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Crossmodal temporal discrimination:

Assessing the predictions of a general pacemaker-counter model

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Abstract

An extended pacemaker-counter model is applied to crossmodal temporal discrimination. In three experiments, subjects discriminated between the duration of a constant standard stimulus and the duration of a variable comparison stimulus. In congruent trials both stimuli were presented to the same sensory modality (i.e. both visual or both auditory) whereas in incongruent trials each stimulus was presented to a different modality. The model accounts for the finding that temporal discrimination depends on the presentation order of the sensory modalities. Nevertheless, the model fails to explain why temporal discrimination was much better with congruent than with incongruent trials. The discussion considers possibilities to accommodate the model for this and other shortcomings.

Crossmodal temporal discrimination:

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model

Time is an essential component of our mental life. Hence, it is not surprising that for many years philosophers and psychologists have been intrigued by the question of how time enters into our experiences and thus shapes our cognitions (Roeckelein, 2000). For example, the great philosopher Immanuel Kant (1787/1998) argued that space and time are basic intuitions ("a priori Anschauungen"), which structure our cognitions. In addition, he believed that time involves a more subjective intuition than does space (cf. Boring, 1957). Thus, amongst other things, the study of time perception derives from Kant's proposal about time. The perception of time also attracted early psychophysicists (e.g. Mach, 1865; Vierordt, 1868) and remained an active field of research in psychology up to the present day (cf. Grondin, 2001; Meck, 2003). More recently, time perception has become a major object of research in the field of the cognitive neurosciences (cf. Lewis & Miall, 2003; Nobre & O'Reilly, 2004).

The question of how humans perceive time, however, is still a matter of controversy (cf. Grondin, 2001). Nowadays there exist various theories about the mechanism(s) underlying time perception. Many theories share the core assumption of an internal clock based on neuronal counting (e.g. Allan & Kristofferson, 1974; Creelman, 1962; Gibbon, 1991; Grondin, 2003; Treisman, Faulkner, Naish, & Brogan, 1990). The main features of such an internal-clock mechanism are a pacemaker and an accumulator. The pacemaker generates pulses and these are registered by the accumulator. The number of pulses counted by the accumulator during a certain physical time interval represents the perceived duration of this interval. This pacemaker-counter model (PCM) has been successfully applied to time-related behavior of humans (Bendixen, Grimm, & Schröger, 2005; Killeen & Taylor, 2000; Penney, Gibbon, & Meck, 2000; Rammsayer & Ulrich, 2001)

and animals (Fetterman & Killeen, 1995; Gibbon, 1977).

The present study tests new predictions of PCM. More specifically, we generalized the model such that it can be applied to a crossmodal temporal-discrimination task. In this task, subjects were asked to discriminate between the duration of a constant standard and the duration of a variable comparison stimulus. The sensory modalities of the standard and the comparison were either congruent or incongruent. In congruent trials both the comparison and the standard stimulus were either auditory or visual, i.e. auditory-auditory (a-a) or visual-visual (v-v), whereas in incongruent trials, one stimulus was auditory and the other visual, i.e. auditory-visual (a-v) or visual-auditory (v-a). As shown below, PCM makes intriguing predictions for this task. These predictions were assessed with the results of three experiments. In Experiments 1 and 2 the standard preceded the comparison, whereas in Experiment 3 the comparison preceded the standard.

Applying PCM to Crossmodal Temporal Discrimination

In this section we extend a general version of the PCM for temporal discrimination (Rammsayer & Ulrich, 2001) to the more complicated situation in which the standard stimulus and the comparison stimulus differ in sensory modality. The traditional formulation of PCM (Creelman, 1962) assumes that the pulse rate is identical for both the standard and the comparison interval. There exists, however, strong evidence that the internal clock runs at a faster rate when the stimulus is auditory than when it is visual (Penney et al., 2000; Wearden, Edwards, Fakhri, & Percival, 1998). Thus, this traditional formulation of PCM cannot be applied to a bimodal temporal discrimination task, when the standard and the comparison differ in sensory modality. To adapt the model to a bimodal situation, we will assume that the mean interpulse time for auditory stimuli is shorter than for visual ones. On the basis of this assumption, we derive the predicted psychometric function of PCM for congruent and incongruent trials. In addition, we

derive the difference limen (DL) and the constant error (CE) of this function.

Creelman's (1962) original PCM assumes that the pulse stream follows a Poisson process. This process implies an exponential interpulse distribution with a modal value of zero, which, however, is generally implausible (see Rammsayer & Ulrich, 2001). For example, this property is incompatible with the refractory period of neurons. Accordingly, some time needs to cease after the production of a pulse before the next pulse can be generated. Hence, the interpulse time would never attain a value of zero. Therefore, Rammsayer and Ulrich (2001) generalized the assumptions of PCM and provided quantitative predictions, which do not require specific distributional assumptions about the interpulse time.

In order to derive the psychometric function of the generalized PCM, let t_s and t_c be the duration of the standard interval and the comparison interval, respectively. In any trial, t_c may be either shorter or longer than or equal to t_s. Furthermore, let $\mathbf{N}(t_s)$ be the number of pulses counted during t_s and likewise let $\mathbf{N}(t_c)$ be the number of pulses counted during t_c. As in the traditional PCM, subjects are assumed to judge the comparison longer than the standard, if $\mathbf{N}(t_c) > \mathbf{N}(t_s)$. Therefore, the response probability of this judgment "$C > S$" is computed as

$$
\begin{aligned}
\Pr\{\text{``}C > S\text{''}|t_s, t_c\} &= \Pr\{\mathbf{N}(t_c) > \mathbf{N}(t_s)\} \\
&= \Pr\{\mathbf{N}(t_c) - \mathbf{N}(t_s) > 0\} \\
&= \Pr\{\mathbf{N}(t_s) - \mathbf{N}(t_c) \leq 0\} \\
&= \Pr\{\mathbf{D}(t_s, t_c) \leq 0\}. \qquad (1)
\end{aligned}
$$

In other words, the response probability $\Pr\{\text{``}C > S\text{''}|t_s, t_c\}$ corresponds to the probability of the event that the difference $\mathbf{D}(t_s, t_c) = \mathbf{N}(t_s) - \mathbf{N}(t_c)$ is less than or equal to zero.

According to a theorem of renewal theory (see Rammsayer & Ulrich, 2001, p. 276), the number of pulses $\mathbf{N}(t)$ counted during the time interval t is approximately normally

distributed with mean $E[\mathbf{N}(t)] = t/\mu$ and variance $\mathrm{Var}[\mathbf{N}(t)] = t \cdot \sigma^2/\mu^3$. The constants μ and σ denote the mean and the standard deviation of the interpulse duration.[1] Note that this theorem holds for any interpulse distribution and therefore, no specific assumptions about this distribution will be required for deriving predictions from this model.

