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Prospective duration judgments: The role of temporality and executive demands of concurrent tasks

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ABSTRACT

It is known that concurrent non-temporal tasks shorten reproduced temporal durations in prospective duration judgments. Two experiments were carried out, one comparing a concurrent temporal task to a minimally demanding concurrent task (Experiment 1) and one comparing an executive concurrent (Simon) task with a less demanding non-executive concurrent task (Experiment 2). An effect of the concurrent task type on temporal reproductions was found. Furthermore, a duration length effect was found, where longer durations were underestimated more than shorter durations. This effect tended to be stronger for the experiments that included a concurrent task that demanded high attention.

1. Introduction

Accurate timing is required for the sake of efficient adaptive behavior in humans. Representation of time intervals on different scales from milliseconds to years is a crucial necessity for various mechanisms. However, psychologically relevant characteristics of temporal operations (e.g., estimation of a time interval to perform a particular task) usually are necessary on a scale of several seconds (Block, Zakay, & Hancock, 1999).

It is widely accepted that performance in a dual-task design is dependent upon the competition for attentional resources between temporal and non-temporal features of a stimulus since they share a limited common pool (e.g., Block & Zakay, 2006; Block et al., 1999; Brown, 1985; Brown & Boltz, 2002; Casini & Macar, 1999; Zakay, 1993; Zakay & Block, 2004). Performing concurrent non-temporal tasks during an interval decreases the accuracy of subsequent temporal reproduction and this decline increases with more difficult tasks. Attentional demands of the concurrent task influence prospective judgment, that is, subjects underestimate the time duration (Block & Zakay, 2006). Underestimation of durations when there are less available attentional resources for the temporal task has been explained by various internal clock models of time perception. In these models, pulses are emitted at a constant rate by the pacemaker and registered by an accumulator. In the attentional gate model (Block & Zakay, 2006), an advancement of the internal clock model more suitable for human subjects, attentional resource allocation is achieved by an attentional gate. If more resources are allocated to timing, more pulses pass through the gate since it is more open and more signals reach the accumulator. Concurrent non-temporal tasks consume some attentional resources and leave fewer resources for timing, which leads to the experience of shorter durations and underestimation of reproductions.

There are numerous concurrent tasks which affect time perception. For instance, syntactic ambiguity in reading and task switching (Zakay & Block, 2004), the Stroop task and its variations (Marshall & Wilsoncraft, 1989; Zakay, 1993; Zakay & Fallach, 1984), picture naming (Gautier & Droit-Volet, 2002), driving a car in a simulator or watching a videotape of a car (Gruber & Block, 2005), working memory span test (Ulbrich, Churan, Fink, & Wittmann, 2007), the randomization task (Brown, 2006), categorizing words (Macar, 1996), visual search (Brown, 1997), and the card sorting task (Zakay & Shub, 1998). Zakay (1993) could show effects of highly resource demanding tasks (such as Stroop) on the timing of a single interval (12 s) as compared to less resource demanding tasks. These studies indicate that time perception is sensitive to a large variety of concurrent tasks. However, there are also studies which failed to find concurrent task effects on timing between a secondary task that demanded verifying additions, an active cognitive process, and letter recognition, a more passive perceptual process (e.g., Taatgen, Van Rijn, & Anderson, 2007). Given these varied results, it would be more explanatory if those concurrent tasks in the literature could be categorized under some types of cognitive load.

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Block, Hancock, and Zakay (2010) categorized cognitive load types of concurrent tasks in the dual task paradigm of duration judgment studies in terms of attentional, response and memory demands, familiarity, processing changes and difficulty. This classification will be considered to explain the nature of the two experiments in the present study.

Although there are numerous non-temporal tasks that are used as concurrent tasks in time perception studies, to our knowledge, there are only few studies in the literature that directly investigate the effect of a concurrent temporal task within a duration judgment task. One example is the study by Brown and West (1990) that showed inaccurate reproductions when performing multiple timing tasks. Multiple temporal tasks were either consecutive or overlapping in this study. Whereas the results of Brown and West (1990) indicated the limited capacity of the attentional resources if they have to be allocated to more than one timing task, in the present study, we aim to show the effect of a concurrent temporal task that is entirely embedded in a longer interval which should be reproduced. We suggest that performance in a concurrent temporal task should be tested with the same method as in usual dual-task experiments (in which a non-temporal concurrent task is always carried out during the interval) to observe more clearly the effect of the concurrent temporal task on the actual time experience of the entire duration. Therefore, in Experiment 1 (temporal group), we used an interval comparison method including three relatively brief durations in the concurrent task embedded in the entire duration to be reproduced. As a control condition (sequence group) we used the same design, however, subjects had to report only the sequence of the colors and not to attend to the durations of the stimuli. Therefore, we could equalize memory demands (keeping track of the order of the sub-intervals and reporting them) of the two conditions and reveal the effect of Block et al.'s (2010) attentional demand types in the temporal task.

