COGNITIVE RESOURCES THAT HELP US TICK: RECRUITMENT OF THREE OFTEN POSTULATED CORE EXECUTIVE FUNCTIONS IN HUMAN PROSPECTIVE TIMING

Ladislav LOVAŠ, Pavol KAČMÁR

Department of Psychology, Faculty of Arts, Pavol Jozef Šafárik University in Košice
Moyzesova 9, 040 59 Košice, Slovak Republic
E-mail: ladislav.lovas@upjs.sk, pavol.kacmar@upjs.sk

Abstract: Time is ubiquitous to our everyday life, therefore, the current research was conducted with the aim to further elucidate the nascent topic of an executive resources recruitment in human prospective timing. For this purpose, a specific within-subject experimental procedure was conducted. Participants (N = 43) completed a timing task (reproduction of intervals) and tasks tapping three core executive functions (working memory, inhibitory control and cognitive flexibility), under single and dual-task conditions. Statistical analysis of the interference effect revealed disruption of timing similarly under all three core executive loads. This was reflected in under-reproductions of intervals in comparison to control conditions. Furthermore, an analysis revealed a significant effect of duration, thus, timing impairment was observed in longer durations, not in the shortest one. For an interpretation of the results, an executive-gate model (modification of an attentional-gate model) was used. Results and limitations are further discussed.

Key words: timing, time perception, cognitive load, interference effect, executive functions

Introduction

Time is ubiquitous to human experience and shapes our everyday life (Zakay, 2012). It is, therefore, no wonder that the psychology of time is "a seminal topic of psychological science, and although it entered a phase of decline and even moribund neglect, the past several decades have seen a prominent renaissance of interest" (Hancock & Block, 2012, p. 267).

Acknowledgements: This study was supported by the grant agency VEGA no. 1/0924/ 15. Authors would like to thank anonymous reviewer for helpful comments.

In particular, prominent recent research avenue is related to various aspects of time processing, specifically, how timing is affected by a *cognitive load* (e.g., Block, Hancock, & Zakay, 2010; Brown, 2006, 2008, 2010; Brown, Collier, & Night, 2013; Dutke, 2005; Ogden, Salominaite, Jones, & Fisk, 2011).

It is well known that in *retrospective paradigm* (remembered duration), participants are unaware of upcoming judgments about the length of intervals, thus, in such temporal processing, memory processes seem to be involved as higher load leads to longer time-related judgments. However, in a *prospective paradigm* (experienced duration), participants are aware of the fact that a duration estimation has to be made, therefore, attentional resources seem to be involved as higher load leads to shorter time-related judgments (Block & Zakay, 1996; Block et al., 2010; Grondin, 2008).

With an aim to understand human timing capabilities, a plethora of explanatory realms has occurred. Some suppose that duration of time is coded as an intrinsic property of non-dedicated neural activity (Irvy & Schlerf, 2008). However, the majority assume an existence of some kind of an "*internal clock*" represented by a dedicated (modular) neural mechanism and by the involvement of a network of various neural areas, such as basal ganglia, pre-supplementary and supplementary motor areas, cerebellum and prefrontal cortex (Allman, Teki, Griffiths, & Meck, 2014; Grondin, 2010; Irvy & Schlerf, 2008).

One of the most prominent prospective theories of the internal clock, *SET (Scalar expectancy theory)*, postulated by Church, Gibbon, and Meck in 1984, supposes the existence of three fundamental processes – *clock, memory, and decision*. Specifically, at the onset of the to-be-timed interval, a *pacemaker* emits pulses at a relatively constant rate. These pulses are accumulated, transferred into the *working memory store* and compared to those in the *reference memory*. Based on this comparison, *a decision* is made, producing an estimate of elapsed time (Allman et al., 2014; Church, 1984; Gibbon, Church, & Meck, 1984; Zakay & Block, 1995).

