Temporal reproduction: Further evidence for two processes

Pamela Ulbrich a,*, Jan Churan a, Martina Fink a, Marc Wittmann b

a Generation Research Program, Human Science Centre, Ludwig-Maximilian University of Munich, Prof.-Max-Lange-Platz 11, 83646 Bad Toelz, Germany
b Department of Psychiatry, University of California, San Diego, USA

Received 28 February 2006; received in revised form 7 June 2006; accepted 19 June 2006

Abstract

Some authors have suggested separate mechanisms for the processing of temporal intervals above versus below 2–3 s. Given that the evidence is mixed, the present experiment was carried out as a critical test of the separate-mechanism hypothesis. Subjects reproduced five standard durations of 1–5 s presented in the auditory and visual modalities. The Corsi-block test was used to assess effects of working-memory span on different interval lengths. Greater working-memory span was associated with longer reproductions of intervals of 3–5 s. A factor analysis run on mean reproduced intervals revealed one modality-unspecific factor for durations of 1–2 s and two modality-specific factors for longer intervals. These results are interpreted as further indications that two different processes underlie temporal reproductions of shorter and longer intervals.

© 2006 Elsevier B.V. All rights reserved.

PsycINFO classification: 2340; 2320

Keywords: Estimation of time; Temporal reproduction; Working memory

* Corresponding author. Tel.: +49 8041 799 29 0; fax: +49 8041 799 29 11.
E-mail address: mail@grp.hwz.uni-muenchen.de (P. Ulbrich).

0001-6918/S - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.actpsy.2006.06.004

Please cite this article as: Pamela Ulbrich et al., Temporal reproduction: Further evidence for two processes, Acta Psychologica (2006), doi:10.1016/j.actpsy.2006.06.004.
1. Introduction

1.1. Theoretical background

Several approaches have been applied to describe how temporal intervals in the seconds-to-minutes range are processed in humans and animals. A single mechanism is usually suggested to explain the whole range of possible durations. Some researchers, however, argue that there may be distinct processes at work, depending on the duration of the respective interval (Fraisse, 1984; Mauk & Buonomano, 2004; Pöppel, 1997; Wittmann, 1999). Four main tasks are usually employed to assess temporal processing of durations in humans: verbal estimation, temporal production, temporal reproduction and duration comparison (Zakay & Block, 1997). The present paper focuses on the method of reproduction.

Most models of timing (internal-clock models) assume three basic processing stages (e.g. Church, 1984; Wearden, 2004): (1) a pacemaker-accumulator clock (the clock stage), (2) a memory stage and (3) a decision stage. The actual clock is described as an oscillatory pacemaker emitting pulses at a constant rate that are fed into an accumulator when a switch is closed. This switch is closed at the beginning of a duration that has to be processed. It is reopened at the end of the processed period. The representation of duration (the number of pulses) is then transferred to short-term (working) memory, where it is transiently stored. Alternative versions of the model combine the working-memory stage with the accumulator. At the decision stage, a mechanism compares a currently perceived/produced duration with the time interval stored in short-term memory, and a decision is made on the adequate temporal response. Thus, in addition to the pacemaker (the actual clock component), cognitive processes, such as working memory, attention and decisional mechanisms, are involved in time perception and the timing of motor acts (Baudouin, Vanneste, Isingrini, & Pouthas, 2006; Franssen & Vandierendonck, 2002).

It has been shown that a secondary task performed during the encoding phase of a temporal-reproduction task leads to shorter reproductions. A concurrent cognitive task performed during temporal production or during the reproduction phase, however, causes longer reproductions (e.g. Fortin & Rousseau, 1998; Macar, Grondin, & Casini, 1994; Zakay, 1993). These effects can be interpreted by attention distraction caused by the secondary task (e.g. attentional-gate model, Zakay & Block, 1997). Since less attention is drawn to time, fewer pulses are recorded in the accumulator. As a result, when the secondary task is executed during the encoding phase of a temporal-reproduction task, the standard duration is represented by fewer counts than under conditions without a secondary task, which means that intervals are underestimated. When the concurrent task is performed during the reproduction phase, more time to collect the number of counts representing the standard duration is required, leading to longer reproductions.