Predicted Psychometric Function

This theorem from renewal theory allows the computation of response probability $\Pr\{\text{``}C > S\text{''}|t_s, t_c\}$ and consequently the predicted psychometric function. Because $\mathbf{N}(t_s)$ and $\mathbf{N}(t_c)$ are (approximately) normally distributed, the difference $\mathbf{D}(t_s, t_c)$ must also be normally distributed. Specifically, the mean and the variance associated with this difference is

$$
\begin{aligned}
\mathrm{E}[\mathbf{D}(t_s, t_c)] &= \mathrm{E}[\mathbf{N}(t_s)] - \mathrm{E}[\mathbf{N}(t_c)] \\
&= \frac{t_s}{\mu_s} - \frac{t_c}{\mu_c}
\end{aligned}
\tag{2}
$$

and

$$
\begin{aligned}
\mathrm{Var}[\mathbf{D}(t_s, t_c)] &= \mathrm{Var}[\mathbf{N}(t_s)] + \mathrm{Var}[\mathbf{N}(t_c)] \\
&= \frac{t_s \cdot \sigma_s^2}{\mu_s^3} + \frac{t_c \cdot \sigma_c^2}{\mu_c^3}.
\end{aligned}
\tag{3}
$$

The constants μ_s and σ_s are the mean and the standard deviation of the interpulse distribution of the counting process that prevails during the standard interval. The corresponding mean and standard deviation of the counting process during the comparison interval are μ_c and σ_c, respectively. Hence, if the standard is auditory and the comparison is visual, one would assume $\mu_s < \mu_c$, whereas $\mu_s > \mu_c$ should be assumed if the standard is visual and the comparison auditory.

Since $\mathbf{D}(t_s, t_c)$ is approximately normally distributed with the mean and the variance given by Equations 2 and 3, respectively, Equation 1 extends to

$$
\Pr\{\text{``}C > S\text{''}|t_s, t_c\} = \Phi\left[\frac{0 - \mathrm{E}[\mathbf{D}(t_s, t_c)]}{\sqrt{\mathrm{Var}[\mathbf{D}(t_s, t_c)]}}\right]
$$

$$= \quad \Phi \left[\frac{0 - \left(\frac{t_s}{\mu_s} - \frac{t_c}{\mu_c} \right)}{\sqrt{\frac{t_s \cdot \sigma_s^2}{\mu_s^3} + \frac{t_c \cdot \sigma_c^2}{\mu_c^3}}} \right]$$

$$= \quad \Phi \left[\frac{\frac{t_c}{\mu_c} - \frac{t_s}{\mu_s}}{\sqrt{\frac{t_s \cdot \sigma_s^2}{\mu_s^3} + \frac{t_c \cdot \sigma_c^2}{\mu_c^3}}} \right] . \tag{4}$$

Note that the symbol Φ represents the cumulative distribution function of a standard normal distribution. (It should be noted, however, that the predicted shape of the psychometric function does not correspond to the shape of a normal distribution. This is because the variable t_c not only occurs in the numerator but also in the denominator.)

The last expression can be employed to establish the psychometric function for the temporal discrimination task. This is achieved by plotting the response probability $\Pr\{\text{``}C > S\text{''}|t_s, t_c\}$ against the duration t_c of the comparison interval. Examples of the predicted psychometric functions are depicted in Figure 1. This example displays psychometric functions for a standard duration of $t_s = 100$ ms and for each modality combination of standard and comparison (a-a, v-v, a-v, and v-a). In agreement with previous studies, a smaller mean interpulse time for auditory intervals than for visual intervals is assumed. In addition, we assume a larger standard deviation for the visual than for the auditory stimuli, since previous results indicate a larger pacemaker variability for visual than with auditory intervals (e.g. Wearden et al. 1998).

Figure 1 reveals several specific features. First, as one expects, response probability $\Pr\{\text{``}C > S\text{''}|t_s, t_c\}$ increases monotonically with the duration t_c of the comparison. Second, the predicted point of subjective equality (PSE) of the psychometric functions is equal to the standard duration (100 ms) in congruent but not in incongruent trials. Third, the psychometric function for the congruent auditory condition (a-a) is steeper (i.e. has a smaller DL) than the one for the congruent visual condition (v-v). Fourth, the magnitude of PSE in incongruent trials depends on whether the comparison is visual or auditory. If

it is auditory, the duration of the comparison has to be shorter than that of the visual standard in order to perceive both intervals as equally long. If the comparison is visual, however, the duration of the visual comparison has to be longer than that of the auditory standard to achieve subjective equality. Both predictions simply reflect the assumption that the internal clock runs faster for auditory than for visual signals.

Finally, the presumably most striking and counterintuitive prediction is that the slope of the psychometric function in v-a-trials is steeper than in a-v-trials. In other words, PCM predicts a smaller DL in the former than in the latter condition. This non-obvious order effect on DL is basically due to the longer interpulse time for visual compared to auditory intervals. For example, consider an auditory standard of 100 ms and assume that on average one pulse is counted each 5 ms during this auditory interval. Consequently, 20 pulses will be counted on the average during this interval. Now conceive a visual comparison with a mean interpulse time of 10 ms and assume that an average of 25 pulses must be registered during the visual interval in order to perceive on 75% of all trials the comparison as longer than the standard. In this case, the PSE would correspond to $20 \cdot 10 = 200$ ms and the DL would reflect the additional duration for generating the five remaining pulses, that is, $DL = 5 \cdot 10 = 50$ ms. For the reversed stimulus order, only 10 pulses would be counted on average during the standard interval. Thus, the PSE would be equal to $PSE = 10 \cdot 5 = 50$ ms. Crucially, however, the comparison has to be further lengthened by $DL = 5 \cdot 5 = 25$ ms in order to generate five more pulses, on average, for attaining a discrimination probability of 0.75 and this lengthening is less than that required for the comparison in the original order. In summary, then, the predicted order effect on DL can also be attributed to a different clock speed for visual and auditory stimuli.[2]

Predicted DL and CE as a Function of Congruency, Modality of the Standard, and

Standard Duration

In order to enhance the comparison of the predicted with the obtained results of this paper, it is useful to derive DL and CE of the generalized PCM. First, CE is commonly defined as the difference between the value of $t_c(0.5)$, which yields $\Pr\{\text{``}C > S\text{''}|t_s, t_c\} = 0.5$ (i.e. PSE), and the standard duration t_s (i.e. the point of objective equality). The CE can be negative, zero, or positive. A positive CE means that subjects tend to overestimate the duration of the standard. By contrast, a negative CE indicates an underestimation of the standard.[3] According to Equation 4 and because $\Phi(0) = 0.5$, this value of $t_c(0.5)$ must satisfy the equation

$$\frac{t_c(0.5)}{\mu_c} - \frac{t_s}{\mu_s} = 0. \tag{5}$$

Solving this equation for $t_c(0.5)$ yields the PSE and inserting the resulting expression into the definition $CE = PSE - t_s$ gives

$$CE = t_s \cdot \left(\frac{\mu_c}{\mu_s} - 1\right). \tag{6}$$

Note that the predicted CE is zero if $\mu_s = \mu_c$, negative if $\mu_s > \mu_c$, and positive if $\mu_s < \mu_c$.