However, as it was stressed, e.g., by Brown (2008) and Block et al. (2010), SET arose from the animal timing research with lack of cognitive perspective, thus, regarding nascent findings, there exist attempts to connect basic assumptions of SET with prominent cognitive theories and processes, such as attention. In accordance, Block and Zakay (1995) have developed the augmented version of the SET called *an attentional-gate model* (AGM). Their modification is based on the addition of *the attention gate* component. This component is situated between pacemaker and accumulator (cognitive counter). Such model is graphically depicted in Figure 1 (see version A of the model).

Metaphorically speaking, in a low temporal relevance situation, the gate mediating the flow of pulses narrows due to the reduction of resources allocated to timing. In particular, if less amount of attention is directed to time (fewer resources are allocated to time due to focusing simultaneously on the non-temporal task), the gate opens narrowly, allowing to pass a smaller amount of pulses. Consequently, the smaller amount of pulses is accumulated and compared (and vice versa). This situation leads to distorted duration judgments. Specifically, depending on the task, under-estimation, under-reproduction, but over-production of intervals occur. This is phenomenologically reflected in the proverb: 'Time flies when you are having fun' (Block & Zakay, 1996; Block & Zakay, 2008; Block et al., 2010; Brown, 2008; Zakay & Block, 1995; Zakay, 2012).

Such detriment of timing caused by simultaneously focusing on a concurrent non-temporal task in dual-task condition is a "robust" and "well-replicated" phenomenon (Brown, 2010, p. 111) called the *interference effect* (Brown, 2006, 2008, 2010). Nevertheless, as it was stressed by Dutke (2005), it may be fruitful "to further specify the cognitive processes addressed by the metaphor of directing attention to time" (p. 1412).

In line with this suggestion, Block et al. (2010) conducted an extensive meta-analysis of 117 experiments, evaluating the effects of cognitive load on duration judgments. They stressed the importance of central executive processes in prospective paradigm (as an important moderator), proposing the modification of an attentional-gate model (AGM) to an *executive-gate model* (EGM), where the gate controlled by attention is replaced by the gate controlled by executive resources. Such modification is graphically depicted in Figure 1 (see version B of the model).

Executive functions (also called executive control and cognitive control; Diamond, 2013) can be characterized as a "set of general-purpose control mechanisms, often linked to the prefrontal cortex of the brain that regulate dynamics of human cognition and action" (Miyake & Friedman, 2012, p. 8) or more specifically, as a "family of top-down mental processes needed when you have to concentrate and pay attention, when going on automatic or relying on instinct or intuition would be ill-advised, insufficient, or impossible" (Diamond, 2013, p. 136).

Nevertheless, executive functions can be characterized by both unity and diversity (Miyake & Friedman, 2012; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Therefore, there is often postulated an existence of three core executive functions: *inhibitory control, cognitive flexibility, and working memory* (Diamond, 2013). Alternatively, in more concrete manner, terms inhibition, shifting, and updating are used (Miyake et al., 2000). These facets of executive functioning are the cornerstones for high-order executive functions, such as

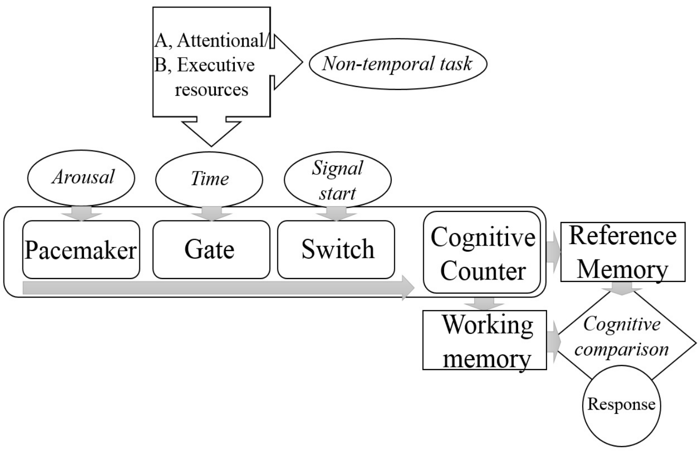

Figure 1 Schematic depiction of A, an attentional-gate model (AGM); and B, its modification, an executive-gate model (EGM), where the gate controlled by attention is replaced by the gate controlled by the executive resources (adapted from Zakay & Block 1995; Block et al., 2010)

