of the target interval. In the second phase, the participant initiates and executes the required response. The waiting time is assumed to be proportional to the target

duration (e.g., 70% of the target duration), whereas the response time is on average constant across different target durations. This model can, for example, explain the common finding that short intervals are overreproduced whereas long intervals are underreproduced (i.e., the Vierordt effect). The present finding of a reversed filled reproduction illusion for short sample durations, however, cannot be explained by Wearden's model without further assumptions.

Wearden's (2003) model can nevertheless provide a useful theoretical frame for explaining the present results if one additionally takes into account the empirical observation that RT can be longer for key releases than for key presses (Björklund, 1991). It is indeed possible to model the reversal of the filled-reproduction illusion for short intervals using Wearden's two-phase model, namely, assuming shorter representations for filled than empty reproductions (due to a higher pacemaker rate for filled than empty reproductions) and longer response times for the key-release responses at the end of filled reproductions than for the key-press responses at the end of empty reproductions. However, this explanation seems still unlikely because there is no reason to assume that these effects should only occur for empty intervals. Additionally, the largest reversed filled-reproduction illusion observed in the present study was 125 ms (for empty intervals of 400 ms duration in Experiment 1), which clearly exceeds the RT difference one could expect between key-release and key-press responses (about 25 ms in Björklund's study).

There are other motor-related factors that might have contributed to the partially reversed reproduction effect. Participants can produce finger taps with a rate up to 5–7/s, which corresponds to intertap intervals of 150–200 ms (see Repp, 2005). Accordingly, even the shortest intervals in the present study (i.e., 400 ms) should not have posed substantial motor difficulties for the participants in case of empty reproductions. In case of filled reproductions, however, it is conceivable that the reproductions need to have a certain minimum duration in order to be experienced as a filled reproduction. If so, this should prolong reproductions predominantly in case of rather short filled reproductions. This explanation, however, is also unlikely, because previous studies (e.g., Tse et al., 2004) have reported mean reproductions that were clearly shorter (down to 250 ms) than the shortest mean filled reproduction in the present study (560 ms for empty intervals with 400 ms duration in Experiment 1). Another argument against this explanation is that the reversal of the reproduction effect was even more pronounced in Experiment 2, in which reproductions were on average longer than in Experiment 1. Nevertheless, we cannot rule out that a tendency to produce at least a certain minimum duration in case of filled reproductions might have contributed to the present results.

Mioni et al. (2014) also addressed the potential role of the different motor actions in temporal reproduction, adopting the resource perspective of the attentional gate model (Zakay &

Block, 1997). They hypothesized that preparing and executing a motor action reduces the attentional resources that can be devoted to the perception of time, and, consequently, reproductions should be rather variable and underestimate the duration of the target intervals. Initially, Mioni and colleagues hypothesized that of the three reproduction variants, empty reproduction should require the most resources because of the two key presses involved in this variant. Their results, however, showed shorter reproductions for filled than for empty reproductions. The authors revised their hypothesis accordingly, now arguing that the continuous motor action in filled reproductions probably required more resources than the two key presses in empty reproductions. As Wearden et al. (2007) already noted in their study on the filled-duration illusion, such an attentional account is essentially indistinguishable from a pacemaker rate account. Accordingly, an attentional account can also explain the basic findings of the present study, that is, the filled-duration and the filled-reproduction illusion, if one assumes that the motor actions involved in the reproduction substantially draw on attentional resources. However, such an attentional account is also not capable of fully explaining the interaction pattern between interval and reproduction type observed in the present study.

We were particularly interested in the effect of the different motor actions involved in filled and empty reproductions and therefore did not provide any sensory feedback during the reproduction interval. There are numerous examples of both kinds of studies, those providing no sensory feedback (e.g., Bangert et al., 2011; Bausenhardt et al., 2014; Bryce & Bratzke, 2015; Fortin & Rousseau, 1998; Jazayeri & Shadlen, 2010; Tse et al., 2004) and those providing feedback (e.g., Buetti & Walsh, 2010; Elbert, Ulrich, Rockstroh, & Lutzenberger, 1991; Gibbons & Rammsayer, 2004; Kononowicz, Sander, & Van Rijn, 2015; Mioni et al., 2014; Riemer et al., 2012; Ulbrich et al., 2007). If sensory feedback is provided, often the same stimulus is presented during the sample and the reproduction interval. Besides the motor-related effects of reproduction type investigated in the present study, it would also be interesting to examine potential effects of sensory feedback provided during the reproduction interval.

For example, a pacemaker account would predict that presentation of filled and empty sensory feedback during the reproduction should result in an inversed filled-duration illusion (i.e., reproductions should be shorter instead of longer for filled than for empty feedback). That is because during the reproduction the same number of pulses is accumulated earlier in case of a higher pacemaker rate. Interestingly, two recent studies failed to show this inverse pattern for two temporal illusions similar to the filled-duration illusion, namely, the effect of stimulus size (Rammsayer & Verner, 2015) and numerical magnitude (Cai & Wang, 2014) on temporal reproductions. In both studies, the respective stimulus

characteristics affected reproductions when the relevant stimuli were presented during the sample interval, but not when they appeared during the reproduction. In both studies, the authors interpreted this result pattern as evidence against a pacemaker and in favor of a memory-related account of the respective illusions. Investigating stimulus-related temporal illusions during the reproduction phase can thus provide additional evidence regarding the perceptual or cognitive origin of a temporal illusion.