An alternative explanation for the effects a concurrent task has on time estimation is the hypothesis of short-term memory control of time estimation suggested by Fortin and Rousseau (1998). Assuming that the accumulation process takes place in working memory, a secondary task with high working-memory demands can interrupt the accumulation process. If this happens during the encoding phase of a temporal-reproduction task, intervals are reproduced shorter. If it happens during the reproduction phase, intervals are reproduced longer. This short-term-memory-control hypothesis is supported by studies showing...
that concurrent tasks exert either no or less influence on the performance on temporal tasks when they merely require attention (e.g. a simple visual-search task (Fortin, Rousseau, Bourque, & Kirouac, 1993) where the subject has to decide whether a target was present among several distractors). These effects only occur when short-term memory (or working memory) is involved and increase in magnitude with the amount of short-term memory processing required (Brown, 1997; Fortin, 1999; Fortin et al., 1993). The difference between this short-term-memory hypothesis and the attention–distraction hypothesis is the functional locus at which a secondary task affects the accumulation of pulses. According to the attention–distraction hypothesis, some pulses do not pass the attentional gate and, therefore, cannot be directed to the accumulator. The short-term-memory hypothesis locates the disturbance in the accumulator, where working-memory constraints interfere with the accumulation process.

Duration-specific processing has been discussed on different time scales. An integration window of 100–150 ms has been postulated for auditory perception (Repp, 2004). In sensorimotor timing a critical interval of around one second has been proposed to correspond to qualitative changes in tapping performance (Madison, 2001). In addition, some authors distinguish between durations of above approximately 500 ms and very brief intervals below that value (Michon, 1985; Rammsayer, 1994). The processing of intervals longer than ca. 500 ms is thought to be cognitively mediated, since performance deteriorates when a secondary demanding task has to be performed simultaneously (Rammsayer & Lima, 1991). The processing of very short durations is not affected by a concurrent cognitive task. Furthermore, pharmacologic agents causing memory dysfunctions have been shown to impair temporal processing of around 1 s, while processing of durations below 100 ms was not influenced (Rammsayer, 1994). However, a recent study conducted to replicate the effects of concurrent non-temporal tasks on duration discrimination could not detect differences for short (100 ms) and long (1000 ms) intervals (Rammsayer & Ulrich, 2005).

Fraisse (1984) established the categorical distinction between perception of duration (applying to intervals up to approximately 3 s) and estimation of duration (applying to intervals exceeding 3 s), thus introducing a two-process model of time perception. According to this model, perception of duration is based on the subjective present, which has been described in a further development of this two-process model as a low-frequency binding mechanism that integrates sensory inputs into a coherent experience, or temporal gestalt (Pöppel, 1997). This temporal integration interval, which has been identified in various studies, has been estimated to last approximately 2–3 s (for an overview, see Wittmann, 1999).

According to the two-process model, intervals that are longer than 2–3 s can no longer be perceived as a unit, but have to be estimated from memory. The temporal-integration process limits, for example, the perception of rhythmic coherence in a regular sequence of tones. If the tones are separated by intervals exceeding 3 s, the perception of rhythm becomes impossible (Szelag, Steinbüchel, Reiser, de Langen, & Pöppel, 1996; Wittmann & Pöppel, 1999–2000). The capability to synchronise movements to a regular sequence of beats breaks down when the interstimulus interval between the beats exceeds 2–3 s (Mates, Müller, Radil, & Pöppel, 1994). Further indications for this temporal integration span derive from phenomena of speech segmentation (Vollrath, Kazenwadel, & Krüger, 1992) and the perception of ambiguous figures, where the two perspectives alternate every few seconds (Gomez, Argandona, Solier, Angulo, & Vazquez, 1995).
Of course, the theory that there are two duration-dependent processes does not exclude the possibility that one of these processes can be described according to internal-clock models.

1.2. Studies testing the two-processes hypothesis

With respect to temporal reproduction, studies have shown that intervals up to 3 s are reproduced veridically (or slightly longer), whereas intervals above approximately 3 s are reproduced with shorter intervals (e.g. Kagerer, Wittmann, Szelag, & Steinbüchel, 2002; Szelag, Kowalska, Rymarczyk, & Pöppel, 2002).