planning, reasoning, and problem solving (Diamond, 2013) and seem to be linked to more general concepts, such as self-regulation (Hofmann, Schmeichel, & Baddeley, 2012).

In general, *working memory* (updating of working memory representations) resources are likely to be recruited in prospective timing due to processes of the online maintenance, replacing and tagging of information related to the time in working memory; *cognitive flexibility* (shifting) resources due to requirement of shifting attention back and forth between timing and non-temporal task; and *inhibitory resources* (inhibition), due to the involvement of inhibitory delay mechanism or, more specifically, due to inhibition of prepotent responses in timing task, resistance to distractors in the environment, and so on (Brown et al., 2013; Diamond, 2013; Ogden et al., 2011).

The Present Study

In the present study, we aim to further elucidate prospective human time processing in dual-task paradigm through the analysis of executive resources involvement with respect to three often postulated core executive functions (working memory, cognitive flexibility, and inhibitory control; Diamond, 2013).

Similar attempts have emerged recently, however, the results are sometimes ambiguous (compare, e.g., Brown et al., 2013, and Ogden et al., 2011). This ambiguity can be caused by many factors (Mathews & Meck, 2014). Nevertheless, in the present study, we are trying to deal with some of the recently emerged challenges by constructing specific experimental tasks and complex experimental procedure.

For example, despite the existence of a plethora of experimental methods (Grondin, 2008), four basic methods can be delineated: *the method of verbal estimation, interval reproduction, interval production and interval comparison* (Grondind, 2010). Furthermore, a growing body of empirical evidence indicates that various methods produce different results under different circumstances (Gil & Droit-Volet, 2011; Mioni, Mattalia, & Stablum, 2013; Ogden, Wearden, & Mongomery, 2014). Moreover, a widely used method in timing literature, the method of temporal production, seems to be less suitable to assess cognitive factors in timing, compared to the method of reproduction, as a various higher order cognitive functions was not reflected in production, compared to a reproduction of temporal intervals (Mioni et al., 2013; for similar results see also Baudouin, Vanneste, Isingrini, & Pouthas, 2006). Furthermore, even within various variants of the method of reproduction, differences exist, and it seems that the start-stop variant produces most accurate results (Mioni, Stablum, Mcclintock, & Grondin, 2014).

In addition, in longer (supra-second) durations, different processes, cognitive in nature (in comparison to sensory processes) (Rammsayer, 1999; Ulbricht, Churan, Fink, & Wittmann, 2007) and the prefrontal cortex (in comparison to sub-cortical areas) (Lewis & Miall, 2006; Radua, del Pozo, Gómez, Guillen-Grima, & Ortuńo, 2014; Wiener, Turkeltaub, & Coslett, 2010) seem to be involved.

Last but not least, studies use various executive tasks heterogeneous in nature (compare, e.g., Ogden et al., 2011 and Brown et al., 2013), and, therefore, it is questionable if results are not a mere reflection of such intrinsic diversity, rather than consequence of a core executive functions involvement, as it seems that various factors are capable to influence time processing (Matthews & Meck, 2014).

Based on above-mentioned delineation, the following assumptions are proposed:

The general assumption is that executive load and, in particular, increased duration of such load will affect timing captured by the method of reproduction (start-stop variant).

Specifically, based on an executive-gate model (EGM), it is assumed that reproduction of the to-be-timed interval will shorten under the executive load as less amount of "pulses" will be accumulated when gate narrows. Such narrowing of gate is caused by the depletion of shared resources between timing and non-temporal executive task.