The Simon task (Hommel, 2011; Proctor, 2011) is one of the most widely used executive tasks to study cognitive control and has similar demands as the Stroop task used by Zakay (1993). The spatial position of the stimulus activates a fast response tendency to respond to the stimulus location even if the subjects should respond considering the shape, color, etc. of the stimulus. In a Simon task, interference occurs during the response selection part of information processing. The conflict that is present in incongruent cases (when the irrelevant spatial and the relevant non-spatial dimension of the stimulus do not overlap) has to be resolved by cognitive control. Response selection in conflicting situations is dealt with by the executive control mechanism. In Experiment 2, we aim to reveal the effect of response selection demand (Simon task) by equalizing motor response execution demands.

Another goal of this study is to investigate the effect of duration on time judgment. According to Zakay (1990) there is a tendency for longer durations to be more underestimated than shorter durations. Moreover, also other time-based processes such as prospective remembering seem to be sensitive to the length of the interval (Block & Zakay, 2006). Therefore, three different duration lengths (15, 30, and 45 s) are chosen which are thought to be appropriate for a prospective duration estimation study covering the most relevant part of the second scale of the interval timing paradigm.

2. Concurrent temporal task effect (Experiment 1)

A between-subject design was used to study the effect of a concurrent temporal task on duration reproduction. Participants in the “sequence task” group, which served as a control group, had to remember the sequence of three different background colors, blue, red, and yellow. Participants in the “temporal task” group were asked to pay attention to the relative durations of the three background colors with respect to each other. Subjects had to order the background colors with respect to their duration as short, medium and long on a sheet of paper. This makes the concurrent task a temporal task too. Subsequently, subjects in both groups had to reproduce the time interval. There might be a small difference in terms of workload while ordering just the color sequence vs their durational lengths. While reporting the sequence of colors requires just keeping track of that sequence, ordering the colors in terms of their duration (short, medium, long) requires some minimal update after the presentation of each color, i.e., whether the current color's duration was short, medium, or long relative to the other colors' durations. However, the memory demands of both ordering tasks seem minimal.

2.1. Participants

A total number of 23 subjects participated voluntarily in this study. There were 11 participants in the sequence group (*Mean age* = 21.1, *SD* = 2.3) and 12 participants in the temporal group (*Mean age* = 25.4, *SD* = 2.1). All subjects had normal or corrected-to-normal vision.

2.2. Procedure

Experiments were run in a silent room at METU Cogs-Lab, in front of a CRT monitor at a comfortable distance for the subjects and conducted with E-prime 1.2. They started with a practice phase including one trial from each duration length, namely short, medium and long. However, these durations (12, 25, 37 s) were not the same durations that were used during the experimental sessions. In the main test phase, there were five trials for each duration (15, 30, 45 s) that were randomly presented to the subject. All participants were instructed not to count loudly or silently during their performance.

The general set-up was as follows: a black square was shown in the center of the screen and the background color changed randomly between white, yellow, red, and blue. The white background was used as a default and participants were asked to write down the sequence of the other randomized background colors ((the Turkish equivalents of) Y for yellow, R for red, and B for blue) on a sheet of paper according to their order of appearance (sequence task group) or relative durations (temporal task group) after completing the study phase. Participants were asked to pay equal attention to both tasks, namely the duration comparison of the three background colors and the duration of the entire interval. During short intervals (15 s) yellow, red and blue backgrounds were seen on the screen for periods lasting 1, 2, or 3 s. The background durations were 2, 4, or 6 s for medium and 3, 6, or 9 s for long intervals (background colors appeared in 40% of the entire duration for each duration length).

Then an instruction page was shown that informed the subjects to continue with the duration reproduction part of the trial. After the instruction page, the same black square was shown on the screen to let them know the clock was ticking. Then they had to press a defined key to stop their estimation for the most recent entire duration that they had perceived in the sequence or temporal ordering task (Fig. 1).

2.2.1. Ranking of the comparison scores (temporal task group)

If the sequence that subjects noted on the response sheet was correct, they obtained 2 points because distinguishing two different durations is sufficient to obtain the correct order of the color durations. On the other hand, if they were correct about the longest (or shortest) duration but were mistaken about the short and medium (or medium and long) colors, they obtained 1 point as in this case that they could distinguish only one color's duration as longer (or shorter) than the remaining ones correctly, while being unable to do so for colors of short and medium (medium and long) length. Therefore they were given 1 point, or half of the total points available. As a last option, they could be wrong about all color durations. In this case the subject obtained 0 points.

