Journal of Experimental Psychology: Human Perception and Performance

A "View From Nowhen" on Time Perception Experiments

Martin Riemer, Jörg Trojan, Dieter Kleinböhl, and Rupert Hölzl

A "View From Nowhen" on Time Perception Experiments

Martin Riemer
University of Mannheim

Jörg Trojan
Heidelberg University

Dieter Kleinböhl and Rupert Hölzl
University of Mannheim

Systematic errors in time reproduction tasks have been interpreted as a misperception of time and therefore seem to contradict basic assumptions of pacemaker-accumulator models. Here we propose an alternative explanation of this phenomenon based on methodological constraints regarding the direction of time, which cannot be manipulated in experimental settings. In two experiments, we demonstrate the influence of the direction of a dimensional change for pitch and brightness estimates. The results support the assumption that errors in time reproduction tasks do not reflect a systematic temporal misperception, but rather a methodological artifact. Implications for contemporary models of time perception are discussed.

Keywords: time perception, time reproduction, psychophysics, pacemaker-accumulator models

Pacemaker-accumulator models are to date the most promising models of time perception. According to these models, subjectively experienced durations are represented by the number of pulses generated by an internal oscillator over a certain period of time (as objective durations are represented by the ticks of a clock) (Treisman, 1963; Pöppel, 1971; Treisman, Faulkner, Naish, & Brogan, 1990). One advantage of these models is that they easily account for alterations in the subjective experience of time by assuming that the pulse rate of the internal oscillator is not constant, but varies depending on bodily states (Craig, 2009). This assumption is supported by the fact that distorted time perception coincides with altered emotional states (Droit-Volet & Meck, 2007), physical arousal (Angrilli, Cherubini, Pavese, & Mantredini, 1997) and increased interoceptive awareness (Cohen, 1981).

However, the adequacy of pacemaker-accumulator models has been challenged by the finding of systematic errors in so-called time reproduction tasks (Wackermann & Ehm, 2006). In such tasks, a standard interval of a specified duration is presented. The participants are then required to reproduce its duration by indicating the time point at which a reproduction interval is perceived as temporally equal to the standard interval. Both intervals can be triggered by auditory or visual cues. In a typical version of the task, participants are presented with a sound of a specific duration and then asked to interrupt a second sound once it has reached exactly the same duration (Ulbrich, Churan, Fink, & Wittmann, 2007).

Applications of these tasks reveal a systematic underreproduction of durations. In an extensive meta-analysis of studies using the method of time reproduction, Eisler (1976) concluded that reproduction errors can be approximated by a psychophysical function with an exponent less than 1, that is, reproduced intervals are shorter than the standards (Eisler, 1976; Wittmann, 2009). This phenomenon has been interpreted as a systematic misperception of durations, which seems to contradict pacemaker-accumulator models (Wackermann, 2005; Wackermann & Ehm, 2006).

The idea of an internal pacemaker with a varying pulse rate convincingly explains temporal misperceptions, when the task requires a translation between the direct experience and the cognitive representation of durations (i.e., seconds, minutes). However, in time reproduction tasks, both standard and reproduction intervals are directly experienced and no abstract translation into conventional time units is required. A decelerated pacemaker rate resulting in a misperception of the standard interval would produce the same temporal misperception during the reproduction interval. Consequently, any influence of the pacemaker rate should affect the perception of both intervals to the same extent, which would result in accurate performance even if time is perceived as speeded up or slowed down (Wearden, 2004; Wackermann & Ehm, 2006). This argument seems to contradict accumulator-pacemaker models, unless they contain auxiliary assumptions which are capable of accounting for the finding of systematic errors in time reproduction tasks.

All suggested explanations for the phenomenon of time underreproduction are based on the assumption of an altered perception of time regarding the standard and the reproduction interval. Some of the timing models which can account for the phenomenon, the attentional-gate model (Zakay & Block, 1997), the parallel-clock model (Eisler, 1975) and the dual

klepsydra model (Wackermann & Ehm, 2006), shall be shortly reviewed in the following.

The attentional-gate model (Zakay & Block, 1997) states that time perception is affected by the attentional resources allocated to the timing process. When a time-related reaction is required, more attention is focused on the timing process, which leads to an increased accumulation of pulses emitted by the pacemaker during the reproduction interval as compared to the standard interval. Consequently, the reproduction interval is perceived as lasting longer.

The parallel-clock model (Eisler, 1975) assumes two separate sensory registers for time, the first accumulating the subjective duration from the onset of the standard interval and the second from the onset of the reproduction interval. These two quantities are continuously compared, and when the former subjective duration (standard plus reproduction interval) is twice as high as the latter, the reproduction interval is terminated. Assuming that the exponent of the psychophysical power function is less than 1, this criterion is reached earlier for subjective than for physical time, which explains the phenomenon of time underreproduction (Eisler, 1981).