In particular, based on Diamond's (2013) delineation of executive functions, it is assumed that in temporal reproduction, *working memory* resources will be recruited due to progressive updating of temporal and non-temporal information; *cognitive flexibility* due to shifting attention back and forth between temporal and non-temporal task; and *inhibitory control* due to top-down selectivity in attending to temporal and non-temporal aspects of a situation and by suppressing attention to other aspects. Nevertheless, it is assumed that working memory will be recruited mainly as it seems to be a basic component of temporal functioning (Ogden et al., 2011).

Furthermore, it is assumed that executive load will affect reproduction more in longer durations, as, in longer duration, more hypothetical pulses will be "lost". Additionally, it seems that in longer durations, cognitive processes seem to be involved (e.g., Ulbricht et al., 2007).

Methods

Research Sample

A total of 43 undergraduate students (39 women, 4 men) from the Pavol Jozef Šafárik University in Košice, aged 19-24 ($M = 20.84$, $SD = 1.65$), voluntarily participated in the study.

Methods and Procedure

To present stimuli and record the participant's responses, desktop computers equipped with the computer program SuperLab 4.5 were used. The experiment took place in the psychology lab of the Department of Psychology of the Faculty of Arts at the Pavol Jozef Šafárik University in Košice. The experimental session lasted approximately 90 minutes.

The whole procedure, characterized by within-subject experimental design, consisted of two conditions (single and dual-task condition), and every condition comprised of four blocks (three types of core executive load and absence of load). Each block involved repetition of sub-blocks. Each sub-block contained two parts (solving executive tasks and consequent rest, or time passing and its reproduction in the single-task condition; or solving tasks and consequent reproduction of time in the dual-task condition). Additionally, each part consisted of construction subparts of load tasks, reproduction, or relaxation phase.

In particular, the single-task condition 1 was characterized by focusing on solving the task only (100% on task) or on the presentation and reproduction of temporal intervals only (100% on time passage). The dual-task condition 2 required dividing attention between solving the task (50%) and awareness of the passage of time (50%), because of the subsequent need to reproduce a duration of the task. The order of presentation of the aforementioned conditions (condition 1 first, condition 2 second; or, alternatively, condition 2 first, 1 second) was randomized across participants.

The blocks represented types of cognitive load. Cognitive load was manipulated by the usage of superficially similar tasks. Nevertheless, these tasks were characterized by specific executive demands, tapping primarily one of three core executive functions. These tasks were based on the number-letter task principle for cognitive flexibility (mental set shifting specifically), the Eriksen flanker principle for inhibition control (distractor interference specifically), and the continuous mental math principle for working memory (updating of working memory representations specifically) (Diamond, 2013; Friedman & Miyake 2004; Miyake et al., 2000). Also used was a task that can be characterized by the absence of executive load with retaining superficial (perceptive and motor) characteristic of the aforementioned tasks (in the dual-task condition) and a task representing the static absence of load (in the single-task condition). Blocks within each of two conditions were counterbalanced with the Latin square principle (four groups per conditions were created, with specific order of blocks – ABCD, BDAC, CADB, DCBA). The nature of conditions and blocks is graphically depicted in Figure 2.