Kagerer et al. (2002) let several groups of patients with brain lesions reproduce durations between 1 and 5.5 s. They calculated regressions for intervals up to and below 3 s separately and compared the respective slopes. They found a significant effect of interval length, i.e. regression lines were steeper for short durations up to 3 s than for longer intervals above 3 s. More importantly, they found an interaction effect between interval length and patient group. For patients suffering from lesions in the right cerebral hemisphere anterior to the central sulcus, lower slopes were observed for long intervals, that is, they were underestimated to a greater amount by those patients as compared to the other subjects. This indicates that the respective brain region is involved in the processing of durations above 3 s, but not in the processing of shorter ones (that were unaffected), and, therefore, supports the assumption that there are two separate processes at work.

A recent pharmacologic study with the serotonin (5-HT)2A/1A receptor agonist psilocybin in healthy subjects revealed selective effects of the drug on temporal-processing abilities (Wittmann et al., in press). Psilocybin was found to significantly impair subjects’ abilities to reproduce durations only for intervals longer than 2.5 s – probably due to interactions with working-memory components of temporal processing. Reproduction of durations below 2.5 s were unaffected by psilocybin.

Further support for separate processes during reproduction of shorter and longer intervals comes from electrophysiological research. Elbert and colleagues measured event-related potentials (ERPs) during visual reproduction of intervals ranging in duration between 1 and 8 s. They reported accurate reproductions up to 3 s accompanied by a slow negative shift in the ERP signal. This shift was reduced or absent when durations longer than 3 s were processed (Elbert, Ulrich, Rockstroh, & Lutzenberger, 1991). On the other hand, Gibbons and Rammsayer (2004) were unable to replicate this finding – slow-wave measurements did not reveal any indication for two different processes depending on the interval processed. However, in this study no secondary task was performed during reproduction. In addition, subjects were paid to perform with high accuracy and received feedback on their performance immediately after each reproduction trial. Therefore, subjects may have used a counting strategy involving different brain structures (Hinton, Harrington, Binder, Dutgerian, & Rao, 2004).

Fortin and Couture (2002) tested whether there are differential effects of working-memory load on intervals above and below 2–3 s. They had subjects reproduce acoustically marked empty intervals with durations between 1.85 and 6.45 s while doing a concurrent memory task. The authors claimed that their specific memory task would additionally
strain working memory only during the reproduction phase. Therefore, they hypothesised that response intervals would lengthen with memory-set size. The results of the experiment actually showed such an effect on mean reproduced durations, but there was no interaction between set size and standard duration. The working-memory induced lengthening was observable for all intervals from 1.85 to 6.45 s. Hence, there was no support for two distinct processes operating for short versus long intervals.

Eisler (1976) used a psychophysical power function to describe the relationship between the sample duration and the reproduced interval. Summarising a large number of studies on temporal reproduction conducted between 1868 and 1975, he found a median power-function exponent of 0.81 (Eisler, 1976). Some more recent experiments have yielded values in the same range (e.g. Eisler & Eisler, 1992, 1994). Power-function curves with exponents below one attenuate with increasing values on the abscissa, therefore describing the pattern found for temporal reproduction of accurate estimation for short intervals and pronounced underestimation for longer durations. The fact that temporal-reproduction data can be described by one power function argues against the assumption of two separate processes.

To sum up, although several attempts have been made to clarify whether there are two separate processes at work during temporal reproduction of intervals below and above 1–3 s duration, results supporting and discounting the hypothesis are mixed.

1.3. Study aims

The aim of the present study was to further investigate whether there are two distinct processes operating during a temporal-reproduction task. As described in Section 1.2, this question has not properly been answered yet. Therefore, we chose two new approaches to investigate this topic.

One was to compare two groups of subjects with different working-memory capacity, an approach inspired by the study of Fortin and Couture (2002) who manipulated memory load experimentally. However, we chose to investigate inter-subject differences in working memory in a large sample of subjects between 21 and 84 years of age. As described in Section 1.1, working memory plays an important role in time estimation. Subjects with high working-memory capacity should, therefore, make longer reproductions than subjects with low working-memory capacity. Furthermore, these two subject groups should differ less when reproducing durations below 3 s since – according to the theory by Fraisse (1984) – these intervals are perceived as a unit, that is, are less dependent on attention or working-memory influences.