Secondly, DL is commonly defined as half the interquartile range of the corresponding psychometric function, that is,

$$DL = \frac{t_c(0.75) - t_c(0.25)}{2} \tag{7}$$

where $t_c(0.25)$ and $t_c(0.75)$ are those values of t_c which yield $\Pr\{\text{``}C > S\text{''}|t_s, t_c\} = 0.25$ and $\Pr\{\text{``}C > S\text{''}|t_s, t_c\} = 0.75$, respectively. Proceeding from this definition and from Equation 4, it can be shown that the predicted DL for PCM is

$$DL = \frac{z \cdot \sqrt{z^2 \cdot \sigma_c^4 \cdot \sigma_s^2 + 4 \cdot t_s \cdot \mu_c^2 \cdot (\mu_c^2 \cdot \sigma_s^2/\mu_s + \mu_s \cdot \sigma_c^2)}}{2 \cdot \mu_c \cdot \mu_s} \tag{8}$$

with $z = 0.6744$.

The upper panel of Figure 2 provides a numerical illustration for the predicted effects in a bimodal temporal discrimination task. Specifically, it shows the predicted DL and the predicted CE as a function of congruency, sensory modality of the standard, and standard duration t_s. First, as one expects, DL is larger for the longer standard. Second, DL is predicted to be somewhat larger for visual than for auditory standards. Third, DL tends to be slightly smaller in congruent than in incongruent trials. Finally, the factors congruency and sensory modality are predicted to interact strongly. As explained before, DL is predicted to be larger in a-v than in v-a-trials and, as one would expect, larger in v-v than in a-a-trials. In addition, this counterintuitive interaction becomes amplified as standard duration increases. The lower panel of Figure 2 reveals the predicted CE. In agreement with the previous analysis and as one should expect, the CE is zero in congruent trials, whereas different from zero in incongruent trials. Specifically, a negative CE is predicted for v-a-trials and a positive CE in a-v-trials. According to PCM, the absolute size of CE in these incongruent trials should increase with standard duration.

We report the results of three experiments to assess the prediction of PCM for crossmodal discrimination. Specifically, we investigated whether the psychophysical data reveal a qualitatively similar pattern as the one depicted in Figure 2.

Experiment 1

Experiment 1 employed a temporal discrimination task. On each trial, two successive time intervals were presented. The first interval was the constant standard and the second one the variable comparison. Subjects had to indicate whether the comparison appeared to be shorter or longer than the standard. In congruent trials, the sensory modality of both the standard and the comparison was identical (a-a or v-v), whereas in incongruent trials the modality of both stimuli differed (a-v or v-a). The duration of the standard was either short (100 ms) or long (1,000 ms).

When subjects are asked to estimate or compare time intervals in the range of seconds, subvocal counting becomes a very common timing strategy (Grondin, Meilleur-Wells, & Lachance, 1999; Poynter, 1989). However, counting has been shown to be an ineffective strategy for the timing of intervals below approximately 1,200 ms (Grondin et al., 1999). Therefore, in order to avoid explicit counting as an auxiliary timing strategy, the standard interval for temporal discrimination of longer intervals was chosen not to exceed the critical duration of 1,200 ms.

Method

Subjects. The subjects were 3 male and 17 female adult volunteers ranging in age from 19 to 40 years (M=25.4, SD=5.0). All subjects were undergraduate or graduate students at the University of Tübingen and were paid € 7.50 for taking part in this experiment. All had normal hearing and normal or corrected-to-normal vision. They were naive about the purpose of the experiment.

Apparatus and Stimuli. A PC controlled the presentation of the standard stimulus and the comparison stimulus as well as the recording of the subjects' responses. The standard and the comparison stimuli were filled auditory or visual intervals. The auditory stimulus was a white-noise burst (55.7 dB SPL) generated by a SoundBlaster-compatible sound card and presented through headphones (Sony MDR-CD 550). The visual stimulus was generated by a green LED (diameter 0.48^o, viewing distance 60 cm, luminance 48 cd/m^2), which was attached 1 cm above the center of the computer screen. The intensity of the LED was clearly above threshold, but not dazzling.

Procedure. The subject was seated at a table with a keyboard and a computer monitor. A trial started with the presentation of a fixation point in the center of the monitor screen. Then, the subject initiated the trial sequence by pressing a designated start key on the computer keyboard. This also terminated the presentation of the fixation

point. After 1,000 ms, the standard was presented. Its duration was either 100 or 1,000 ms and kept constant within a block of trials. The modality of the standard was either visual or auditory and was varied randomly from trial to trial. Presentation of the variable comparison started 1,000 ms after the offset of the standard. Again, the comparison was either a visual or an auditory stimulus. Subjects were required to indicate whether the comparison appeared to be shorter or longer than the standard by pressing one of two designated keys on the computer keyboard. This response also reactivated the fixation point. The next trial could be initiated by pressing the start key again.

There were eight different types of trials defined by the factorial combination of standard duration (100 vs. 1,000 ms), sensory modality of the standard (auditory vs. visual), and sensory modality of the comparison (auditory vs. visual). Each trial type was presented 48 times during a single experimental session of 384 trials. This sequence of 384 trials was divided into eight blocks of 48 trials each. Half of all subjects received at first four blocks with the short standard and then four blocks with the long standard. For the other half of subjects, this order was reversed. For each subject, the order of congruent and incongruent trials was randomized within a single block. There was a rest period between blocks, during which performance feedback on the preceding blocks was provided on the monitor screen. Subjects initiated the next block when they felt ready to proceed.

Before the experiment, subjects were informed that they would be presented with two successive stimuli and that the durations of the two stimuli would be slightly different. The subjects were told that the sensory modality of the two stimuli might be identical or different. They were instructed to ignore the variation of sensory modality and to focus on stimulus duration. Furthermore, the instructions emphasized accuracy and there was no requirement to respond quickly.

To introduce the task, the experiment began with the presentation of 32 demonstration trials. After these trials, the subjects were asked whether they understood

the procedure. The purpose of these demonstration trials was to familiarize subjects with the stimuli. Then 96 practice trials were administered. These practice trials consisted of a random sample of 48 trials from the 100-ms condition and 48 trials from the 1,000-ms condition. The main session with the 384 experimental trials began after this training phase.