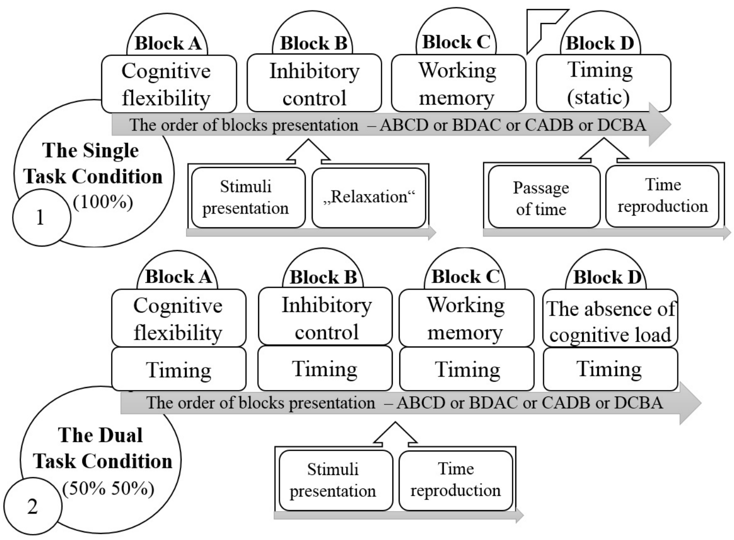

Figure 2 Graphical depiction of the general procedure in the conceptual manner, where 1 represents the single task condition and 2 represents the dual task condition

Each block consisted of multiple presentations of stimuli – and responding to them – and consequently, of duration reproduction (in the dual-task condition), or, alternatively, of a phase of "relaxation" without attention directed to time (in the single-task condition). One stimulus was presented for 1000 ms. Before the presentation of each stimulus, a fixation point was presented for 100 ms. Stimuli were presented in three ways (lengths) – 3, 15, or 27 stimuli (3300 ms, 16500 ms, or 29700 ms, respectively), creating three types of sub-blocks. The reverse counterbalancing method (ABBA) was used for presenting the length of the stimuli (the order of the length of a stimulus in every block was therefore 3, 15, 27, 27, 15, 3 stimuli).

The presented stimuli consisted of strings of letters and numbers (e.g., ##4#K##), or of picture of the clock (for the timing-only task). The type of font used was Tahoma, regular style, font size 3, black color. These stimuli were presented sequentially in four quadrants of the screen (clockwise) – upper left (X = -100, Y = 100), upper right (X = 100, Y = 100), lower right (X = -100, Y = -100) and lower left (X = 100, Y = -100). The procedure within blocks and the nature of stimuli are depicted in Figure 3.

The cognitive flexibility task (shifting of mental sets, specifically) was based on the number letter task (Miyake et al., 2000). Number-letter pairs (e.g., ##4#K##) were presented in one of four quadrants. Participants were instructed to respond with the keys F and J on the keyboard. In two upper quadrants, participants were instructed to determine whether the number was even (2, 4, 6, 8 – F key) or odd (3, 4, 7, 9 – J key). In two lower quadrants, participants were instructed to determine whether the letter was a vowel (A, E, I, U – F key) or a consonant (G, K, M, R –

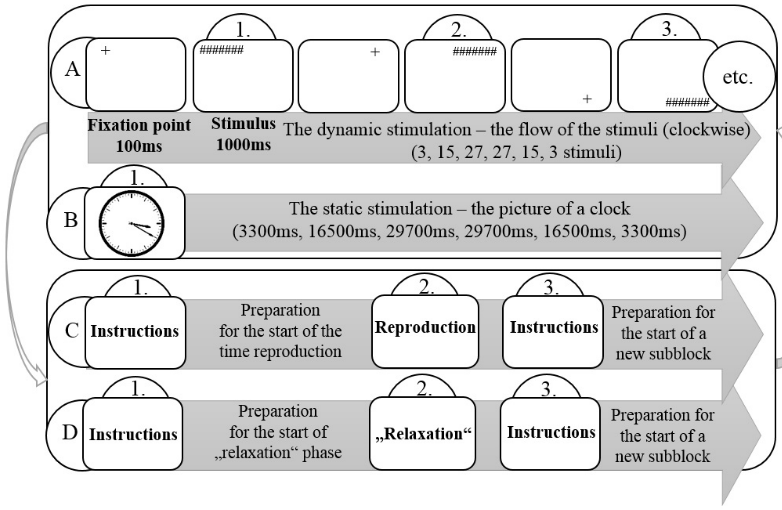

Figure 3 Graphical depiction of the procedure within the blocks in chronological manner, where A represents the dynamic stimuli presentation phase, and B represents an alternative, the static stimuli (passage of time) presentation phase; & C represents the temporal reproduction phase, and D represents an alternative, the "relaxation" phase

J key). In the training phase, participants firstly solved the upper and lower quadrant separately (no task switching involved), later solved all 4 quadrants successively in a clockwise rotation, where switching between two categories was involved.