The second idea was to compare temporal reproductions in two modalities (auditory and visual). Again, since the theory by Fraisse (1984) proposes that intervals up to 3 s are perceived as a unit independent of stimulus properties, the modality of the presented intervals should have no effect on these short durations. On intervals above 3 s, however, modality may have an effect, because an estimation process takes place that might be influenced by several factors such as stimulus properties or cognitive abilities. Therefore, we investigated the pattern of correlations between reproductions of different sample durations in different modalities by factor analysis. If there were actually two separate processes, reproductions of short intervals and long intervals should load on different factors.
2. Method

2.1. Subjects

One hundred adults (52 males, 48 females) participated in the experiment. Their ages ranged between 21 and 84 years with a mean of 49.46 years (SD = 17.19). Their vision was normal or corrected to normal, and their hearing was within normal range (<30 dB sound pressure level) as controlled by pure-tone audiometry (Audiometer MA 15, Maico Diagnostic GmbH). They were paid for taking part in the study.

2.2. Apparatus

Temporal-reproduction tasks were conducted on a PC with an Intel Celron 2 GHz processor, using a NVidia GeForce4 graphic card and a Soundblaster Audigy sound card. Auditory stimuli were presented via headphones (Sony stereo headphones MDR-CD 480). Visual stimuli were presented on a 22-inch monitor (Iiyama Vision Master Pro 514; 600 x 800 pixel; frame rate 200 Hz). Stimulus generation and the conduction of the reproduction tasks was implemented using MatLab 5.3 (MathWorks Inc.) and the WinVis Toolbox (Neurometrics Institute). Data analyses were performed with SPSS 11.5 for Windows.

2.3. Stimuli

Sample durations lasted 1000 ms, 2000 ms, 3000 ms, 4000 ms, and 5000 ms. In the auditory task, a 300-Hz tone denoted the sample duration, and a 600-Hz tone denoted the response duration. Both were presented at an intensity of 70 dB sound-pressure level. In the visual task, a white square indicated the sample duration, and a yellow square indicated the response duration. Both squares were presented at the centre of the screen and had a side length of 2.9°. There was a pause of 1000 ms between sample and response duration. Symbols for the non-temporal concurrent task (see below) were a wave, a cross, a triangle and a circle. Two of them were presented for 3000 ms before each sample duration, which was started 625 ms after the symbols had vanished. A single symbol was presented directly after subjects had stopped the response interval.

2.4. Procedure

The auditory and visual reproduction tasks were performed on two separate days in counter-balanced order. Subjects were seated approximately 48 cm in front of the monitor with their heads fixed to a head rest. They were told that they would hear a tone (see a white square) lasting for a certain amount of time. Afterwards they would hear another tone (see a yellow square) lasting until they pressed a button on the computer keyboard. They were told to press the button when they thought the same amount of time had elapsed as for the first stimulus. Subjects were instructed not to count. It was stressed that the investigator was not interested in the subjects’ counting abilities, but subjective estimates of time. Nevertheless, these instructions could not ensure a non-counting approach to subjective time estimation. Therefore, a non-temporal concurrent task was employed. Before presentation of the sample stimulus, two symbols were presented which the subjects were told to memorise. After reproduction of the interval, a single symbol appeared on the
screen, and the subjects had to decide whether it was one of the former two or not. Their answers were recorded by the experimenter. Each sample duration was presented eight times, leading to a total of 40 trials. The order of presentation was randomised. Each of the two reproduction tasks lasted about 12 min.

2.5. Assessment of working memory

To assess working-memory capacity the Corsi-block test was applied (Corsi, 1972). Nine cubes (1 x 1 cm) are attached to a plate and placed in front of the subject. The experimenter demonstrates a sequence of cubes by pointing to them. The subject has to repeat the sequence and receives one point for every correctly reproduced sequence. The number of cubes increases (beginning with three) with every second trial. If the subject fails on both trials with the same number of cubes, the test is terminated. Both versions, forward and the backward sequence reproduction, were performed, and the sum of the scores was used for further analyses. The Corsi-block test was conducted after the reproduction tasks on a separate day.

We preferred to measure visuospatial rather than verbal working memory for two reasons. First, it has been shown that visuospatial working memory is more strongly correlated with age than is verbal working memory (e.g. Wilde, Strauss, & Tulsky, 2004). To guarantee a wide range of working-memory capacity in our sample we investigated people with a wide age range. Based on the results by Wilde et al. (2004) this strategy promised to be more successful with a measurement of visuospatial rather than verbal working memory.