The dual klepsydra model of time reproduction[1] (Wackermann & Ehm, 2006) also proposes that time is represented by the state of an internal variable. In the absence of external input, however, the model assumes a passive return to the base state. Such a leaky integrator for time accounts for reproduction errors because the temporal representation of the standard interval decays with elapsed time, that is, during the reproduction interval.

Inherent in each of these models is the assumption that the systematic errors in time reproduction tasks are caused by a disrupted perception of time. Indeed, the phenomenon of time underreproduction is commonly interpreted as a temporal misperception, implying that the reproduction interval is perceived as being longer than it really is. Here we will present and argue for an alternative explanation of the phenomenon, which is based on methodological constraints in timing experiments. According to this new interpretation, the systematic underreproduction of time duration does not reflect a genuine misperception of time, but instead is based on a fundamental judgment bias. This interpretation is completely consistent with the idea of a pacemaker-accumulator device for time perception.

Time reproduction tasks involve a high degree of uncertainty. In every time point during the reproduction phase, participants are uncertain about the temporal equality of standard and reproduction intervals. The subjective likelihood of their equality varies as a function of elapsed time (see Figure 1). At the beginning of each reproduction interval, this likelihood is very low, but it increases constantly as the reproduction interval continues. Without an interruption of the reproduction interval, it would reach its maximum at the point of objective equality of both intervals (given the premise of mean accuracy), and decrease constantly afterwards. Because participants are not able to exactly determine the point of objective equality, it seems plausible that their judgments are based on a less restrictive criterion (dashed line in Figure 1) than the maximum of the probability curve. If the subjective likelihood of equality exceeds this critical value, participants prematurely accept this time point and stop the reproduction interval.

The phenomenon of duration underreproduction becomes entirely comprehensible, once we consider the fact that the experimental investigation of time perception is subject to an
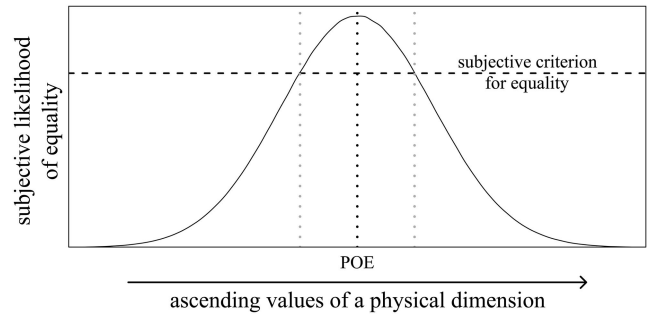

Figure 1. Course of the probability for a correct response during a single trial within reproduction tasks. Depending on the direction of the dimensional change, the subjective criterion for equality is reached at smaller or higher values than the true value of the standard (POE: point of objective equality).

essential methodological constraint: Subjective time always runs in the same direction.[2] Although changes in all other perceivable dimensions (e.g., length, weight) can be presented bidirectionally in experimental settings (i.e., lines can grow or shrink, weight can increase or decrease), the presentation of time is always unidirectional. To present an interval of 3s, we have to start at zero; we cannot start by presenting a 6s-interval which then continually declines. In conjunction with an application of a less restrictive criterion for equality judgments, this naturally results in a premature interruption of the reproduction interval, as can easily be seen in Figure 1. If this judgment bias is the true reason for the systematic underreproduction of durations, the conclusion would be as follows: The phenomenon does not occur because shorter reproduction durations are more likely to be perceived as temporally equal to the standard interval than longer durations, but solely because short temporal intervals inevitably precede longer ones.

The term "view from nowhen" was suggested by Price (1996) and denotes the demand to refrain from time-asymmetric presuppositions about reality, which are not justified by any theory (Castagnino, Gadella, & Lombardi, 2006). Since physical laws are time-reversal invariant, they do not imply a specific direction of time. This fact has generally been considered of great importance (Price, 1996; Castagnino et al., 2006; Maccone, 2009).

The demand for a "view from nowhen" also applies to the field of psychophysics, which is defined as the scientific study of the functional interrelations between the physical and psychological realms (Fechner, 1860). The characteristics of physical reality need to be accounted for in psychophysical laws. The present study is an attempt to adopt a "view from nowhen" on time perception experiments, and to provide a new understanding of the phenomenon of duration underreproduction.

---

[1] The name of the model was inspired by the analogy to ancient Greek water-clocks, so-called *klepsydrae* (Wackermann & Ehm, 2006).

[2] The intuitive presupposition that physical time has one specific direction is arbitrary and has constantly been criticized by philosophers (Borges, 1936/1999) and physicians (Price, 1996). There is unanimous agreement that "both (directions of time) are equally probable—and equally unverifiable" (Borges, 1936/1999).