During the main session, the duration of the comparison interval was varied according to an adaptive rule (Kaernbach, 1991) to estimate the values $t_c(0.25)$ and $t_c(0.75)$, that is, the two comparison intervals at which the response "comparison longer" was given with a probability of .25 and .75, respectively. To estimate $t_c(0.25)$, the duration of the comparison interval was increased by Δ_+ ms if the subject had judged the comparison interval to be shorter, and decreased by Δ_- ms after a "comparison longer" judgment. The opposite step sizes were employed for $t_c(0.75)$. This adaptive procedure was performed for each of the eight different trial types, resulting in 16 randomly interleaved runs. Because duration discrimination is easier for auditory than for visual intervals (cf. Goodfellow, 1934; Grondin, 2001) and because absolute precision of timing depends on the standard duration (Rammsayer & Grondin, 2000), the step sizes Δ_+ and Δ_- were adjusted for each trial type (Table 1). The starting value of the comparison for the $t_c(0.25)$ runs was equal to the standard duration minus two times the value of Δ_-. Analogously, the starting value for the $t_c(0.75)$ run was equal to the standard duration plus two times the value of Δ_+. A maximum likelihood procedure was used to estimate the difference limen DL and the constant error CE (see Mattes & Ulrich, 1998).

Results and Discussion

Figure 3 depicts the average DL and CE as a function of standard duration, congruency, and sensory modality of the first stimulus. It is obvious that the results resemble the qualitative predictions of PCM. A separate three-way analysis of variance

(ANOVA) for these three within-subject factors was performed on DL and on CE to provide a more explicit assessment of the data.

Difference Limen. As one would expect according to Weber's Law, DL increased with the duration of the standard interval, $F(1,19) = 207.2$, $p < .001$, $MS_e = 1,349.3$. The average DL was 24 ms for the short and 108 ms for the long standard. The sensory modality of the first stimulus produced no significant main effect and did not interact with standard duration, $Fs < 1$. Mean DL was 65 ms when the standard was auditory and 67 ms when it was visual. Nevertheless, the direction and the size of this difference agrees with PCM which predicts only a marginally larger DL for auditory than for visual standards. The present results clearly replicated the common finding that temporal discrimination is more precise for auditory that for visual stimuli (i.e. Grondin, 2001). For the short standard, mean DL was 30 ms on v-v-trials and 13 ms on a-a-trials, $t(19) = 4.61$, $p < .001$. An analogous pattern emerged for the long standard, 123 vs. 76 ms, $t(19) = 4.87$, $p < .001$. Both simple effects are consistent with PCM.

Also in qualitative agreement with PCM, discrimination performance was significantly better in congruent than in incongruent trials, $F(1,19) = 10.1$, $p = .005$, $MS_e = 556.1$. Mean DL was 60 and 72 ms, respectively. However, this congruency effect did not significantly vary with the duration of the standard interval, $F(1,19) = 2.7$, $p = .116$, $MS_e = 461.0$; a significant congruency effect was obtained both for the short standard, 21 vs. 27 ms, $t(19) = 2.37$, $p = .028$, and for the long one, 99 vs. 117 ms, $t(19) = 2.63$, $p = .017$.

As predicted by PCM, the congruency effect was strongly modulated by the sensory modality of the standard stimulus, as indicated by the significant interaction of congruency and modality, $F(1,19) = 22.4$, $p < .001$, $MS_e = 1,619.5$. As one would expect, performance on temporal discrimination decreased when an auditory standard was combined with a visual rather than with an auditory comparison. In this case, the average

DL was 45 ms for congruent and 86 ms for incongruent trials. In line with PCM, temporal discrimination actually improved when a visual standard was combined with an auditory comparison (DL=58 ms) rather than with a visual one (DL=76 ms).

The threefold interaction of all factors revealed that this congruency by modality interaction became more pronounced as standard duration was increased, $F(1, 19) = 5.6$, $p = .029$, $MS_e = 1,229.7$. For short intervals, DL was 19 ms when the presentation order was v-a, and it was 36 ms when this order was reversed, $t(19) = 2.78$, $p = .012$. For the long standard, the corresponding figures were 97 and 137 ms, respectively, $t(19) = 2.24$, $p = .037$. This threefold interaction is also in accord with PCM.

Constant Error. Unlike the DL, the CE provides information on whether subjects tend to over- or underestimate the duration of the standard stimulus. Except for the main effect of standard duration, $F(1, 19) = 1.1$, $p = .314$, $MS_e = 16,468.7$, all factors and their interactions yielded statistically reliable effects on CE.

Sensory modality of the standard produced a significant main effect, $F(1, 19) = 11.5$, $p = .003$, $MS_e = 10,793.7$. Subjects tended to overestimate the duration of auditory standards compared to visual ones (CE =25 vs. −31 ms, respectively). In other words and consistent with previous research (e.g. Goldstone & Lhamon, 1974; Wearden et al., 1998), subjects judged auditory standards generally longer than visual ones. Also in line with previous research (e.g. Goldstone & Goldfarb, 1964; Stevens & Greenbaum, 1966), this modality effect was more pronounced for long than for short standards, $F(1, 19) = 10.5$, $p = .004$, $MS_e = 8,479.6$. Furthermore, the main effect of congruency was significant, $F(1, 19) = 6.4$, $p = .020$, $MS_e = 5,733.7$. CE was different between congruent and incongruent trials (12 vs. -18 ms) and this congruency effect was modulated by standard duration, $F(1, 19) = 13.5$, $p = .002$, $MS_e = 3,088.6$. Both main effects, however, were basically a consequence of the significant interaction of standard modality by congruency, $F(1, 19) = 6.5$, $p = .019$, $MS_e = 11,666.8$.

Consistent with PCM, CE differed considerably between the two incongruent conditions. Specifically, the average CE was 6 ms on v-v-trials and 18 ms on a-a-trials, whereas it was -68 ms for v-a-trials and 32 ms for a-v-trials. Finally, this twofold interaction was modulated by standard duration, $F(1,19) = 9.7$, $p = .006$, $MS_e = 8,393.5$. At variance with PCM, however, the CE difference between both incongruent conditions was only present for long but not for short standards.

All things considered, CE was most strongly affected when standard and comparison differed in modality and when standard duration was long. Specifically, subjects tended to underestimate the duration of a visual comparison after an auditory standard. By contrast, they were inclined to overestimate the duration of an auditory comparison when it followed a visual standard. This result replicates and extends the findings reported by Goldstone and Goldfarb (1964). These authors also employed congruent and incongruent trials and their subjects were asked to judge the duration of a variable comparison on a 9-point rating scale. The duration of the standard was always equal to 1,000 ms and the comparison varied from 600 to 1,400 ms. As in the present study, mean judged duration was virtually identical for the two congruent conditions but differed considerably in the incongruent conditions, since auditory stimuli were judged longer than visual ones. The present results indicate, however, that this intramodal effect on perceived duration depends on stimulus duration (see Wearden et al. 1998, Experiment 3, for a similar effect).