Second, patients with a damage to the right cerebral hemisphere have been shown to be more impaired in the Corsi-block test than patients with lesions to the left hemisphere (Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000) suggesting that the right hemisphere might be involved in visuospatial working-memory tasks. For verbal working memory, neural circuits in the left hemisphere are proposed (Hickok & Poeppel, 2004). The right hemisphere is also involved in the processing of durations (e.g. Kagerer et al., 2002; Smith, Taylor, Lidzba, & Rubia, 2003). Therefore, visuospatial working memory might be more strongly associated with the performance in temporal-reproduction tasks as similar brain regions might be involved.

2.6. Data analysis

Intervals reproduced longer than twice the respective standard duration were regarded as outliers and removed from the dataset for each subject. Then three characteristic values were calculated: (a) the mean reproduced interval, (b) the ratio between reproduced and standard interval and (c) the coefficient of variation, that is, the standard deviation divided by the mean reproduced interval. These values were calculated for each standard duration, modality and subject separately. Further analyses were performed on these variables. To compare groups with different working-memory capacity, the sample was dichotomised along the 50. percentile of the distribution of scores obtained from the Corsi-block test.

To test for effects of standard duration, modality, working-memory capacity and possible interactions, three-way analyses of variance (ANOVA) were performed on mean reproduced intervals, ratio scores and coefficients of variation. We also calculated
one-tailed $t$-tests to check whether subjects with high working-memory capacity reproduced longer intervals than subjects with low working-memory capacity. Finally, we conducted a factor analysis to investigate the pattern of intercorrelations between mean reproduced intervals.

3. Results

3.1. Tests for normality and working-memory capacity

From the total number of 100 subjects, two cases of the auditory and one of the visual reproduction task had to be omitted because of incorrect values due to technical difficulties. All mean reproduced intervals, ratio values and coefficients of variation were normally distributed over all subjects, as indicated by the Kolmogorov–Smirnov test ($p > 0.05$).

To assess whether there is an age-related decline in working-memory capacity, six age groups were created (20–29; 30–39; 40–49; 50–59; 60–69; 70–84), and the performances of these groups on the Corsi-block test were compared. A one-way ANOVA yielded a significant main effect of age, $F(5, 93) = 8.50, p < 0.001$. The values decreased progressively from 20.29 points in the youngest group (20–29 years) to 15.18 points in the oldest group (70–84 years) (see Table 1). The correlation between age and the performance in the Corsi-block test was $r = -0.53, p < 0.001$.

The two groups of low versus high working-memory capacity differed significantly in their performance on the Corsi-block test, $t(97) = -14.71, p < 0.001$, with means of 14.76 (SD = 1.81, $n = 50$) for the low-score group and 20.06 (SD = 1.91, $n = 49$) for the high-score group. They also differed significantly in age, $t(97) = 5.98, p < 0.001$, with means of 58.18 years (SD = 15.20) for the low-score group and 40.37 years (SD = 14.42) for the high-score group. However, age was not significantly correlated to mean reproduced intervals, ratio scores or coefficients of variation ($p > 0.05$, Bonferroni corrected). Therefore, no distortion of results due to age effects is expected.

3.2. Working-memory capacity and temporal reproduction

Overall means and standard deviations of the reproduced intervals are displayed in Fig. 1. Ratio scores and coefficients of variation are summarised in Table 2. Reproduced intervals increase with increasing standard durations, whereas the ratios and coefficients of variation decrease. Also, visual intervals seem to be reproduced longer and with greater variability than auditory ones.