The influence of the direction of the dimensional change on time perception cannot be investigated directly, because it is impossible to reverse the subjectively experienced direction of time flow. Nevertheless, inferences from analogous effects in other physical dimensions can be drawn. If it is a fundamental judgment bias that the direction of a dimensional change systematically affects estimates of that dimension (i.e., increasing values cause underestimation and decreasing values overestimation), it would be highly plausible to postulate that the same principle holds for the perception of time. There is no reasonable argument for disclaiming a general principle for judgments when it comes to time, especially because the perception of time is entangled with many other dimensions, for example, space (Sarrazin, Giraudo, Pailhous, Bootsma, & Giraudo, 2004; Casasanto & Boroditsky, 2008), pitch (Cohen, Hansel, & Sylvester, 1954), and even general stimulus intensity (Matthews, Stewart, & Wearden, 2011).

To relate time reproduction errors to those in other dimensions, we implemented analogous reproduction tasks for the metathetic continuum of pitch (Experiment 1) and the prothetic continuum of brightness (Experiment 2). In metathetic continua, dimensional changes are perceived qualitatively and in prothetic continua, quantitatively. The starting points for the dimensional change within these dimensions were systematically manipulated (e.g., ascending vs. descending values).

If comparable reproduction errors also occur in pitch and brightness reproduction tasks, and if the direction of these errors depends on the starting point of the dimensional change, this would strongly suggest that the systematic underreproduction of durations is based on the same psychophysical principle rather than on a time-specific perceptual mechanism. Accordingly, it would not contradict pacemaker-accumulator models.

Experiments

The question investigated was whether the reproduction errors for durations are equal to those in other physical dimensions. For this purpose, we conducted basic time reproduction tasks together with analogous reproduction tasks with respect to other dimensions. In Experiment 1, a sound of a specific pitch had to be reproduced by stopping a second sound, which ran through a wider pitch spectrum in ascending order. In Experiment 2, the increase in brightness of a visually presented gray square had to be stopped when it reached a specific value.

In both experiments, the reproduction task of the respective other dimension (pitch and brightness) was also performed under a descending condition, in which the direction of the dimensional change was reversed. In Experiment 1, the target pitch had to be detected out of a sound of a slowly decreasing pitch, and in Experiment 2, the second square started bright and became continuously darker. Accordingly, three reproduction tasks were implemented in each experiment: One for time and two for pitch in Experiment 1, and one for time and two for brightness in Experiment 2.

We hypothesized that the direction of errors in the pitch and the brightness reproduction tasks depends on the direction of the dimensional change. The estimates of all investigated dimensions should be biased toward the starting point of the respective dimensional change. More precisely, in time reproduction and in the ascending conditions of pitch and brightness reproduction we expected an underreproduction of the standard stimuli, whereas in the descending conditions of pitch and brightness reproduction we expected them to be overreproduced with reference to the respective scale.

We further hypothesized that the variability of reproduction errors increases with higher temporal intervals between the beginning of the reproduction phase and the point of objective equality. In time reproduction and the ascending conditions of pitch and brightness reproduction, variability was expected to increase with higher standard stimuli, and in the descending conditions of pitch and brightness reproduction, variability was expected to decrease with higher standard stimuli.

Method

Participants. Fifteen healthy participants (7 males, mean age 27.9) took part in Experiment 1. Exclusion criteria were self-reported auditory impairments (e.g., tinnitus).

Experiment 2 included 17 healthy participants (8 males, mean age 26.6), four of whom had already participated in Experiment 1. All had normal or corrected to normal vision.

All participants were recruited from the University of Mannheim and the local community. They were either paid for their participation or received course credit. Prior to the experiments, participants gave written, informed consent.

Stimuli for Experiment 1. In the time reproduction task, one of five standard durations (1 to 5 seconds) was presented, triggered by a 300 Hz sound (filled interval). The reproduction interval was indicated by a 600 Hz sound, and had to be stopped by the participants via mouse click when it was perceived to be temporally equal to the standard interval.

In the ascending condition of the pitch reproduction task, five sounds of different pitch (900, 950, 1000, 1050 and 1100 Hz) presented for 3 seconds, served as standard sounds. During the reproduction phase, a sound slowly increasing in pitch was presented, starting at 850 Hz and constantly gaining 50 Hz per second. Participants were instructed to stop the reproduction sound via mouse click when it reached the same pitch as the respective standard sound.

In the descending condition of the pitch reproduction task, standard sounds were the same as in the ascending condition, but the reproduction sound started at 1150 Hz, constantly losing 50 Hz per second. Again, participants had to stop the sound as soon as it reached the same pitch as the standard sound.

All sounds were sinus waves, generated in MATLAB (Version 7.5.0.342, R2007b) and presented via stereo headphones (XL-300V Pro-Luxe, Conrad, Mannheim, Germany). Headphones were calibrated to 50 dB SPL (decibel sound pressure level).