2.3. Results

The descriptive results of the reproductions and ratios (reproduced/objective durations) are given in Table 1. A mixed ANOVA with the three

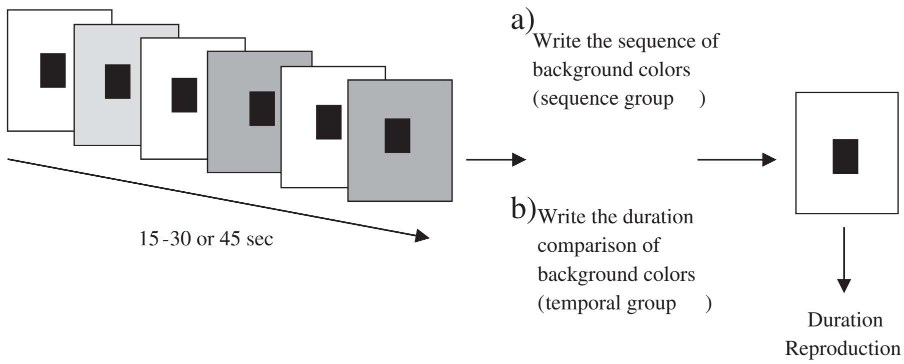

Fig. 1. Flow of an experimental trial. The procedures differ in instructions of the concurrent task for the two groups. (a) Subjects are instructed to attend to the sequence of the background colors in the sequence task group and (b) relative durations in the temporal task group before the duration reproduction part of the experiment.

Table 1
Reproductions (in s) and ratios according to task type (sequence task, temporal task) and duration (15, 30, 45 s) in the time reproduction task.

	Sequence group			Temporal group		
	Durations					
	15 s	30 s	45 s	15 s	30 s	45 s
Reproductions (SD)	15.7 (6.9)	30.4 (10.3)	42.1 (11.6)	13.9 (5.0)	23.8 (7.7)	32.7 (8.2)
Ratio (reproduced/objective duration) (SD)	1.05 (0.33)	1.01 (0.27)	0.93 (0.20)	0.93 (0.26)	0.79 (0.20)	0.73 (0.15)

durations (15, 30, 45 s) as within-subject factor and group (sequence task, temporal task) as between-subject factor was conducted on the ratios of the reproduced/objective durations. A marginally significant main effect of group on ratios was found which revealed that ratios in the temporal task group tended to be lower than in the sequence task group ($F(1,21) = 4.135$, $p = .055$, $\eta_p^2 = .165$). There was a main effect of durations which indicated that ratios decreased as duration increased ($F(2,42) = 7.884$, $p < .05$, $\eta_p^2 = .273$). Simple contrasts revealed that medium durations ($M = 0.91$, $SE = 0.05$) yielded lower ratios than short durations ($M = 0.99$, $SE = 0.06$, $F(1,21) = 5.599$, $p < .05$, $\eta_p^2 = .210$). Furthermore, long durations ($M = 0.83$, $SE = 0.04$) yielded lower ratios as compared to short durations ($M = 0.99$, $SE = 0.06$) ($F(1,21) = 10.045$, $p < .01$, $\eta_p^2 = .324$) (Fig. 2). The interaction between group∗durations was insignificant ($F(2,42) = 0.79$, $p = .46$; $\eta_p^2 = .037$).

2.3.1. Accuracy of sequencing in the sequence task group

Inspection of subjects' responses revealed that they experienced little difficulty in reporting the sequence of the three background colors correctly, in any of the three temporal durations. Only a few mistakes were seen throughout the study.

2.3.2. Accuracy of temporal comparison in the temporal task group

A Friedman test was conducted on the accuracy scores of the temporal comparison in order to reveal any effects of duration. It was found that accuracy significantly decreased in parallel with decrease in duration ($\chi^2(2) = 6.727$, $p < .05$). Following up on this general result, we furthermore conducted the Wilcoxon signed rank tests in order to differentiate between each duration length.[1] Accuracy was higher for long durations ($M = 1.85$, $SD = 0.40$) as compared to medium ($M = 1.64$, $SD = 0.22$) ($Z = -2.687$, $p < .01$) and short durations ($M = 1.46$, $SD = 0.13$) ($Z = -2.443$, $p < .0167$), however, there was no significant difference between short and medium durations ($p > .0167$) (Fig. 3).

[1] The significance level for all comparisons involving the three durations was Bonferroni corrected to $p = .0167$.

2.4. Discussion

The mixed ANOVA revealed a marginally significant main effect of group. Overall, temporal reproductions tended to be shorter (and hence ratios to be lower) in the temporal task group as compared to the sequence task group, indicating that the temporal task had a higher attentional demand as compared to the sequence task, whose reproductions were close to the objective durations. As stated earlier, the concurrent temporal task that was performed during the primary temporal task may have consumed some part of the limited amount of attentional resources and thus may have led to the shortened reproductions, due to fewer pulses being received in the accumulator part of the internal clock model.

Furthermore, the mixed ANOVA revealed a significant main effect of duration, such that medium and longer durations were more severely underestimated than the shorter durations. This "duration length effect" is inconsistent with the scalar timing model (Church, 2003), however consistent with the idea that the internal representation of time is non-linear (Van Rijn & Taatgen, 2008). In non-linear models the distances between pulses increase non-linearly to the effect that less pulses will be received towards the end of the duration as compared to its beginning.