Three-way ANOVAs were performed using standard duration and modality as within-subject factors, memory group as a between-subject factor and mean reproduced interval, ratio (of reproduced interval and sample duration) and coefficient of variation as depen-

<p>| Table 1 |
| Number of subjects ($n$), mean Corsi-block scores ($M$) and standard deviation (SD) of the scores of the six age groups |</p>
<table>
<thead>
<tr>
<th>n</th>
<th>20–29</th>
<th>30–39</th>
<th>40–49</th>
<th>50–59</th>
<th>60–69</th>
<th>70–84</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>17</td>
<td>16</td>
<td>17</td>
<td>16</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>$M$</td>
<td>20.29</td>
<td>18.19</td>
<td>17.47</td>
<td>18.00</td>
<td>15.13</td>
<td>15.18</td>
</tr>
<tr>
<td>SD</td>
<td>2.59</td>
<td>2.37</td>
<td>2.83</td>
<td>3.83</td>
<td>2.16</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Please cite this article as: Pamela Ulbrich et al., Temporal reproduction: Further evidence for two processes, Acta Psychologica (2006), doi:10.1016/j.actpsy.2006.06.004.
dent variables. For the mean reproduced interval, significant main effects of sample duration, $F(1.46, 137.34) = 2124.83$, $p < 0.001$, $\eta^2 = 0.96$, modality, $F(1,94) = 13.42$, $p < 0.001$, $\eta^2 = 0.13$, and memory group, $F(1,94) = 5.67$, $p < 0.05$, $\eta^2 = 0.06$, were found. Furthermore, there was a significant interaction between duration and modality, $F(2.05, 192.46) = 6.16$, $p < 0.01$, $\eta^2 = 0.06$, and between duration and memory group, $F(1.46, 137.34) = 4.82$, $p < 0.05$, $\eta^2 = 0.05$.

Values for the two memory groups are presented in Fig. 2. Subjects with higher scores on the Corsi-block test reproduced sample durations longer than subjects with lower scores. $T$-tests showed significant differences between the two memory groups in the auditory modality for sample durations of 4000 ms, $t(95) = -2.23$, $p < 0.05$, and 5000 ms, $t(95) = -2.18$, $p < 0.05$. In the visual modality significant differences were found for 3000 ms, $t(96) = -2.59$, $p < 0.05$, and 5000 ms, $t(96) = -2.48$, $p < 0.05$ (all $p$-values in this paragraph are Bonferroni corrected).

For the ratio score (reproduced interval divided by sample duration), significant main effects of sample duration, $F(1.53, 143.33) = 106.83$, $p < 0.001$, $\eta^2 = 0.53$, modality, $F(1,94) = 13.00$, $p < 0.001$, $\eta^2 = 0.12$, and memory group, $F(1,94) = 4.28$, $p < 0.05$, $\eta^2 = 0.04$, were found. There were no significant interactions. As for the mean reproduced intervals, significant differences between the two memory groups were found for sample durations of 4000 ms, $t(95) = -2.23$, $p < 0.05$, and 5000 ms, $t(95) = -2.18$, $p < 0.05$ in the auditory modality.
and for 3000 ms, $t(96) = -2.59$, $p < 0.05$, and 5000 ms, $t(96) = -2.48$, $p < 0.05$, in the visual modality ($p$-values Bonferroni corrected). Subjects attaining higher scores on the Corsi-block test showed higher ratio scores than subjects performing with lower scores on the Corsi-block test.

Please cite this article as: Pamela Ulbrich et al., Temporal reproduction: Further evidence for two processes, Acta Psychologica (2006), doi:10.1016/j.actpsy.2006.06.004.
For the coefficient of variation there were significant main effects of sample duration, $F(3.35, 314.72) = 38.85$, $p < 0.001$, $\eta^2 = 0.29$, and modality $F(1, 94) = 59.46$, $p < 0.001$, $\eta^2 = 0.39$. The effect for memory group, $F(1, 94) = 2.92$, $p < 0.10$, $\eta^2 = 0.03$, and the interaction between memory group and sample duration, $F(3.35, 314.72) = 2.26$, $p < 0.08$, $\eta^2 = 0.02$, were only marginal and did not attain the significance level of $p < 0.05$.

Ratio scores and coefficients of variation for the two memory groups are presented in Fig. 2.

### 3.3. Intercorrelations between modalities

To further examine the relationship between long and short intervals, correlation analyses over the ten mean reproduced intervals (five durations in two modalities) were conducted. Since reproductions were different in the two working-memory groups, the performance in the reproduction task was controlled for the performance in the Corsi-block test by using partial correlations. The partial correlation coefficients between standard intervals within the auditory modality ranged between $r = 0.40$ and $r = 0.91$ and within the visual modality, between $r = 0.22$ and $r = 0.86$. They were all significant at $p < 0.01$, except the coefficient between 1000 ms and 5000 ms of visual reproduction with $p < 0.05$. Intercorrelations between the modalities for each sample duration ranged between $r = 0.44$ and $r = 0.49$ and were all significant, $p < 0.01$.