Inhibitory control task was based on Eriksen flanker task (Eriksen & Eriksen, 1974), specifically, on its numeric version (Lindgren, Sternberg, & Rosen, 1996). Selection of the present task was based on the notion that inhibitory control consists of a variety of distinct processes (Friedman & Miyake, 2004; Diamond, 2013). For instance, the results of Friedman and Miyake's (2004) study imply that resistance to proactive interference seems to be dissociable from two other inhibitory functions – response inhibition and resistance to distractor interference, which are closely related. Furthermore, it seems that the two last mentioned functions involve active and controlled resources-dependent processing (Friedman & Miyake 2004; Brown et al., 2013; Diamond, 2013). The present task is considered as a measure of inhibitory control of attention – resistance to distractor interference (Friedman & Miyake 2004; Diamond, 2013). In this task, participants were attending to a stimulus (number) presented centrally, ignoring the surrounding distractors (flanking stimuli). Such flankers had interfering (e.g., 7778777), or a facilitating (e.g., 7777777) effect. Nevertheless, participants were instructed to press the F key for odd numbers (1, 7) and the J key for even numbers (0, 8) in the center, regardless of distractors.

The present task for updating of working memory representations was based on Diamond's (2013) suggestion that holding information only (short-term memory) differs from holding information and manipulating with it in the mind (working memory), and that mental math is a good example of such updating processes. In the present task, participants saw numbers (e.g., ###4###) successively presented in one of four quadrants (clockwise) and were instructed to mentally update a numeric value of just presented number to the value of numbers presented before. With the beginning of new rotation (four new quadrants), a new mental numeric addition started. When new number occurred, participants were instructed to press F when the value added to the values of former numbers in a given set (4 quadrants) exceeded 10, and to press J when it did not.

The dynamic absence of executive load task (dynamic control) was based on basic perceptual and motoric characteristics of the aforementioned tasks. Therefore, participants were instructed to monitor (to focus attention on) presented stimuli (e.g., ##1#5##) occurring successively in four quadrants. However, no further mental effort was needed.

Additionally, in the single-task condition, there was timing only task (static control), consisting of the presentation of a clock picture, instead of a stream of stimuli. This task was characterized by the absence of non-temporal executive load task as participants were instructed to fully attend to time while the picture of a clock was presented.

The dependent variable was timing performance. The method of reproduction was used. The reason for selection of this method was based on the evidence that the method of reproduction seems to be more suitable to assess cognitive factors than the widely used method of temporal production (Mioni et al., 2013). Furthermore, the start-stop variant of this method was selected due to a high accuracy (Mioni et al., 2014).

Results

For data transformation and consequent statistical analysis, Cedrus Data Viewer 2.0, IBM SPSS 20, Microsoft Excel 2013, and effect size spreadsheet (Lakens, 2013) were used.

To examine the influence of cognitive load on time reproduction, 5x3 ANOVA with repeated measures was conducted. Five load conditions (three executive load conditions – cognitive flexibility, working memory, inhibitory control; and two absence of an executive load conditions – dynamic and static absence of load) and three lengths of load duration (3.3 s; 16.5 s; and 29.7 s) were analyzed. For load, duration and interaction, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .57$; $\varepsilon = .62$; $\varepsilon = .29$, respectively), due to fact that Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(9) = 55.9, p < .001$; $\chi^2(2) = 40.0, p < .001$; $\chi^2(35) = 255.9, p < .001$, respectively). Additionally, effect size measures, η^2_p and η^2_G, were calculated (Lakens, 2013).