The duration length effect was mainly due to the performance of subjects in the temporal task group, considering the accurate timing in the sequence task group. Long and medium durations were more severely underestimated than the short duration.

Accuracy in the secondary sequence task was at ceiling, indicating that this secondary task imposed almost no attentional demand on

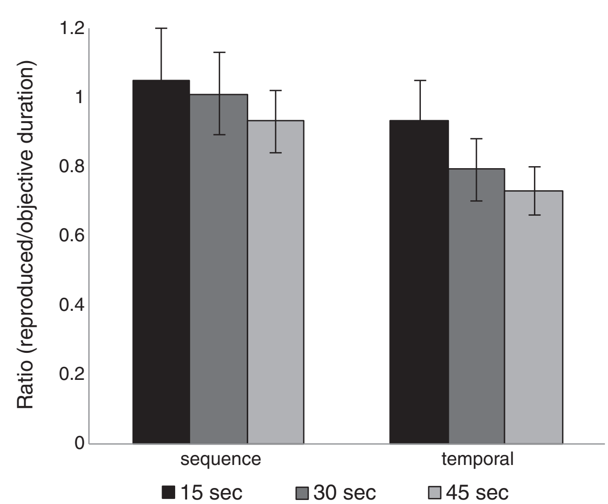

Fig. 2. Ratios of reproduced/objective durations according to group (sequence, temporal task) and durations (15, 30, 45 s) (Error bars represent SE).

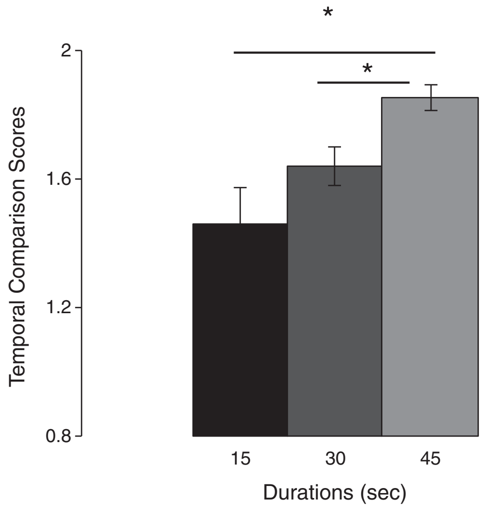

Fig. 3. Temporal comparison scores. Error bars indicate SE (temporal task group).

subjects. Hence, this task can be considered as a proper control condition for comparison with the temporal task, but also for comparison with any other attention-demanding secondary task. Accuracy in the secondary temporal task declined with decreasing duration. Remember that subjects had to order the three background colors in terms of short, medium, or long. Although subjects in the post-experimental interview were unable to report it, subjects may have used the regularity that the background colors filled equal proportions of the entire interval, as a clue for the duration of the whole interval. The possible facilitation due to this regularity cannot, however, explain why subjects had less difficulty in ordering the colors in terms of duration in the long interval. At longer durations this task may be easier since the three ordinal ranks may become more discernible as compared to short durations. The decreasing difficulty of the secondary temporal task with increasing duration might have made more attention available for the timing task at longer durations and prevented any interaction with the duration length effect.

3. Concurrent executive task effect (Experiment 2)

This experiment aimed to test the effect of a concurrent executive task on reproduced durations. In a between-subject design, a Simon task was used in the executive group and a simple choice-reaction (SCR) task implying the same visual stimuli and motor activity was used as a control group. In the Simon task, automatic processing of spatial stimuli (S) and correct response (R) selection requirements lead to S–R compatibility effects. In the case of incongruent trials a conflict between S and R locations arises that needs to be resolved. As with all interference tasks, the Simon task is expected to consume a relatively high amount of attentional resources. Durations should in particular be underestimated in the executive group as compared to the SCR group since there is a stronger effect of performing an executive task on temporal duration judgments than a similar non-executive task.

3.1. Participants

A total of 24 subjects (11 females) participated voluntarily in this study. There were 11 participants in the SCR group (*Mean age* = 25.5, *SD* = 3.5) and 13 participants in the executive group (*Mean age* = 26.1, *SD* = 2.3). All of them had normal or corrected-to-normal vision. Two participants in the executive group were excluded from the analysis after the experiment, as they reported that they had been counting while reproducing the durations.

3.2. Procedure

Subjects in the SCR group were asked to perform a non-executive task, within three different intervals (15, 30, 45 s). In the task, a red rectangle was presented either on the left or on the right ride side randomly. Participants were asked to press the left or right button according to the location of the red rectangle on the screen (left or right) while attending to the duration interval. They used both hands during the experiment. The task design was simple, however, in crucial respects mimicked the Simon task (in the executive group), namely in its perceptual workload and motor action characteristics. The two tasks solely differed in the workload due to interference as it is a characteristic only of the concurrent Simon task. After the subjects had performed the task for a given duration, they had to reproduce the previous interval (see Fig. 4a).