This matrix of partial correlations was then entered into a factor analysis. The Kaiser–Guttman criterion (eigen values $> 1$) was used for extraction, and the varimax-rotation procedure was applied. Three factors emerged which explain 85.96% of variance. Factor loadings for the 10 variables are displayed in Table 3. Two modality-specific factors and one modality-unspecific factor were found. On the first factor, which accounts for 34.79% of variance, the auditory reproduced intervals of 2000, 3000, 4000, and 5000 ms standard duration load highest. The second factor (explaining 28.76% of total variance) contains the mean reproduced intervals of 3000, 4000, and 5000 ms of the visual task. The 1000 ms auditory and 1000 and 2000 ms visual intervals constitute the third factor (explaining 22.41% of total variance).

<table>
<thead>
<tr>
<th>Mean reproduced intervals</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory 1000 ms</td>
<td>0.544</td>
<td></td>
<td>0.707</td>
</tr>
<tr>
<td>Auditory 2000 ms</td>
<td>0.784</td>
<td>0.474</td>
<td></td>
</tr>
<tr>
<td>Auditory 3000 ms</td>
<td>0.921</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory 4000 ms</td>
<td>0.878</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory 5000 ms</td>
<td>0.873</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual 1000 ms</td>
<td></td>
<td>0.859</td>
<td></td>
</tr>
<tr>
<td>Visual 2000 ms</td>
<td></td>
<td>0.517</td>
<td>0.726</td>
</tr>
<tr>
<td>Visual 3000 ms</td>
<td></td>
<td>0.813</td>
<td></td>
</tr>
<tr>
<td>Visual 4000 ms</td>
<td></td>
<td>0.888</td>
<td></td>
</tr>
<tr>
<td>Visual 5000 ms</td>
<td></td>
<td>0.913</td>
<td></td>
</tr>
</tbody>
</table>

Loadings $< 0.40$ are not presented because they are not interpretable (Bortz, 1993).
4. Discussion

Our results replicate findings of earlier studies showing a pattern of veridical reproduction (or slightly longer reproduction) for shorter intervals and an underestimation for longer intervals (e.g. Elbert et al., 1991; Kagerer et al., 2002; Szelag et al., 2002). In addition, we found visual sample times to be reproduced longer than auditory ones, which also coincides with the literature (e.g. Brown & Hitchcock, 1965; Goldstone, 1968; Hirsh, Bilger, & Deatherage, 1956; for a thorough discussion on modality differences in interval timing, see Penney, 2003). The fact that pronounced underestimations occurred in intervals longer than 2 s indicates that the secondary task employed in this study successfully prevented subjects from counting. In the experiment by Gibbons and Rammsayer (2004), for example, where no secondary task was used, reproductions of the longer intervals were much more accurate, suggesting that subjects used a counting strategy to solve the task.

4.1. Working-memory capacity

Two groups of subjects with high versus low working-memory capacity were compared on their mean reproduced intervals, ratio scores, and coefficients of variation. If there were two separate processes at work, as proposed, for example, by Fraisse (1984) or Pöppel (1997), then subjects with high versus low working-memory capacity should differ in their reproductions more for longer intervals than for shorter ones. Durations of 3 s and longer are assumed to require more working-memory capacity to process (time estimation). Shorter intervals up to 2–3 s are thought to be perceived/integrated as a temporal unit (time perception). Therefore, these shorter intervals are less dependent on cognitive variables, such as working memory.

For the mean reproduced intervals and the ratio scores significant main effects of memory group were found. Subjects with a bigger memory span showed longer reproductions and higher ratio scores. A significant interaction effect between standard duration and memory group was found for the mean reproduced intervals. T-tests revealed significant differences only for 4000 and 5000 ms in the auditory modality, and for 3000 and 5000 ms in the visual domain. This supports the hypothesis that there are two separate processes operating during a reproduction task. However, no effect of working memory was observed for the coefficient of variation.