Stimuli for Experiment 2. All visual stimuli in Experiment 2 were achromatic; gray levels are defined in terms of black/white contrasts, indicated by the percentage of white content (i.e., 0 % corresponds to black and 100 % to pure white).[3]

In the time reproduction task, a gray square (40 %) was presented for one of five standard durations (1 to 5 seconds). The reproduction interval was indicated by another square (60 %), and

---

[3] For convenience of presentation, reported values are rounded to multiples of 10.

had to be stopped by the participants via mouse click when it was perceived to be temporally equal to the standard interval.

In the ascending condition of the brightness reproduction task, five gray squares of different brightness (30, 40, 50, 60 and 70 %) served as standard stimuli and were presented for 3 seconds. During the reproduction phase, a relatively dark square appeared on the screen, slowly increasing in brightness. It started at 20 % and was constantly raised by 10 % per second. Participants were instructed to indicate with a mouse click when it reached the same brightness as the respective standard square.

In the descending condition of the brightness reproduction task, standard squares were the same as in the ascending condition, but the reproduction phase started with a bright square (80 %), constantly losing 10 % per second. Again, participants had to press the button as soon as it reached the same brightness as the standard square.

All squares (88 mm^2) were presented in the middle of the screen against a dark background (0 %). To keep the influence of possible afterimage effects constant, participants were instructed to fixate on a black cross (0 %) in the middle of each square. Visual stimuli were generated in Presentation v14.2 (Neurobehavioral Systems, Inc., Albany, CA.).

Experimental Procedure

Participants were seated at a desk with their dominant hand resting on a computer mouse. In Experiment 1, they were instructed to close their eyes, and in Experiment 2, they looked at a computer screen and wore noise-cancelling headphones (ATH-ANC7, Audio Technica, Mainz-Kastel, Germany). Participants were asked to refrain from mental counting. After completion of the experiment, participants were asked whether they experienced difficulties adhering to this specific instruction. No difficulties were reported.

In both experiments, the order of the tasks was randomized. In all tasks, each of the five respective standards was presented 10 times in randomized order, resulting in 50 trials per task, and the intertrial interval was approximately normally distributed within a range of 3–5 seconds. The interstimulus interval between standard and reproduction intervals was set to 1 second. The beginning of both the standard and the reproduction intervals was triggered by the onset of the sound (Experiment 1) or the appearance of the square (Experiment 2). All stimuli were presented with Presentation v14.2 (Neurobehavioral Systems, Inc., Albany, CA).

Due to the specifications of the experimental stimuli, the temporal intervals between the beginning of the reproduction phase and the point of objective equality are comparable between all tasks. For example, the highest standard pitch in the ascending condition of the pitch reproduction task, the highest brightness in the ascending condition of the brightness reproduction task and the longest standard duration in the time reproduction task were reached at the same time relative to the beginning of the respective reproduction phase (i.e., at 5 seconds).

Statistical Analysis

Reproduction errors were calculated as deviations of estimated values from the respective standard stimuli. To account for outliers, statistical analysis of reproduction errors was based on median values and interquartile ranges.

The data of participants with extremely low performance[4] were excluded from the analysis of the respective task.

Statistical analysis was conducted using linear mixed-effects models, including the factors task (three levels) and standard stimuli (five levels). Participants were specified as a random factor. One-tailed t tests were used to test the direction of reproduction errors.

Effects of the standard stimuli on the variability of reproduction errors were tested by computing linear regression models between standard stimuli and the coefficient of variation (IQR). The slope of the regression line was calculated for each participant and each task. Wilcoxon signed-rank tests were used to test whether the slopes were positive or negative.

Data were analyzed in R (Version 2.13.1).

Results

Results are shown in Figures 2 and 3. In both experiments, we found significant main effects of task (Experiment 1: $F_{2/179} = 60.7$, $p < .0001$; Experiment 2: $F_{2/202} = 120$, $p < .0001$) and standard stimuli (Experiment 1: $F_{4/179} = 38$, $p < .0001$; Experiment 2: $F_{4/202} = 56.7$, $p < .0001$), indicating that the reproduction errors differed for the three respective tasks and for the five different standard stimuli. Helmert contrasts on the main effect of task, specifically comparing reproduction errors in the ascending versus the descending conditions, were significant in Experiment 1 ($t_{179} = 9.7$, $p < .0001$) and in Experiment 2 ($t_{202} = 15.2$, $p < .0001$).