Summary. The psychophysical data of Experiment 1 agree with the qualitative predictions made by PCM. Most interestingly, the DL data are consistent with the interactions predicted by PCM. Especially, PCM predicted correctly that discrimination performance should be better in v-a than in a-v-trials. Second, the CE data also tended to be consistent with the predictions of PCM and also with previous CE results on crossmodal temporal discrimination.[4]

Experiment 2

The data of Experiment 1 support the predictions of PCM and thus validate its assumptions. Nevertheless, it is possible that the outcome of Experiment 1 is the signature of a different account. For example, the task requirements might have forced subjects to adopt a specific strategy. In particular, the sensory modality of both the standard and the comparison varied randomly from trial to trial. Thus in each trial there was uncertainty about the relevant input modality of both the standard and the comparison. As a result, subjects might have encountered problems in allocating sufficient attentional resources to the relevant input modality.

In order to cope with this input uncertainty, subjects might have ignored to some extent the sensory information of the standard, which occurred before the comparison, but boosted the sensory information of the comparison. Such a strategy would entail a smaller *DL* when the comparison is auditory, because it is well-documented that the auditory system has a better temporal resolution than the visual one (Goodfellow, 1934). Consequently, temporal discrimination performance should be better for v-a-trials than for a-v-trials. Although PCM entails this order effect, such an alternative account should be ruled out.

For this reason, Experiment 2 examined the possibility that the previous results reflect strategic effects due to the input uncertainty mentioned above. In order to avoid such an input uncertainty, all conditions were blocked in Experiment 2. That is, the sensory modality of both the standard and the comparison was kept constant across all trials within a separate block. As for all other aspects, this experiment was identical to Experiment 1.

Method

Subjects. A fresh sample of 20 subjects, 5 male and 15 female adult volunteers ranging in age from 19 to 39 years (M = 24.9, SD = 5.5) were recruited. All subjects had normal hearing, normal vision, and were naive about the purpose of the experiment.

Apparatus, Design, and Stimuli. These were identical to Experiment 1.

Procedure. The procedure was the same as in Experiment 1 except for one modification. In contrast to Experiment 1, the modality of the standard and the modality of the comparison were blocked. Thus, each modality combination (a-a, v-v, a-v, and v-a) was administered within a single block. As in Experiment 1, there was a total of eight blocks and the duration of the standard was again changed after the first four blocks. Block order of all modality combinations was controlled across subjects according to a balanced Latin square.

Results and Discussion

Experiment 2 generally replicated the data of Experiment 1 and thus provided further support for PCM (Figure 4). Thus these results rule out the possibility that the outcome of Experiment 1 was due to an strategy associated with input uncertainty.

Difference Limen. As before, mean DL was smaller for the short than for the long standard duration, 16 vs. 101 ms, $F(1, 19) = 121.1$, $p < .001$, $MS_e = 2,375.8$. As in Experiment 1, sensory modality of the standard did not produce a significant main effect, $F(1, 19) = 1.3$, $p = .273$, $MS_e = 477.4$, and did not interact with standard duration, $F(1, 19) = 1.4$, $p = .253$, $MS_e = 490.1$. Yet and in line with PCM, DL was again somewhat smaller when the standard was auditory rather than visual (56 vs. 60 ms). In addition, DL was again smaller for pure auditory trials compared to pure visual trials 35 vs. 63 ms, $t(19) = 4.69$, $p < .001$. Discrimination performance was again better in

congruent than in incongruent trials, 49 vs. 68 ms, $F(1, 19) = 36.3$, $p < .001$, $MS_e = 403.3$. The long standard duration even augmented this congruency effect as revealed by the significant interaction of congruency and standard duration, $F(1, 19) = 21.1$, $p < .001$, $MS_e = 446.7$; the size of the congruency effect was 4 ms for the short standard and increased to 35 ms for the long standard. Congruency interacted again with the sensory modality of the standard, $F(1, 19) = 25.4$, $p < .001$, $MS_e = 961.2$. As one should expect, discrimination performance was impaired when an auditory standard was combined with a visual comparison ($DL = 78$ ms) instead of an auditory one ($DL = 35$ ms), $t = 8.65$, $p < .001$. Discrimination performance appeared to slightly improve when a visual standard was paired with an auditory comparison ($DL = 58$ ms) rather than with a visual one ($DL = 63$ ms), although this difference was not reliable, $t = 0.86$, $p = .402$. Finally, the threefold interaction of all factors was again significant, since the interaction between congruency and modality turned out to be more pronounced for the long than for the short standard, $F(1, 19) = 7.2$, $p = .015$, $MS_e = 797.6$.

Constant Error. The *CE* results agrees well with the one of Experiment 1, although this time an ANOVA yielded no reliable results. There were no significant main effects nor significant interactions, $ps > .161$. Only the interaction of modality and congruency approached statistical significance, $F(1, 19) = 3.1$, $p = .096$, $MS_e = 19,455.0$. As before, *CE* was virtually identical for the two congruent conditions but appeared to differ for the two incongruent conditions.

Summary. The present results clearly confirm the ones of Experiment 1. Therefore the notion that the previous results were due to input uncertainty and thus strategies to cope with this uncertainty has to be rejected. As before, the complete pattern of results is qualitatively consistent with the predictions of PCM.[5]

Experiment 3

The previous two experiments disclosed a striking order effect indicating that temporal discrimination performance was clearly better on v-a than on a-v-trials. As shown in the introduction, PCM can account for this order effect. Nevertheless, one might be inclined to assume that it merely matters in which order the two sensory modalities are processed. According to this simple order account, discrimination performance should always be better on v-a than on a-v-trials. In order to assess this order account, we reversed the presentation order of the comparison and the standard in Experiment 3. PCM makes the rather interesting prediction that this reversal should also reverse discrimination performance on v-a and a-v-trials.[6] In contrast, the order account would predict that this change does not matter and the same effects as in the previous two experiments should be observed.

Figure 5 illustrates the predicted effects of reversing the presentation order of the comparison and the standard. The predictions are based on the identical model parameters as in Figure 2. A comparison of both figures reveals the following similarities and differences: (a) As one would suppose, discrimination performance in congruent trials does not depend on the order of standard and comparison. (b) Most importantly, discrimination performance in incongruent trials is predicted to reverse, though the average performance in these trials does not depend on the presentation order. In other words, performance should now be better for a-v than for v-a trials — the predicted reversal effect. Note that this reversal simply reflects the fact that DL is predicted to be smaller when the standard is auditory than when it is visual due to the higher clock speed associated with auditory than visual stimuli. As discussed in the introduction of the PCM, only a small change of t_c is necessary for perceiving a difference between t_c and t_s when the clock speed is relatively high during the processing of the standard. (c) The CE pattern is identical in both figures with the exception that the new pattern is turned

upside down. All other effects are predicted to be the same as the ones before.[7]

Method

Subjects. A fresh sample of 20 subjects, 3 male and 17 female adult volunteers ranging in age from 19 to 33 years (M = 24.1, SD = 4.6) were recruited. All subjects had normal hearing, normal vision, and were naive about the purpose of the experiment.

Apparatus, Design, Stimuli, and Procedure. These were identical to Experiment 2. In contrast to Experiment 2, however, the comparison stimulus preceded the standard stimulus.