Our finding is inconsistent with the results reported by Fortin and Couture (2002), who found similar influences of working memory on all reproduced intervals regardless of their duration. This could, of course, be due to the different operationalisations employed in the two studies. While Fortin and Couture (2002) manipulated working-memory load experimentally using a non-temporal secondary task, we compared two groups of subjects with high versus low working-memory capacity. The specific implementation of the concurrent task in the study by Fortin and Couture (2002) mostly affected the reproduction phase. In our study, however, the naturally occurring differences in working memory between subjects were present during the whole experiment.

These two different operationalisations on probing working-memory effects may have involved different memory components during the reproduction task. Performing a secondary task during a temporal-reproduction task is thought to impair the accumulation process, resulting in shorter or longer reproductions, depending on whether the concurrent task was performed during the presentation of the sample duration or during the repro-
duction phase (e.g. Fortin & Rousseau, 1998). When comparing groups of subjects with different working-memory capacities, the relevant memory process may be the storage of the sum of pulses in short-term memory, which represents the sample duration. Due to a limited storage size, some temporal units can get lost, either simply as a function of time or because of the interfering effect of a secondary task.

The results of the present study support this view. Having high or low working-memory capacity is a feature present during the whole temporal-reproduction task. If the accumulation process had been affected, then no differences should have been observed between the two memory groups because the same influence (low versus high working-memory capacity) was present during both the encoding phase (the accumulation during the presentation of the sample duration) and the reproduction phase (the accumulation during the presentation of the second stimulus). We did, however, observe longer reproductions in subjects who performed better on the Corsi-block test. Therefore, the critical memory process must have been the storage of temporal units representing the sample duration. This information was preserved better in subjects with good working-memory abilities, which resulted in longer reproductions. In participants performing with a smaller working-memory span on the Corsi-block test, the number of pulses is more readily subject to decay. Those participants reproduced shorter durations (in case of intervals of 3 s and above), as a smaller number of pulses is left in memory to define the period of time to be reproduced.

This decay may arise from our secondary task implemented to prevent subjects from counting. During the reproduction task participants had to remember the two symbols presented before each trial. Therefore, less memory capacity was available to retain the number of pulses representing the respective sample duration, which especially affects the performance of subjects with a smaller working-memory capacity.

Independent of the question of which memory components were involved in our specific behavioural outcome, we observed differences between the two memory groups only for intervals of 3000, 4000, and 5000 ms. The role of memory, therefore, seems to be more important for durations beyond the critical value of 2–3 s, suggesting that two different processes underlie the temporal reproduction of short and long intervals. Coefficients of variation over different time intervals are not, however, affected by the degree of working-memory capacity. This indicates that the size of transient memory storage may affect the duration of reproductions, but not the stability of performance.

4.2. Intercorrelations between modalities

Further support for the hypothesis of two processes comes from the results of the factor analysis. Mean reproduced intervals of short durations (1000, 2000 ms) load on one common factor for both modalities, whereas longer intervals (3000, 4000, 5000 ms) load on two modality-specific factors. This means that mean reproduced intervals of shorter duration in one modality correlate more strongly with mean reproduced intervals of shorter duration in the other modality than with longer intervals of the same modality. Longer durations, in contrast, are correlated more strongly within the same modality than with intervals of equal duration but different modality.

Since the factor analysis was run on intercorrelations after the performance in the Corsi-block test had been factorised out, this pattern cannot be attributed to differential influences of working-memory capacity on short and long durations. Rather it seems that intervals of 1–2 s of both modalities are processed by one common mechanism that is
distinct from the mechanism underlying the processing of intervals exceeding 3 s. The processing of intervals longer than 3 s seems to depend on the modality of the stimuli used since two factors emerged for durations of 3–5 s.

5. Summary

Our results are in accordance with the conceptual idea of Fraisse (1984) that differentiates between perception of duration (intervals up to 3 s) and estimation of duration (intervals longer than 3 s). He suggests that shorter durations might be “perceived” as a unit. This idea is corroborated by our data showing no effects of modality and working-memory capacity on temporal reproduction of intervals of 1–2 s duration. The reproduction of intervals longer than 3 s, however, seems to be an “estimation” process, since it is strongly influenced by cognitive functions (e.g. working memory) and the modality in which the task was performed.

Acknowledgements

This study was supported by BMBF grants 01 IBC 01H and 01 GZ 0301. We thank Nicole Krueger, Kristina Starke, and Florian Wiech for their help in collecting the data.

References