In conclusion, the present study provides evidence for both a filled - duration and a filled - reproduction illusion which work in opposing directions. As a consequence, reproductions of the same interval can vary dramatically depending on the combination of interval and reproduction type. The question of whether these illusions are driven by variations in pacemaker rate or other factors could not be clearly answered on basis of the present results and is thus awaiting further research.

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References

- Adams, R. D. (1977). Intervening stimulus effects on category judgments of duration. *Perception & Psychophysics*, 21(6), 527–534. doi:10.3758/BF03198733
- Bangert, A. S., Reuter-Lorenz, P. A., & Seidler, R. D. (2011). Dissecting the clock: Understanding the mechanisms of timing across tasks and temporal intervals. *Acta Psychologica*, 136, 20–34. doi:10.1016/j.actpsy.2010.09.006
- Bausenhardt, K. M., Dyjas, O., & Ulrich, R. (2014). Temporal reproductions are influenced by an internal reference: Explaining the Vierordt effect. *Acta Psychologica*, 147, 60–67. doi:10.1016/j.actpsy.2013.06.011
- Birngruber, T., Schröter, H., & Ulrich, R. (2014). Duration perception of visual and auditory oddball stimuli: Does judgment task modulate the temporal oddball effect? *Attention, Perception & Psychophysics*, 76, 814–828. doi:10.3758/s13414-013-0602-2
- Björklund, R. A. (1991). Reaction time and movement time measured in a key-press and a key-release condition. *Perceptual and Motor Skills*, 72, 663–673.
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10, 433–436. doi:10.1163/156856897X00357
- Bratzke, D., Seifried, T., & Ulrich, R. (2012). Perceptual learning in temporal discrimination: Asymmetric cross-modal transfer from audition to vision. *Experimental Brain Research*, 221, 205–210.
- Bryce, D., & Bratzke, D. (2015). Are introspective reaction times affected by the method of time estimation? A comparison of visual analogue scales and reproduction. *Attention, Perception & Psychophysics*, 77, 978–984. doi:10.3758/s13414-014-0804-2
- Buetti, D., & Walsh, V. (2010). Memory for time distinguishes between perception and action. *Perception*, 39(1), 81–90. doi:10.1068/p6405
- Buffardi, L. (1971). Factors affecting the filled-duration illusion in the auditory, tactual, and visual modalities. *Perception & Psychophysics*, 10(4), 292–294. doi:10.3758/BF03212828
- Cai, Z. G., & Wang, R. (2014). Numerical magnitude affects temporal memories but not time encoding. *PLoS ONE*, 9(1), e83159. doi:10.1371/journal.pone.0083159