Results and Discussion

Figure 6 depicts the results for mean *DL* (upper panel) and for mean *CE* (lower panel). A separate ANOVA with factors standard duration, congruency, and modality of the first stimulus was computed for each dependent measure.

Difference Limen. The pattern of results differed from that of the previous two experiments. Specifically, the results for auditory-first trials were similar, whereas those for visual-first trials were different. Most importantly, temporal discrimination performance was now better for a-v than for v-a-trials confirming the crucial prediction of PCM.

In addition, several other features of the data agree qualitatively with the results of the previous experiment.

It is quite evident that discrimination performance was generally poorer in this experiment compared to Experiment 2; the overall mean *DL* was 58 ms in the previous and 115 ms in this experiment, $t = 5.1$, $df = 24.6$ $p < .001$, two-sided *t*-test with *df* corrected for unequal variances. One reason for this worse overall performance in this experiment is that the response was delayed with respect to the relevant comparison

stimulus in this but not the previous two experiments. (We will return to this point in the General Discussion).

As in the two previous experiments, DL was considerably larger for the long than for the short standard, $F(1, 19) = 69.0$, $p < .001$, $MS_e = 13,348.5$, $DL = 40$ vs. 191 ms. In contrast to the previous results, temporal sensitivity was higher when the first stimulus was auditory than visual, $F(1, 19) = 42.1$, $p < .001$, $MS_e = 3,990.9$. This difference, however, is basically a consequence of the reversed performance effect observed with incongruent trials, which reflects an especially strong deterioration of discrimination performance in v-a-trials. In addition, this effect was larger for long than for short intervals, $F(1, 19) = 15.1$, $p = .001$, $MS_e = 2,523.7$.

Discrimination performance was again clearly better in congruent than in incongruent trials, $F(1, 19) = 18.2$, $p < .001$, $MS_e = 4,618.8$, $DL = 93$ vs. 138 ms. This effect increased substantially with the duration of the standard interval, $F(1, 19) = 8.4$, $p = .009$, $MS_e = 3,556.8$. Due to the reversed performance effect in incongruent trials, the interaction of modality by congruency disappeared this time. In addition, there was no significant interaction of all three factors, $Fs < 1$.

Constant Error. The CE results were analogous to those of Experiments 1 and 2. As one should expect, however, means of the incongruent condition revealed just the opposite pattern as compared to the preceding CE results. Though overall mean CE was close to zero, subjects tended to overestimate the comparison when it was short, but underestimated it when it was long, $F(1, 19) = 9.6$, $p = .006$, $MS_e = 15,796.3$. As before, subjects tended to underestimate the duration of the first stimulus when it was visual, $F(1, 19) = 7.9$, $p = .011$, $MS_e = 27,802.6$. Again, this tendency was especially pronounced for long standards, $F(1, 19) = 14.1$, $p = .001$, $MS_e = 20,066.8$. Although there was no main effect of congruency, $F < 1$, the interaction of modality and congruency reached statistical significance, $F(1, 19) = 7.1$, $p = .015$, $MS_e = 24,621.1$; this interaction effect

basically reflects the fact that CE was close to zero for both congruent conditions but different from zero and of opposite sign for the two incongruent conditions. Contrary to Experiment 1, the interaction of congruency and modality did not reach statistical significance, $F(1, 19) = 1.3$, $p = .275$, $MS_e = 12,034.2$, which can be attributed to the predicted performance reversal. In line with the preceding results, this interaction was especially pronounced for long standards, as indicated by the threefold interaction of all factors, $F(1, 19) = 8.1$, $p = .010$, $MS_e = 20,146.4$.

Summary. In this experiment, the variable comparison was presented before the standard. As implied by PCM, this experimental change reversed discrimination performance for incongruent trials and this clearly rejects the idea that the performance difference for incongruent trials reflects a mere order effect. Accordingly, performance should always be better for v-a than for a-v-trials. The observed reversal, however, might quite naturally arise from the timing mechanism postulated by PCM, even though this model property is difficult to grasp.[8] It is also possible that subjects mainly focus on the comparison. As discussed in the introduction to this experiment, such a strategy could also account for the observed performance reversal. In fact, the overall decrease in temporal discrimination performance relative to the previous experiment provides some evidence for the latter notion.

General Discussion

This study assessed whether the generalized pacemaker-counter model (PCM; Rammsayer & Ulrich, 2001) provides a reasonable account of the mechanisms underlying crossmodal duration discrimination. In all three experiments, subjects were asked to discriminate between the duration of a constant standard and a variable comparison. The sensory modalities of the standard and the comparison were either congruent (i.e. a-a or v-v) or incongruent (i.e. a-v or v-a). In Experiments 1 and 2, the standard preceded the

comparison, whereas in Experiment 3 the standard followed the comparison. All four experimental conditions were randomized across trials in Experiment 1. In Experiments 2 and 3, however, each condition was administered in a separate block of trials. The difference limen DL was employed to index temporal discrimination performance and the constant error CE to capture changes in perceived duration.

Main Findings

These experiments revealed novel results and also confirmed previous findings. First, the CE data confirmed the notion that subjects perceive auditory stimuli as longer than visual ones (e.g. Goldstone & Lhamon, 1974; Goldstone & Goldfarb, 1964; Wearden et al., 1998). Second, the DL data replicated established findings of time perception, that is, discrimination performance diminished as standard duration increased and performance was worse for visual than for auditory stimuli (cf. Grondin, 2001). Third, discrimination performance was definitely better in congruent than incongruent trials, a result that also is in line with previous studies (Grondin & Rousseau, 1991; Grondin, Ivry, Franz, Perreault, & Metthé, 1996; Klapproth, 2002, 2003). This congruency effect became more pronounced as standard duration increased. Furthermore, an elimination of input uncertainty (Experiment 2) could not remove this effect. Fourth, a strong order effect was obtained on incongruent trials, that is, in Experiments 1 and 2, DL was smaller on v-a than on a-v-trials. In Experiment 3, however, this order effect reversed when the comparison preceded the standard. In other words, discrimination was always better with an auditory than with a visual comparison in the incongruent condition. Finally, reversing the presentation order of the standard and the comparison in Experiment 3 impaired discrimination performance in general.

Pacemaker-Counter Models

Since the pacemaker-counter model often provides a benchmark in research of time perception (cf. Grondin, 2001), we further elaborated this model in order to apply it to the crossmodal temporal-discrimination task of this study. This elaboration took into account that the rate of pulse generation depends on sensory modality, because previous work has suggested a higher pulse rate for auditory than for visual stimuli (Droit-Volet, 2003; Penney et al., 2000; Wearden et al., 1998). We derived explicit expressions to predict DL and CE from the assumptions of this elaborated version.