Durations used in the practice (12, 25, 37 s) and experimental session (15, 30, 45 s) of the executive group were the same as for the previous group. Color was the non-spatial task-relevant dimension for the Simon task. Spatial correspondence or lack of spatial correspondence between the instructed response to the stimulus color on the screen (left or right) with the response on the response-board (left or right) instantiated congruent or incongruent conditions, respectively. Rectangles in two different colors (blue and red) were presented in left or right positions randomly. The mapping rules between color and key were "red-left/blue-right". Subjects were instructed to ignore the location of the stimulus, i.e., spatial location was task-irrelevant. Subjects were instructed to react to the stimuli in accordance with the pre-specified rule as quickly and as accurately as possible and to pay attention to the temporal duration while performing the task. The reproduction part was the same as in the SCR group. The flow of the experimental session is visualized in Fig. 4b. There were again 5 trials for each length of durations, that is, 15 trials in total.

3.3. Results

The descriptive results of the reproductions and ratios (reproduced/objective durations) are given in Table 2. A mixed ANOVA with the three durations as within-subject factor and group (SCR, executive) as between-subject factor was conducted on the ratios of reproduced/objective durations. A significant main effect of group on durations was found which revealed that ratios in the executive group were lower than ratios in the SCR group ($F(1,20) = 5.441$, $p < .05$, $\eta_p^2 = .214$). There was a main effect for duration which indicated that ratios decreased as durations increased ($F(2,40) = 25.150$, $p < .01$, $\eta_p^2 = .557$). Simple contrasts revealed that medium durations ($M = 0.77$, $SE = 0.05$) had significantly lower ratios than short durations ($M = 0.89$, $SE = 0.05$, $F(1,20) = 27.924$, $p < .01$, $\eta_p^2 = .583$). Likewise, long durations ($M = 0.68$, $SE = 0.04$) had significantly lower ratios than short durations ($M = 0.89$, $SE = 0.05$) ($F(1,20) = 30.496$, $p < .01$, $\eta_p^2 = .604$) (Fig. 5). The interaction between group and durations was marginally significant ($F(2,40) = 3.268$, $p = .067$, $\eta_p^2 = .140$). Follow-up *t*-tests[2] revealed that the two groups differed significantly from each other in the long duration ($t(20) = -3.242$, $p < .01$, $\eta_p^2 = .345$), while they did not differ significantly from each other in the short and medium duration.

3.3.1. Simon task

A repeated-measures ANOVA with durations (short, medium, long) and congruency (congruent, incongruent) as within-subject factor was conducted. A main effect of congruency was found which revealed that congruent trials ($M = 538$ ms, $SE = 21$ ms) were responded to faster than incongruent trials ($M = 556$ ms, $SE = 21$ ms) ($F(1,10) = 33.340$, $p < .001$, $\eta_p^2 = .769$). Furthermore, there was a significant effect of

[2] The significance level for all comparisons involving the three durations was Bonferroni corrected to $p = .0167$.

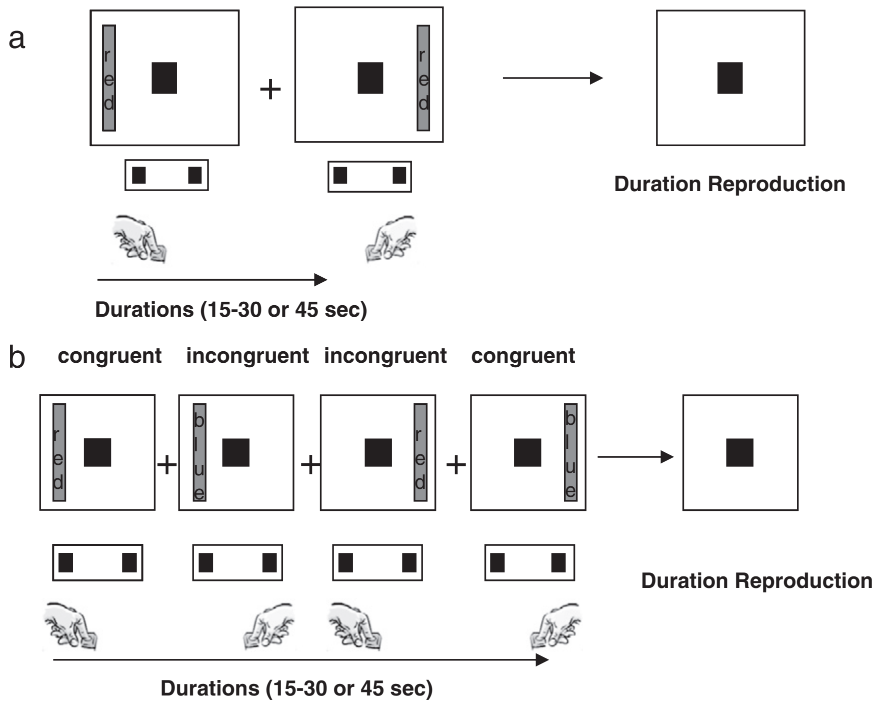

Fig. 4. Concurrent tasks of executive and SCR groups. (a) SCR group: subjects had to press the left or right key when they saw the red rectangle on the left or right side, respectively. (b) Executive group: there were two conditions in the concurrent Simon task: congruent and incongruent. In congruent trials, color and spatial location dimensions coincided (red color/left location and blue color/right location). In incongruent trials, those features interfered.