To confirm that the reproduction errors were negative in the ascending and positive in the descending conditions, all tasks were analyzed separately using one-tailed t tests. Reproduction errors were systematically biased toward the starting point of the dimensional change in Experiment 1 (time: $t_{14} = 6.1$, $p < .0001$; ascending pitch: $t_{12} = 5.5$, $p < .0001$; descending pitch: $t_{11} = 2.8$, $p = .008$) and Experiment 2 (time: $t_{15} = 5.4$, $p < .0001$; ascending brightness: $t_{14} = 6.6$, $p < .0001$; descending brightness: $t_{13} = 5.7$, $p < .0001$). When both conditions (ascending and descending) within the same dimension were pooled together, no systematically directed errors were found for pitch in Experiment 1 ($t_{10} = 1.7$, $p = .114$, two-tailed), while brightness in Experiment 2 was still significantly underreproduced ($t_{13} = 3.7$, $p = .003$, two-tailed).

In a separate analysis for each task, individual slopes of the linear regression between the standard stimuli and the coefficient of variation (interquartile range) were analyzed with Wilcoxon signed-rank tests (one-tailed), in order to test the influence of the dimensional change direction on the variability of reproduction errors. Increasing variability of reproduction errors with higher temporal intervals between the beginning of the reproduction phase and the point of objective equality was confirmed for time reproduction and the descending condition of pitch reproduction in Experiment 1 (time: $V_{14} = 120$, $p < .0001$; descending pitch: $V_{11} = 15$, $p = .032$) and for all tasks in Experiment 2 (time: $V_{15} = 133$, $p < .0001$; ascending brightness: $V_{14} = 120$, $p < .0001$;

[4] Low performance was defined in terms of robust linear models, plotting each participant's estimates against the presented standards. A slope less than 0.5 indicates extremely poor differentiation between the standard stimuli and was therefore chosen as the criterion for low performance. Within each task, this criterion was met by three participants at most.
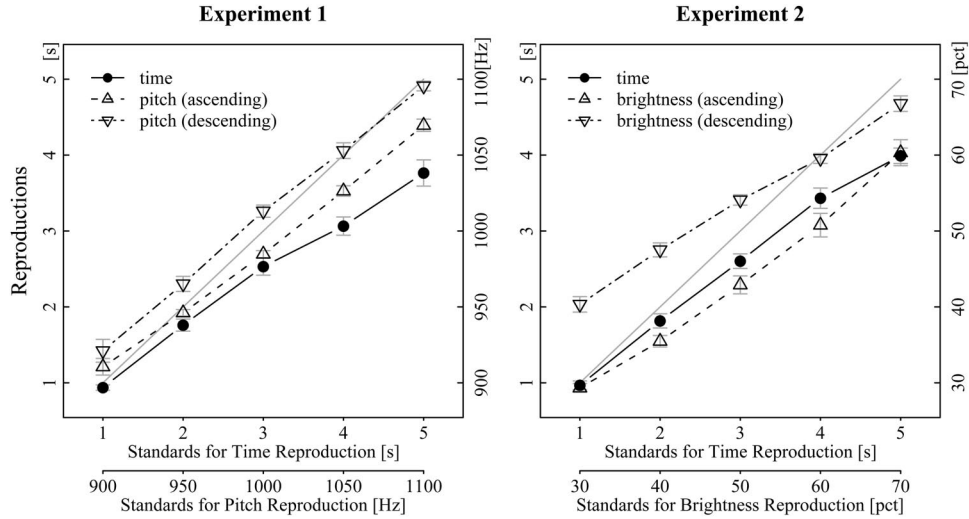
Experiment 1

Experiment 2

Figure 2. Reproductions in Experiments 1 and 2. Gray diagonal lines indicate objective equality between standard stimuli and reproductions. Time units are scaled on the left side of the graphs and units of the respective other dimension are on the right side (pitch in Experiment 1 and brightness in Experiment 2). Error bars show standard errors across subjects.

descending brightness: $V_{13} = 21$, $p = .025$). Only in the ascending condition of the pitch reproduction task of Experiment 1 did variability not significantly increase with the standard stimuli (ascending pitch: $V_{12} = 63$, $p = .122$).

Discussion

The phenomenon of systematic underreproduction of durations, which has consistently been found in time reproduction tasks, has been interpreted as a systematic misperception of durations (Wackermann & Ehm, 2006). As such, it seems to contradict basic

assumptions of pacemaker-accumulator models, which are to date the most promising models of time perception.