As so many times before (e.g. Wing, 2002), this rather simple model can capture several aspects of the data. First, the model predicts a higher temporal discrimination performance in the congruent condition with auditory than with visual stimuli. Second, the model tends to produce the correct prediction concerning the CE. Third, and most surprising to us, the model captures the striking order effect in the incongruent condition. It correctly accounts for the finding that performance in v-a-trials is better than in a-v-trials, if the variable comparison follows the standard. Fourth, the model correctly predicted that this order effect should reverse, when the comparison occurs before the standard (Experiment 3). Fifth, the model can also account for the finding that some of the observed effects become more pronounced as standard duration increases. For example, the model suggests that the effect of sensory congruency should increase and this was actually observed, although the observed congruency effect is clearly larger than PCM indicates.

Nevertheless, this simple model also failed to account for some important aspects of the results. For example, we fitted the model to the data set of each experiment to see whether it would also provide a reasonable quantitative account. These fits, however, were less impressive — the root mean square error ($RMSE$) of these fits ranged from 13 to 35 ms. Apart from problems in identifying the correct model parameters, it is clear that

this model is an oversimplification. For example, when we fitted the model, the pulse rate was not allowed to depend on the standard duration as in the work by Rammsayer and Ulrich (2001) and the identical set of parameters was applied to all subjects. We refrained from including these aspects, because this would have complicated the fitting procedure even more. Given that there are relatively few free model parameters, it seems possible that future research can advance the current model.

This quantitative analysis of PCM also clarified that the current version of the model cannot account for the rather large effect of sensory congruency on temporal discrimination performance. This point was revealed by computing the predicted congruency effect from the fits of the model. With the short standard, the observed DL was on average 9.4 ms larger in the incongruent than in the congruent condition. However, PCM predicted an average increase of only 0.6 ms. Likewise, the average congruency effect was 41.6 ms with the long standard, yet the predicted effects was only 2.7 ms. Thus, it appears possible that temporal discrimination on congruent trials could also benefit from additional sensory yet non-temporal information (e.g. experienced arousal) within a single modality that is not captured by the present version of PCM. For example, if the experienced level of arousal would be the same in such trials, this would inform the subject that the standard and the comparison must be physically identical in magnitude and extent. However, the inclusion of such additional sensory cues would be no longer beneficial when both stimuli belong to different sensory modalities. In agreement with this proposal, Rammsayer and Ulrich (2005) found a performance decrement in temporal discrimination when loudness differed between an auditory standard and an auditory comparison interval compared to when they were equally loud. Although a complete assessment of this proposal is beyond the scope of the present paper, future work should address in greater detail why discrimination performance is usually better when both stimuli belong to the same sensory modality, and extend PCM accordingly.

Finally, there was another finding that cannot be explained within the present framework of PCM without evoking further assumptions. As mentioned above, average *DL* was larger in Experiment 3 than in Experiments 1 and 2. That is, discrimination performance is better when the standard comes before rather than after the variable comparison. This outcome, however, can be easily addressed within the framework of the entrainment model (Large & Jones, 1999). The sequence of time intervals within a single trial in Experiments 1 and 2 formed an isochronous induction sequence (Barnes & Jones, 2000) before the comparison was presented. For example, in the long standard condition the temporal sequence of a trials was as follows: 1,000 ms (warning signal offset to standard onset) — 1,000 ms (standard duration) — 1,000 ms (standard offset to comparison onset). In other words, the induction sequence was composed of three 1,000 ms-intervals before the variable comparison was delivered. This induction sequence might have entrained an activity of an attending rhythm that facilitated the processing of the comparison at the end of this sequence (cf. Barnes & Jones, 2000; McAuley & Jones, 2003). In Experiment 3, however, the induction sequence before the comparison was reduced to only one induction interval and, thus, there was less opportunity for an build-up of such an entraining activity. Consequently, discrimination performance in Experiment 3 was less promoted by this activity than in Experiments 1 and 2. Thus, another option to further advance PCM is to link its core assumptions to the assumptions of the entrainment model.

One or Several Timing Mechanism?

A fundamental assumption of PCM is that a single timing mechanism underlies the perception of time. This notion, however, was already challenged by Hugo Münsterberg (1889). He reasoned that the mechanism underlying the perception of short durations is qualitatively different from the one that underlies the perception of long durations. More

specifically, Münsterberg assumed that durations less than one third of a second can be directly perceived, since they are primarily processed by sensory mechanisms. By contrast, longer durations, he believed, cannot be immediately perceived but need to be reconstructed by higher mental processes. Similarly, Michon (1985) argued that temporal processing of intervals longer than approximately half a second is cognitively mediated, whereas temporal processing of shorter intervals is supposedly "of a highly perceptual nature, fast, parallel and not accessible to cognitive control" (Michon, 1985, p. 40). Several authors have endorsed this view of distinct timing mechanisms (e.g. Buonomano & Karmarkar, 2002; Frankenhaeuser, 1959; Lewis & Miall, 2003; Mitrani, Shekerdjiiski, Gourevitch, & Yanev, 1977; Rammsayer, 1999; Sturt, 1925).[9]

Although experimental work pertinent to this issue is still extremely scant, it has recently received a fresh impetus in the field of timing and time perception (e.g. Michon, 1985; Rammsayer, 1999; Rammsayer & Lima, 1991; Rammsayer & Ulrich, 2005) and in the cognitive neurosciences (Bendixen, Grimm, & Schröger, 2005; Grimm, Widmann, & Schröger, 2004; Lewis & Miall, 2003). For example, Lewis and Miall (2003) recently reviewed neuroimaging data on various temporal tasks. Their review includes studies on timing tasks such as temporal production, tapping, response synchronization, velocity discrimination, and temporal discrimination. These authors concluded that an automatic timing system is involved in the timing of intervals in the sub-second range. This system, is assumed to recruit primarily networks within premotor and motor brain areas, and is not amenable to attention. The other hypothesized timing system is subject to cognitive control associated with activities in prefrontal and parietal brain regions.

The results of the present experiments, however, do not support the idea that distinct timing mechanisms operate at short and long durations. In all three experiments a similar and robust pattern of results emerged for short and long durations. For example, temporal discrimination performance was identically affected by our experimental

manipulations for both short and long durations. This consistent pattern clearly supports the single-clock assumption of PCM and questions the idea of two distinct timing mechanisms. An identical conclusion has been recently reached by Rammsayer and Ulrich (2005) on the basis of psychophysical data from of a dual-task approach. Thus the present results and the ones by Rammsayer and Ulrich appear rather surprising if one considers the evidence from neuroimaging (Lewis & Miall, 2003) and neuropharmacological (Rammsayer, 2003) studies that put forward the notion of two distinct timing mechanisms. In order to reconcile the psychophysical data with the conclusion stemming from these cognitive neuroscience approaches, one might propose that different versions of the same internal clock are located in various brain regions.[10]

Conclusion

In summary then, we applied the pacemaker-counter model to crossmodal temporal discrimination. This model provides a reasonable qualitative account for explaining some intriguing aspects of the data such as that temporal discrimination depends on the presentation order of the sensory modalities. The present data are also consistent with the fundamental notion of PCM claiming that one and the same single-clock mechanism is involved in time perception of short and longer durations. Nevertheless, the model in its present formulation can account neither for the relatively large observed congruency effect nor nor for the finding that the presentation order of the standard and the comparison stimulus has a strong effect on temporal discrimination. We provided some suggestions in order to accommodate these findings within the framework of current psychophysical models of time perception.