duration ($F(2,20) = 16.23$, $p < .001$, $\eta_p^2 = .62$), showing that as durations increased, RTs increased also (short: $M = 527$ ms, $SE = 19$ ms; medium: $M = 548$ ms, $SE = 23$ ms; long: $M = 565$ ms, $SE = 22$ ms). However, there was no significant interaction of durations ∗ congruency, which indicated that duration levels affected congruent and incongruent trials to the same extent.

3.4. Discussion

The significant effect of group in the primary time estimation task indicated that subjects underestimated durations more in the executive as compared to the non-executive SCR group, which acted as a control group, as expected. Tasks such as the Simon task, which demand conflict resolution and executive control draw on the same attentional resource pool as the time estimation task. The effect is quite dramatic: for the medium duration the experienced duration is in the order of 65% of the objective duration and for the long duration in the order of 55%. Attentional demands of the SCR group were much lower despite similar perceptual and motor activities to the executive group.

A duration length effect was observed again. Longer durations suffered more from cognitive demands of the secondary task than shorter durations. This effect was more pronounced in the executive group than in the SCR group, as revealed by a marginal interaction between group ∗ duration. Given these findings, we may tentatively argue that durations are judged differently for different groups. Longer durations seemed to be more underestimated than shorter durations if the attention demand of the concurrent task was high.

Subjects showed a Simon effect in the Simon task which provides good evidence that this task consumed executive resources. Furthermore, increasing RTs in the Simon task with increasing durations suggest that the primary task also withdrew attentional resources from the secondary task — the longer the more. Thus, both tasks competed for the same attentional resource.

Table 2
Reproductions according to task type (SCR, executive) and duration (15, 30, 45 s) in the time reproduction task.

	SCR group			Executive group		
	Durations					
	15 s	30 s	45 s	15 s	30 s	45 s
Reproductions (SD)	14.1 (3.4)	26.3 (7.7)	36.1 (9.1)	12.6 (4.5)	19.6 (6.8)	25.1 (8.6)
Ratio (reproduced/objective duration)	0.94 (0.23)	0.88 (0.26)	0.80 (0.20)	0.84 (0.21)	0.65 (0.18)	0.56 (0.14)

3.5. Overall ANOVA

The four groups as implicated in Experiments 1 and 2 had clearly different attention demands owing to the nature and amount of

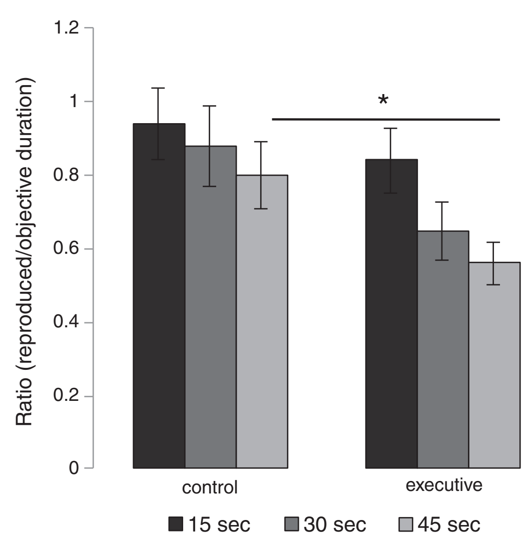

Fig. 5. Ratios of reproduced/objective durations according to task type (SCR, executive) and durations (15, 30, 45 s) (Error bars represent SE).

cognitive load they imposed on the common attention pool used for the primary and concurrent tasks. In order to provide a general overview of the behavior of all groups, we conducted an overall ANOVA with 3 within-subject levels for durations (short, medium, long) and 4 between-subject levels for groups (sequence task, SCR task, temporal task, Simon task). A main effect for group ($F(3,41) = 4.608$, $p < .01$, $\eta_p^2 = .252$) and duration ($F(2,82) = 27.234$, $p < .01$, $\eta_p^2 = .399$) was revealed, as expected. Simple contrasts for group revealed that the difference in ratios between group 3 (temporal) vs 1 (sequence) ($D = -.180$, $SE = .084$) ($p = .038$) and between group 4 (executive) vs 1 (sequence) ($D = -.315$, $SE = .086$) ($p = .001$) was significant. Simple contrasts on the durations revealed that medium durations resulted in lower ratios ($M = 0.84$, $SE = 0.03$) as compared to short durations ($M = 0.94$, $SE = 0.04$) ($F(1,41) = 24.359$, $p < .001$, $\eta_p^2 = .373$). Long durations also resulted in lower ratios ($M = 0.76$, $SE = 0.03$) as compared to short durations ($F(1,41) = 34.097$, $p < .001$, $\eta_p^2 = .454$). The interaction between group*duration was not significant.