Firstly, time reproductions were converted to a timing indicator called *duration judgment ratio* (DJR), calculated as a ratio of subjective reproduction to its objective duration (Block et al., 2010). For instance, the value .9 means that the reproduction is more accurate, compared to the value .7 (where underreproduction occurred due to fact that subjective time ran faster), nevertheless, it is not as precise as the value 1.0.

The statistical analysis revealed a significant effect of various load conditions on time reproductions (F (2.297, 96.459) = 26.517, $p <$ .001, $\eta^2_p = .39$, $\eta^2_G = .13$). Post hoc analysis with Bonferroni correction revealed that there were no significant differences in reproduction of time across the three executive load conditions (for all 3 comparisons, $p > .05$). However, there were significant differences between each of these (3) conditions and the absence of executive load conditions (both static and dynamic) (for all 6 comparisons, $p < .05$). Additionally, there was no statistically significant difference between means across absence of cognitive load conditions (static and dynamic absence of load) ($p > .05$). In particular, time reproduction was better and relatively accurate in both control conditions, characterized by absence of executive load (Mean DJR .930 for static, and .966 for dynamic absence). However, time reproduction was significantly worse similarly in all of executive load conditions (inhibitory control, cognitive flexibility, working memory), with a tendency to under-reproduction of durations (DJR .700, .681, and .736, respectively). Means and standard errors are depicted in Table 1.

Furthermore, the statistical analysis revealed a significant effect of duration of the load ($F(1.232, 51.760) = 70.122, p < .001$; $\eta^2_p =$ .63; $\eta^2_G = .20$). Post hoc analysis with Bonferroni correction revealed that there were significant differences in quality of time reproduction between all three durations of the stimuli presentation ($p < .05$). Furthermore, quality of time reproductions dropped as a function of length of the presented stimuli. The best and relatively correct reproduction of time was presented in the 3 stimuli condition (Mean DJR 1.009), worse quality of time reproduction with tendency to underestimation was presented in the 15 stimuli condition (Mean DJR .758) and the worst quality of time reproduction was presented in the 27 stimuli condition (Mean DJR .641). Means and standard errors are depicted in Table 2.

Table 1 *Means and standard errors of duration judgment ratio scores (DJRs) across various executive load conditions*

Character of load	*The type of the task*	*Mean*	*SE*
Executive load	Inhibitory control (Resistance to distractors)	.700	.031
	Cognitive flexibility (Mental set shifting)	.681	.024
	Working memory (Updating of)	.736	.028
Absence of executive load	Static absence	.930	.044
	Dynamic absence	.966	.027

Note. DJRs were calculated as subjective estimation of the time divided by the its objective duration, therefore, value > 1 represents over-reproduction; = 0 accurate reproduction; < 1 under-reproduction

Table 2 *Means and standard errors of duration judgment ratio scores across various duration conditions*

Number of stimuli presented	*Mean*	*SE*
3 stimuli (3300ms)	1.009	.036
15 stimuli (16500ms)	.758	.023
27 stimuli (29700ms)	.641	.022

Note. Value > 1 represents over-reproduction; = 0 accurate reproduction; < 1 under-reproduction

In addition, statistical analysis revealed a small, but significant effect of the interaction between cognitive load condition and duration of presented stimuli condition (F(2.279, 95.739) = 3.510, $p < .05$, $\eta_p = .08$, $\eta_G = .03$). Nevertheless, with the aim to further elucidate nuances of the length and load interaction, additional statistical analysis was conducted, separating three lengths (3.3 s; 16.5 s; 29.7 s). Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .44$; $\varepsilon = .70$; $\varepsilon = .68$, respectively), due to fact that Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(9) = 88.4$, $p < .001$; $\chi^2(9) = 36.1$, $p < .001$; $\chi^2(9) = 42.6$, $p < .001$; respectively). In the shorter length condition (3 stimuli/3.3 s), there was not a statistically significant difference in time reproduction across load and absence of load conditions (F(1.755, 73.698) = 1.541, $p = .222$). However, in the15 stimuli condition (16500 ms) and in the 27 stimuli condition (29700 ms), there were statistically significant differences (F(2.784, 116.912) = 31.227, $p < .001$, $\eta_p = .43$, $\eta_G = .30$; and F(2.708, 113.725) = 36.687, $p <$