In the present paper we propose an alternative explanation of the phenomenon, based on a fundamental judgment bias and considerations about the direction of dimensional changes. In reproduction tasks, participants experience uncertainty regarding the correct response, and therefore base their judgments on a less restrictive criterion. Participants might consider the probability of a correct response at every time point, and immediately stop the reproduction interval once this probability exceeds the criterion (see Figure 1). If this is true, erroneous reproductions do not reflect a general misperception of the
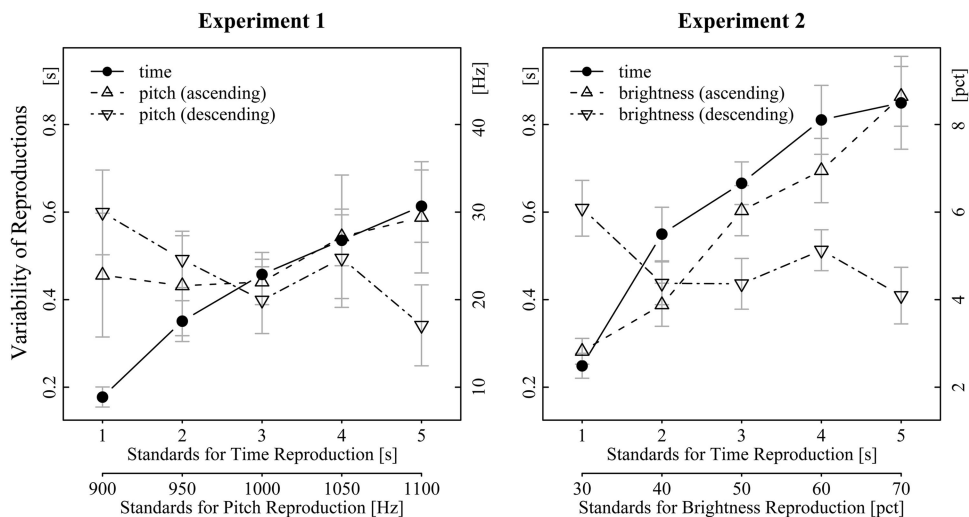
Experiment 1

Experiment 2

Figure 3. Variability of reproductions in Experiments 1 and 2. Time units are scaled on the left side of the graphs and units of the respective other dimension are on the right side (pitch in Experiment 1 and brightness in Experiment 2). Error bars show standard errors across subjects.

dimension in question, but rather the application of a less restrictive criterion for equality judgments. The direction of reproduction errors would depend on the starting point of the dimensional change.

The results of Experiments 1 and 2 clearly show systematic reproduction errors for pitch and brightness, the direction of which depends on the direction of the dimensional change. Pitch and brightness were underreproduced for ascending reproduction stimuli and overreproduced for descending reproduction stimuli. Moreover, the direction of the dimensional change also affects the variability of reproduction errors. Ascending values in the reproduction phase cause an increase of the variability, whereas descending values cause a decrease of the variability with higher standard stimuli. Both the direction and the variability of systematic reproduction errors depend on the direction of the dimensional change. In every single case, estimates were biased toward the starting point of the respective dimensional change.

When these starting points were counterbalanced (i.e., data pooled over the ascending and descending conditions), no systematic estimation errors were found for pitch in Experiment 1, and those found for brightness in Experiment 2 were substantially attenuated. The residual systematic underreproduction of brightness (with pooled conditions) might be explained by certain characteristics of the task: After completion of Experiment 2, some participants indicated that brightness reproduction was more difficult in the descending than in the ascending condition, because they were slightly glared by the appearance of the relatively bright square at the beginning of the reproduction phase. This might have caused an additional response delay, especially when the point of objective equality was reached shortly after the beginning of the reproduction phase (i.e., squares of 60 and 70 % in the descending condition).

The systematic reproduction errors toward the starting point of the dimensional change were demonstrated for metathetic (pitch in Experiment 1) and prothetic continua (brightness in Experiment 2). Thus, they seem to reflect a general bias in dimensional judgments and serve as a simple and very plausible explanation for the phenomenon of systematic underreproduction of durations in time reproduction tasks (Eisler, 1976). Psychophysical experiments on time perception are especially constrained, because it is impossible to experimentally manipulate the direction of the subjectively experienced time flow. Durations can be presented only in an ascending manner, and consequently, only underreproductions can be observed.

The conclusion is simple but profound: The phenomenon of a systematic underreproduction of durations does not reflect a genuine misperception of time, neither during the standard nor the reproduction interval, but results from the basic fact that shorter durations elapse prior to longer ones. This conclusion has relevant implications for pacemaker-accumulator models of time perception, which will be discussed in the last section.

At this point, the question arises whether it is appropriate to draw inferences from other physical dimensions to the domain of time, because time perception undoubtedly reflects a special case in the wide range of perceivable qualities. Although many characteristics of time are unique, there are several indications for its general congruence with other physical dimensions.