4. General discussion

In the general discussion we will take up the effect of the attentional demands of the concurrent temporal and executive tasks on prospective duration judgment, as well as the temporal duration effect in relation to attentional demand.

4.1. Concurrent temporal task

When we distinguish our groups in terms of cognitive load types, according to Block et al. (2010), we can discern meaningful relations between the amount of underestimation in the duration judgments and concurrent secondary task demands. In the sequence group of Experiment 1, the concurrent task was very simple and hardly consumed any attentional resources — except some minimum intentional memory. Although no effects of memory demand (see Block et al., 2010) on prospective duration judgments are expected in the sequence task, it is useful to keep this task for comparison with the temporal group of Experiment 1 and with the executive group of Experiment 2, as we did in the overall ANOVA. It should be noted that Block et al.'s (2010) types of 'attentional demands' are valid for secondary non-temporal tasks such as attending to two word lists at the same time (e.g., Brown, 1985). Our concurrent temporal task in Experiment 1 has not been considered in Block et al.'s classification. It does not require divided attention since durations to be compared are presented sequentially during the primary duration. However it requires some minimal memory and attention to the relative durations of the three colors. Our temporal task is a secondary temporal task embedded in a primary duration estimation task. This is a new approach compared to the studies on multiple timing where any of the multiple overlapping intervals may have to be reproduced later (e.g., Brown & West, 1990). In this study, no consistent underestimations were found, however variability was increased due to multiple timing. Other previous studies also showed that parallel time estimations were quite accurate, contrary to our findings. In Penney, Gibbon, and Meck's (2000) study, using a bisection task, stimuli from different modalities were used which might explain why timing of multiple durations did not interfere. In Rule and Curtis (1985) study verbal estimation of averages of two intervals that started out simultaneously but stopped at different times had to be given. This task might be relatively easy since only the remaining part of the longer interval after the shorter interval had stopped required additional attention. This might give rise to accurate verbal estimations. In our concurrent temporal task, instead of (partially) overlapping intervals as in the other studies, the three intervals were sequential and required independent attention to be timed accurately in relation to each other. Furthermore, they were fully embedded in the primary duration. This may have made our secondary temporal task more difficult and may have caused inaccurate timing. Thus, our embedded design is more suitable for revealing sharing of the same attentional resource pool.

Another cognitive load type which is demanded in the concurrent task of the temporal group is the memory demand. Three background colors and their durational lengths had to be remembered by the participants. The number of colors that are to be remembered is the same in both groups of Experiment 1. Remembering the colors (in terms of their sequence in the sequence group and in terms of their duration length in the temporal group) may cause approximately the same amount of workload for both groups. Given that their memory demands are the same, only an attentional resource-demanding concurrent task such as attending to the durations of the background colors may give rise to a difference in duration reproductions, which is indeed shown in our results.

4.2. Concurrent executive task

Response demands as one cognitive load type can be differentiated as high (both sensory-perceptual and response selection/execution processes) as in active responding and low (just sensory-perceptual processes) as in passive viewing, respectively (Block et al., 2010). The concurrent task in the SCR group of Experiment 2 can be categorized under the response demand type of cognitive load and specifically under response execution processing. As the stimuli do not require any difficult response selection of the motor response (spatially oriented automatic response) they do not cause a high workload during the task.

Processing difficulty is one of the cognitive load types that affects duration judgments most. The Simon task that we used in the executive group of Experiment 2 can be classified as belonging in this group. The conflict between automatic response activation of the irrelevant spatial information and the relevant task rule (color information) in incongruent trials must be resolved in order to produce a correct response. Conflict resolution that is required for the correct performance in the Simon task affects the response selection part of the overall reaction. Automatic activation of the effector (hand) corresponding to the irrelevant spatial dimension must be inhibited in incongruent trials and then the correct response must be executed with the contralateral hand. The response execution requirements of the two groups (SCR and executive) cause the same amount of workload and consume the same amount of resources from the attentional pool. On the other hand, interference is part of the response selection of the concurrent executive task. Executive functions are in charge of conflict resolution, consuming high amounts of attentional resources from the non-temporal processor. If the two tasks differ in only their executive requirements and otherwise have identical perceptual and motor requirements, we can attribute the difference in interval reproductions to the executive nature of the concurrent task that is used. Indeed, the Simon task gave rise to a significant difference in time estimations compared to the SCR task. This finding is consistent with Zakay's (1993) finding that executive concurrent tasks (Stroop, color word associations) lead to stronger effects on duration judgments as compared to a non-executive or no concurrent task.