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Author Note

Footnotes

[1]As demonstrated by Rammsayer and Ulrich (2001), this approximation is usually excellent.

[2]It should be noted, however, that this explanation is somewhat oversimplified, because it completely discounts the variance of the interpulse time.

[3]Alternatively, a positive (negative) CE may also be interpreted to indicate that subjects underestimate (overestimate) the duration of the comparison.

[4]In order to evaluate whether PCM provides also a reasonable quantitative account of the present data, a simplex search algorithm was used to minimize the root-mean-square error ($RMSE$) between observed and predicted values. The minimizing procedure operated simultaneously on the CE and DL data sets. Predicted values for CE and DL were calculated via Equations 6 and 8, respectively. The overall error of this fit was $RMSE = 20.9$ ms, which suggests that PCM does not provide a satisfactory quantitative account. There are, however, at least two reasons why the fits might be suboptimal despite PCM might be approximately correct. First, such search algorithms do not always find the optimal parameter estimates (e.g. due to problems with local minima). Hence, PCM might actually produce somewhat better fits than this. In fact, the parameter estimates, yet not the $RMSE$, were rather sensitive to the starting values of the minimizing routine. This indicates that the true parameter values are not identifiable (see also Rammsayer & Ulrich, 2001). Second, PCM was fitted to aggregated results. Thus this assessment requires implicitly that the identical set of parameter values applies to each subject. This requirement, however, might be too strict and thus be unrealistic.

[5]The model predictions were again fitted simultaneously to the DL and CE results. Although the overall $RMSE = 13.1$ ms was somewhat better than the $RMSE$ for the previous experiment, it does still not indicate a perfect quantitative fit.

[6]It is easy to see that Equations 6 and 8 would also apply to this case.

[7]Although not shown in Figure 5, the model can also make a qualitatively slightly different prediction which, however, is not of particular relevance for the purpose of this paper. According to this alternative, the DL difference between conditions v-v and a-a is smaller than the difference between conditions v-a and a-v. The choice of parameters determines whether this somewhat different pattern emerges. It should be noted, however, that this alternative pattern would also entail the crucial features (a), (b), and (c) that we mentioned before.

[8] The overall fit of the pacemaker-counter model was $RMSE = 34.9$ ms in this experiment and, thus, was notably worse than the $RMSE$ for the two previous experiments.

[9]Another question in the timing literature addresses the issue whether different timing mechanisms underly the perception and production of temporal intervals. Experimental and neuropsychological research suggests that a common mechanism is involved in both tasks (e.g. Ivry & Hazeltine, 1995).

[10]In an experiment with 28 subjects, we employed stimulus durations of 50 and 2,000 ms to examine whether the findings of Experiment 1 generalize to a larger range of stimulus durations. Temporal discrimination became very difficult for our subjects at the long standard durations and, thus, the obtained DL were extremely large and unreliable. Power analysis revealed that a huge sample size is needed to attain the same level of statistical power as in Experiment 1. Nevertheless the pattern of results was very similar to the one of Experiment 1 and again a strong congruency effect emerged for both short and long durations. This indicates that our conclusions may generalize to a larger range of stimulus durations.

Table 1

Step size Δ_+ and Δ_- in Milliseconds to Estimate the Comparison Interval $t_c(0.75)$ for each Standard Duration and for each Stimulus Combination.

	Stimulus Combination			
Standard (ms)	v-v	a-a	v-a	a-v
	Δ_+			
100	8	3	10	10
1,000	80	30	100	100
	Δ_-			
100	24	9	30	30
1,000	240	90	300	300

Note. For the $t_c(0.25)$-runs, the above values of Δ_+ and Δ_- were interchanged.

Figure Captions

Figure 1. Predicted Psychometric Functions of the Counter Model. Each graph depicts the response probability $\Pr\{\text{``}C > S\text{''}|t_s, t_c\}$ as a function of the duration t_c of the comparison interval. The duration of the standard t_s is equal to 100 ms. v-a: visual standard and auditory comparison; a-a: auditory standard and auditory comparison; v-a: visual standard and auditory comparison; a-v: auditory standard and visual comparison. The mean and the standard deviation (μ, σ) of the interpulse time is ($\mu = 10$ ms, $\sigma = 4$ ms) for auditory intervals but ($\mu = 13$ ms, $\sigma = 10$ ms) for visual ones.

Figure 2. Predicted DL (upper panel) and CE (lower panel) of the PCM as a function of congruency, modality of the standard, and standard duration. The legend in the lower panel indicates the modality of the first stimulus and the duration of the standard; for example, "Auditory-100 ms" means that the first stimulus is auditory and the standard duration is equal to 100 ms. The mean and the standard deviation (μ, σ) of the interpulse time is ($\mu = 10$ ms, $\sigma = 4$ ms) for auditory intervals but ($\mu = 13$ ms, $\sigma = 10$ ms) for visual ones.

Figure 3. Results of Experiment 1. Mean Difference Limen (*DL*, upper panel) and Mean Constant Error (*CE*, lower panel) as a function of congruency, modality of the standard, and standard duration. The legend in the lower panel indicates the modality of the first stimulus and the duration of the standard; for example, "Auditory-100 ms" means that the first stimulus is auditory and the standard duration is equal to 100 ms. Following the suggestion made by Loftus (2002), the 95% confidence interval of the mean was computed from the pooled error terms of the repeated-measures ANOVA. The confidence interval associated with mean *DL* and mean *CE* was ±13.9 and ±42.1 ms, respectively.

Figure 4. Results of Experiment 2. Mean difference limen (*DL*, upper panel) and mean

Constant Error (CE, lower panel) as a function of congruency, modality of the standard, and standard duration. The 95% confidence interval associated with mean DL and mean CE was ±17.1 and ±52.3 ms, respectively.

Figure 5. Predicted DL (upper panel) and CE lower panel) of PCM as a function of congruency, modality of the first stimulus (i.e. the comparison in this case), and standard duration. The legend in the lower panel indicates the modality of the first stimulus and the duration of the standard; for example, "Auditory-100 ms" means that the first stimulus is auditory and the standard duration is equal to 100 ms. The same parameter values as in Figure 2 were used.

Figure 6. Results of Experiment 3. Mean difference limen (DL, upper panel) and mean Constant Error (CE, lower panel) as a function of congruency, modality of the first stimulus, and standard duration. The 95% confidence interval associated with mean DL and mean CE was ±31.8 and ±60.6 ms, respectively.

Response Probability
Pr{"C>S"}

Duration of Comparison Interval
t_c (ms)