- Craig, J. C. (1973). A constant error in the perception of brief temporal intervals. *Perception & Psychophysics*, 13(1), 99–104. doi:10.3758/BF03207241
- Creelman, C. D. (1962). Human discrimination of auditory stimuli. *Journal of the Acoustical Society of America*, 34, 582–593.
- Droit-Volet, S. (2010). Stop using time reproduction tasks in a comparative perspective without further analyses of the role of the motor response: The example of children. *European Journal of Cognitive Psychology*, 22(1), 130–148. doi:10.1080/09541440902738900
- Droit-Volet, S., & Meck, W. H. (2007). How emotions colour our perception of time. *Trends in Cognitive Sciences*, 11(12), 504–513. doi:10.1016/j.tics.2007.09.008
- Elbert, T., Ulrich, R., Rockstroh, B., & Lutzenberger, W. (1991). The processing of temporal intervals reflected by CNV-like brain potential. *Psychophysiology*, 28, 648–655.
- Fortin, C., & Rousseau, R. (1998). Interference from short-term memory processing on encoding and reproducing brief durations. *Psychological Research*, 61(4), 269–276. doi:10.1007/s004260050031
- Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, 423, 52–77.
- Gibbons, H., & Rammsayer, T. H. (2004). Current-source density analysis of slow brain potentials during time estimation. *Psychophysiology*, 41(6), 861–874. doi:10.1111/j.1469-8986.2004.00246.x
- Goldstone, S., & Goldfarb, J. L. (1963). Judgment of filled and unfilled durations: Intersensory factors. *Perceptual and Motor Skills*, 17, 763–774.
- Gomez, L. M., & Robertson, L. C. (1979). The filled-duration illusion: The function of temporal and nontemporal set. *Perception & Psychophysics*, 25(5), 432–438. doi:10.3758/BF03199853
- Grondin, S. (1993). Duration discrimination of empty and filled intervals marked by auditory and visual signals. *Perception & Psychophysics*, 54(3), 383–394. doi:10.3758/BF03205274
- Grondin, S. (2008). Methods for studying psychological time. In S. Grondin (Ed.), *Psychology of time* (pp. 51–74). Bingley: Emerald Group.
- Grondin, S. (2012). Violation of the scalar property for time perception between 1 and 2 seconds: Evidence from interval discrimination, reproduction, and categorization. *Journal of Experimental Psychology: Human Perception and Performance*, 38, 880–890. doi:10.1037/a0027188
- Hancock, P. A. (1993). Body temperature influence on time perception. *The Journal of General Psychology*, 120, 197–215.
- Hasuo, E., Nakajima, Y., Tomimatsu, E., Grondin, S., & Ueda, K. (2014). The occurrence of the filled duration illusion: A comparison of the method of adjustment with the method of magnitude estimation. *Acta Psychologica*, 147, 111–121. doi:10.1016/j.actpsy.2013.10.003
- Jazayeri, M., & Shadlen, M. N. (2010). Temporal context calibrates interval timing. *Nature Neuroscience*, 13(8), 1020–1026. doi:10.1038/nn.2590
- Kleiner, M., Brainard, D. H., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception*, 36, ECVF
- Kononowicz, T. W., Sander, T., & Van Rijn, H. (2015). Neuroelectromagnetic signatures of the reproduction of supra-second durations. *Neuropsychologia*, 75, 201–213. doi:10.1016/j.neuropsychologia.2015.06.001
- Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, 106, 119–159.
- Lewis, P. A., & Miall, R. C. (2003). Distinct systems for automatic and cognitively controlled time measurement: Evidence from neuroimaging. *Current Opinion in Neurobiology*, 13(2), 250–255. doi:10.1016/S0959-4388(03)00036-9
- Matthews, W. J., Stewart, N., & Wearden, J. H. (2011). Stimulus intensity and the perception of duration. *Journal of Experimental Psychology: Human Perception and Performance*, 37(1), 303–313. doi:10.1037/a0019961
- Mioni, G., Stablum, F., McClintock, S. M., & Grondin, S. (2014). Different methods for reproducing time, different results. *Attention, Perception & Psychophysics*, 76, 675–681. doi:10.3758/s13414-014-0625-3
- Morey, R. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, 4, 61–64.
- Pelli, D. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 4, 437–442. doi:10.1163/156856897X00366
- Penney, T. B., Gibbon, J., & Meck, W. H. (2000). Differential effects of auditory and visual signals on clock speed and temporal memory. *Journal of Experimental Psychology: Human Perception and Performance*, 26(6), 1770–1787. doi:10.1037/0096-1523.26.6.1770
- Rammsayer, T., & Ulrich, R. (2011). Elaborative rehearsal of nontemporal information interferes with temporal processing of durations in the range of seconds but not milliseconds. *Acta Psychologica*, 137(1), 127–133. doi:10.1016/j.actpsy.2011.03.010
- Rammsayer, T., & Verner, M. (2015). Larger visual stimuli are perceived to last longer from time to time: The internal clock is not affected by nontemporal visual stimulus size. *Journal of Vision*, 15(3), 1–11. doi:10.1167/15.3.5
- Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review*, 12, 969–992.
- Riemer, M., Trojan, J., Kleinböhl, D., & Hölzl, R. (2012). A “view from nowhen” on time perception experiments. *Journal of Experimental Psychology: Human Perception and Performance*, 38(5), 1118–1124. doi:10.1037/a0027073
- Treisman, M. (1963). Temporal discrimination and the indifference interval. Implications for a model of the “internal clock”. *Psychological Monographs*, 77, 1–31.
- Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, 66, 1171–1189. doi:10.3758/BF03196844
- Ulrich, P., Churan, J., Fink, M., & Wittmann, M. (2007). Temporal reproduction: Further evidence for two processes. *Acta Psychologica*, 125(1), 51–65. doi:10.1016/j.actpsy.2006.06.004
- Ulrich, R., Nitschke, J., & Rammsayer, T. (2006). Crossmodal temporal discrimination: Assessing the predictions of a general pacemaker-counter model. *Perception & Psychophysics*, 68, 1140–1152. doi:10.3758/BF03193716
- Vierordt, K. (1868). [Der Zeitsinn nach Versuchen] The time-sense according to experiments. Tübingen, Germany: Laupp.
- Wearden, J. H. (2003). Applying the scalar timing model to human time psychology: Progress and challenges. In H. Helfrich (Ed.), *Time and mind II: Information-processing perspectives* (pp. 21–39). Göttingen, Germany: Hogrefe & Huber.
- Wearden, J. H., Edwards, H., Fakhri, M., & Percival, A. (1998). Why “sounds are judged longer than lights”: Application of a model of the internal clock in humans. *Quarterly Journal of Experimental Psychology*, 51B, 97–120.
- Wearden, J. H., Norton, R., Martin, S., & Montford-Bebb, O. (2007). Internal clock processes and the filled-duration illusion. *Journal of Experimental Psychology: Human Perception and Performance*, 33(3), 716–729. doi:10.1037/0096-1523.33.3.716
- Woodrow, H. (1930). The reproduction of temporal intervals. *Journal of Experimental Psychology*, 13, 473–499.
- Zakay, D., & Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science*, 6(1), 12–16. doi:10.1111/1467-8721.ep11512604