However, Taatgen et al. (2007) had questioned the finding that attention-demanding concurrent tasks lead to inaccurate timing and challenged the explanation of the attentional gate model. In their own study they did not observe such effects. However, their task – unlike the tasks commonly used in the prospective paradigm – was constructed such that the timing performance was only a means to the end of scoring points in a dual-task timing task (DTT). In this task, subjects – while carrying out two primary tasks, one easy (letter recognition), one hard (addition verification) – had to estimate the duration of 7 s as exactly as possible in order to enter a “high profit” interval during which they could score many points, which was the aim in this task. Subjects learned to do this exact timing in the course of many trials through implicit learning until they had established a strong and accurate representation of a 7 s interval. Neither in

Experiments 1 nor 2, the latter of which was a more difficult version of the first, did Taatgen et al. find any effect of task difficulty on timing accuracy. However, they found consistent and reliable differences in another dependent variable, namely the number of optionally given responses in the two tasks which decreased as task difficulty increased. One might consider this difference as an indirect expression of the impact of task difficulty on timing. The fact that in those trials in which a response was made, no quantitative difference in duration length was found might be due to the long learning opportunity and feedback on their accuracy which enabled subjects to reliably time the duration in the easy and difficult condition of the DTT alike. Given that Taatgen et al.'s aim – to study timing more indirectly and therefore in a more ecologically valid way – and task structure – exact timing of one interval, optional responses – their reported absence of any impact of task difficulty on timing accuracy may not seem so surprising after all. Since our own tasks were more similar to the Zakay (1993) study and more related to the attentional gate model, our results can be interpreted more meaningfully within this paradigm; however, they are not contradicted by the findings of Taatgen et al. (2007).

In summary, we could show in Experiments 1 and 2 that higher amounts of attentional demands in secondary tasks, due to various cognitive load types, affect prospective time judgments such that temporal intervals are underestimated proportionate to the amount of the withdrawn attention resource.

4.3. Duration length effect

The duration length effect refers to the situation that longer durations are more underestimated than shorter durations. There is no assumption that resource allocation decreases with duration increase in attentional models (Block & Zakay, 1997). However, there is some evidence indicating better performance of time reproduction in the prospective paradigm and of time-based prospective remembering at shorter durations (Block & Zakay, 2006; Zakay, 1993). This sensitivity to duration was also found in our two experiments: The duration length effect manifested itself reliably in all analyses. We found no underestimation at shorter durations (15 s) even in those tasks that affected timing profoundly, namely in the temporal and the executive task, where especially underestimation at longer durations were consistently found. We suggest that distinct levels of underestimations for different durations (duration length effect) are observable, in particular when subjects had to deal with relatively difficult/attention-demanding tasks. How may this finding be explained? Under the assumption of a non-linear scale, effects that decrease the rate of pulses, such as attentional effects, will affect longer durations more than shorter durations as now two factors conspire in decreasing pulses — the longer duration and the lower attention level. Towards the end of longer durations, pulses are more spaced out, due to the non-linear meter underlying time perception (Van Rijn & Taatgen, 2008). Under conditions of no or low attention-demanding concurrent tasks, longer durations do not affect temporal reproduction since with the same non-linear meter used during encoding even long durations with scarcer pulses towards the end can be faithfully reproduced at retrieval. However, under higher attention demands, pulses being lost at the end of long intervals when attentional resources are depleted, may cause a noticeable shrinkage of reproduced time.[3] Therefore, an interaction between task type and duration is expected. Despite some hints that the duration length effect was more pronounced in the high attention-demanding secondary task, namely in the executive group of Experiment 2, interactions between group ∗ duration were not consistently found in the various analyses. Whether such an interaction may exist or not is an exciting research question for future studies.

5. Conclusion

In this study we found evidence for the effect of various kinds of attentional demands of concurrent temporal and executive tasks on temporal reproductions in the prospective paradigm, in line with the categorization of cognitive load types in Block et al. (2010). As attentional demands increase the ratios of reproduced/objective durations decreased. When memory requirements are equal (as between the two tasks in Experiment 1), the effect of a resource demanding concurrent temporal task on duration judgments is still observed. This finding constitutes evidence for attentional resource sharing between two temporal tasks, which is a new finding. Moreover, conflict which is induced at the response selection level of an executive interference task (Experiment 2) had the most profound effect on time judgments among all other concurrent tasks. We also found evidence for a duration length effect such that longer durations were reliably more underestimated than shorter durations. This finding is consistent with the assumption of a non-linear time-scale underlying time perception (Van Rijn & Taatgen, 2008). Whether both effects – attentional demand and duration – interact deserves further inquiry.

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[3] We are grateful to an anonymous referee for pointing this explanation out to us.

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