First, bidirectional interrelations have been found for time and space (Benussi, 1913; Cohen, Hansel & Sylvester, 1953; Price-Williams, 1954) and for time and pitch (Cohen et al., 1954), suggesting the existence of a common reference system. Second, psychophysical characteristics, like generalization gradients (Church & Gibbon, 1982), are equivalent to those in other dimensions (Walsh, 2003). Third, systematic errors in reproduction tasks are not specific for the domain of time, but also well known for many other physical dimensions. In a series of six experiments, Casasanto and Boroditsky (2008) found exactly the same pattern for reproduced durations and reproduced lengths of growing lines. It is important to note that to reproduce lengths, subjects had to move a mouse cursor from a fixed starting point in a straight line until its trajectory was equal to the standard length (i.e., length was reproduced in an ascending order of values). Indeed, the possibility of systematic estimation errors depending on the direction of the dimensional change is the basic reason for counterbalancing these directions in studies using variants of the reproduction method (e.g., Kammers, de Vignemont, Verhagen, & Dijkerman, 2009).

Given all the corresponding characteristics between the perception of time and the perception of other physical dimensions, the validity of the same underlying psychophysical principles seems plausible. The consistent observation of a systematic underreproduction of durations is merely caused by the constrained direction regarding the presentation of temporal intervals in time perception experiments.

Instead of a general underreproduction, some studies have reported a slight overreproduction of short durations and an underreproduction of long durations (Woodrow, 1951; Fortin & Rousseau, 1998; Ulbrich et al., 2007). This finding is known as Vierordt's law (Vierordt, 1868) and might have some impact on the results presented here. Although no standard duration was overreproduced in the present study, the scale for psychological time was compressed relative to the physical time scale (see Figure 2). Similar compressions of the subjective relative to the physical scale were also observed for pitch and brightness, and this pattern was found for both the ascending and the descending condition. However, the extent of the over- and underproductions was still strongly affected by the direction of the dimensional change. Small values are slightly overreproduced and large values are strongly underreproduced in the ascending conditions, while the former are strongly overreproduced and the latter are slightly underreproduced in the descending conditions. Thus, the direction and size of reproduction errors can be ascribed to the superposition of two independent factors: A compression of the subjective relative to the physical scale, according to Vierordt's law, can explain the overreproduction of small values in the ascending and the underreproduction of large values in the descending conditions. The direction of the overall reproduction errors can only be attributed to the effect of the dimensional change direction.

The systematic errors in time reproduction tasks have generally been interpreted as a disrupted perception of time, and therefore seem to contradict the idea of an internal pacemaker as the basis for time perception. A varying pulse rate of the pacemaker can explain a wide range of temporal misperceptions, but since in time reproduction tasks both the standard and the reproduction interval are directly experienced and no translation from abstract conventional time units (i.e., seconds, minutes) is required, an altered pulse rate would affect the perception of both intervals. This would result in accurate performance and is therefore inconsistent with the finding of a systematic underreproduction of duration.

As it was mentioned initially, several timing models are capable of accounting for the systematic errors in time reproduction tasks (Eisler, 1975; Zakay & Block, 1997; Wackermann & Ehm, 2006). However, in all of these models, duration underreproduction is

regarded as an erroneous perception of time. Here we propose an alternative view of the phenomenon, which is considered an artifact resulting from methodological constraints in time perception experiments, and consequently does not reflect a genuine misperception of time. Instead, it is based on a fundamental judgment bias, namely, that under uncertainty participants tend rather to respond too early than too late. This explanation also accounts for the fact that the same pattern of systematic errors have been found in time production tasks (Pöppel & Giedke, 1970), where the standard interval is presented in abstract numerical values.

The reinterpretation of duration underreproduction suggested in the present study is not in conflict with other timing models like the attentional-gate model (Zakay & Block, 1997) and the parallel-clock model (Eisler, 1975). It provides, however, a parsimonious and plausible explanation for the phenomenon of duration under-reproduction which is entirely compatible with the assumptions of pacemaker-accumulator models. Pacemaker-accumulator models can explain a wide range of observations made in experiments on time perception, including the phenomenon of a systematic under-reproduction of durations.

References

Angrilli, A., Cherubini, P., Pavese, A., & Mantredini, S. (1997). The influence of affective factors on time perception. *Perception & Psychophysics, 59,* 972–982. doi:10.3758/BF03205512

Benussi, V. (1913). Versuche zur Analyse taktil erweckter Scheinbewegungen. *Archiv für die gesamte Psychologie, 36,* 59–135.

Borges, J. L. (1936/1999). A history of eternity. In E. Weinberger (Ed.), *Selected Non-Fictions* (pp. 123–139). New York, NY: Viking.

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition, 106,* 579–593. doi:10.1016/j.cognition.2007.03.004

Castagnino, M., Gadella, M., & Lombardi, O. (2006). Time-reversal, irreversibility and arrow of time in quantum mechanics. *Foundations of Physics, 36,* 407–426. doi:10.1007/s10701-005-9021-0

Church, R. M., & Gibbon, J. (1982). Temporal generalization. *Journal of Experimental Psychology: Animal Behavior Processes, 8,* 165–186. doi:10.1037/0097-7403.8.2.165

Cohen, J. (1981). A preliminary investigation on time perception and autonomic self-regulation. *Biofeedback and Self Regulation, 6,* 289–293. doi:10.1007/BF01000654

Cohen, J., Hansel, C. E., & Sylvester, J. D. (1953). A new phenomenon in time judgment. *Nature, 172,* 901. doi:10.1038/172901a0

Cohen, J., Hansel, C. E., & Sylvester, J. D. (1954). Interdependence of temporal and auditory judgments. *Nature, 174,* 642–644. doi:10.1038/174642a0

Craig, A. D. (2009). Emotional moments across time: A possible neural basis for time perception in the anterior insula. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences, 364,* 1933–1942. doi:10.1098/rstb.2009.0008

Droit-Volet, S., & Meck, W. H. (2007). How emotions colour our perception of time. *Trends in Cognitive Sciences, 11,* 504–513. doi:10.1016/j.tics.2007.09.008

Eisler, H. (1975). Subjective duration and psychophysics. *Psychological Review, 82,* 429–450. doi:10.1037/0033-295X.82.6.429

Eisler, H. (1976). Experiments on subjective duration 1968–1975: A collection of power function exponents. *Psychological Bulletin, 83,* 1154–1171. doi:10.1037/0033-2909.83.6.1154

Eisler, H. (1981). Applicability of the parallel-clock model to duration

discrimination. *Perception & Psychophysics, 29,* 225–233. doi:10.3758/BF03207289

Fechner, G. T. (1860). *Elemente der Psychophysik (Erster Theil).* Leipzig, Germany: Breitkopf und Härtel.

Fortin, C., & Rousseau, R. (1998). Interference from short-term memory processing on encoding and reproducing brief durations. *Psychological Research, 61,* 269–276. doi:10.1007/s004260050031

Kammers, M. P., de Vignemont, F., Verhagen, L., & Dijkerman, H. C. (2009). The rubber hand illusion in action. *Neuropsychologia, 47,* 204–211. doi:10.1016/j.neuropsychologia.2008.07.028

Maccone, L. (2009). A quantum solution to the arrow-of-time dilemma. *Physical Review Letters, 103,* 1–6. doi:10.1103/PhysRevLett.103.080401

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,* 303–313. doi:10.1037/a0019961

Pöppel, E., & Giedke, H. (1970). Diurnal variation of time perception. *Psychologische Forschung, 34,* 182–198. doi:10.1007/BF00424544

Pöppel, E. (1971). Oscillations as possible basis for time perception. *Studium Generale, 24,* 85–107.

Price, H. (1996). *Time's arrow and Archimedes' point: New directions for the physics of time.* New York, NY: Oxford University Press.

Price-Williams, D. R. (1954). The kappa effect. *Nature, 173,* 363–364. doi:10.1038/173363a0

Sarrazin, J. C., Giraudo, M. D., Pailhous, J., Bootsma, R. J., & Giraudo, M. D. (2004). Dynamics of balancing space and time in memory: Tau and kappa effects revisited. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 411–430. doi:10.1037/0096-1523.30.3.411

Treisman, M. (1963). Temporal discrimination and the indifference interval. Implications for a model of the "internal clock". *Psychological Monographs: General and Applied, 77,* 1–31. doi:10.1037/h0093864

Treisman, M., Faulkner, A., Naish, P. L., & Brogan, D. (1990). The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception, 19,* 705–743. doi:10.1068/p190705

Ulbrich, P., Churan, J., Fink, M., & Wittmann, M. (2007). Temporal reproduction: Further evidence for two processes. *Acta Psychologica, 125,* 51–65. doi:10.1016/j.actpsy.2006.06.004

Vierordt, K. (1868). *Der Zeitsinn nach Versuchen.* Tübingen, Germany: Laupp.

Wackermann, J. (2005). Experience of time passage: Phenomenology, psychophysics, and biophysical modelling. In R. Buccheri, M. Saniga & A. Elitzur (Eds.), *Endophysics, time, quantum, and the subjective* (pp. 189–208). Hackensack, NJ: World Scientific.

Wackermann, J., & Ehm, W. (2006). The dual klepsydra model of internal time representation and time reproduction. *Journal of Theoretical Biology, 239,* 482–493. doi:10.1016/j.jtbi.2005.08.024

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7,* 483–488. doi:10.1016/j.tics.2003.09.002

Wearden, J. H. (2004). Decision processes in models of timing. *Acta Neurobiologiae Experimentalis, 64,* 303–317.

Wittmann, M. (2009). The inner experience of time. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences, 364,* 1955–1967. doi:10.1098/rstb.2009.0003

Woodrow, H. (1951). Time perception. In S. S. Stevens (Ed.), *Handbook of Experimental Psychology* (pp. 1224–1236). New York, NY: Wiley.

Zakay, D., & Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science, 6,* 12–16. doi:10.1111/1467-8721.ep11512604