Table 3 *Further means and standard deviations of duration judgment ratio scores across load and duration conditions*

Character of load	*Type of the task*	*3 stimuli (3300ms)*		*15 stimuli (16500ms)*		*27 stimuli (29700ms)*	
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Executive load	Inhibitory control	.91	.24	.65	.27	.54	.22
	Cognitive flexibility	.96	.25	.61	.22	.47	.15
	Working memory	1.02	.32	.65	.21	.54	.21
Absence of executive load	Static absence	1.11	.78	.89	.27	.79	.25
	Dynamic absence	1.03	.31	.99	.22	.87	.26

Note. Value > 1 represents over-reproduction; = 0 accurate reproduction; < 1 under-reproduction

.001, $\eta^2_p = .47$, $\eta^2_G = .33$, respectively). Post hoc analysis revealed similar results as depicted above. There was no difference between load conditions, nor between control conditions (all $p > .05$), however, there were significant differences between core executive load conditions and control conditions (all comparisons $p < .05$). Means and standard errors are depicted in Table 3.

Discussion

Considering human timing capabilities, some researchers assume the existence of some kind of an internal clock device (e.g., Allman et al., 2014). The basic assumption is that the pacemaker emits pulses that are stored and consequently compared to those in reference memory. Based on such comparison, a decision regarding duration is made. Nevertheless, theoretical and empirical evidence of the involvement of attention, and more recently executive processes, in prospective timing has emerged (e.g., Block et al., 2010; Brown et al., 2013; Ogden et al., 2011). Because of limitations in the capacity of such processes, the interference effect, a disruption of timing in dual-task paradigm, was examined in the present study.

With respect to timing performance, results of the present study indicate that executive load significantly interferes with prospective timing. Statistical analysis revealed that under executive load conditions, there was a significant decrease of timing accuracy, reflected in under-reproduction of intervals (time ran faster) (mean duration judgment ratio score was .700 for inhibitory control; .681 for cognitive flexibility; and .736 for working memory load condition) compared to control conditions, characterized by absence of executive load (.930 for static control and .966 for dynamic absence control condition).

In particular, the observed interference between timing and the mental flexibility (specifically, mental set shifting task based on the number-letter principle) is in line with the observation that individual differences in shifting influenced reproduction accuracy (Ogden et al., 2014), with the observation of the existence of the mutual interference between global-local task and timing (production of 5 s intervals) (Brown et al., 2013), as well as with some other studies (e.g., Zakay & Block, 2004).

Nevertheless, in the study of Ogden et al. (2011), production of 2 s intervals was not affected by plus-minus task (however, time performance was more variable under the dual-task condition). Similarly, Fortin, Schweickert, Gaudreault, & Viau-Quesnel (2010) did not find an interference effect between shifting in specific task and timing (production of 2 s intervals). Regarding such discrepancies, the present study offers a preliminary explanation. In the current study, a disruption of timing was evident in the 16.5 s and 29.7 s conditions, but not in the 3.3 s condition, indicating the involvement of higher cognitive resources in a timing of longer durations (Mioni et al., 2013; Ulbricht et al., 2007). Therefore, former observation of the absence of timing disruption can be explained by the usage of too brief intervals (2 s).

The observed disruption of timing performance under working memory task (updating of working memory based on the continuous mental math principle) and inhibitory control task (inhibition based on Eriksen flanker principle) is mainly in line with majority of relevant recent research literature (for further review see e.g., Brown et al., 2013). Nevertheless, some of the eventual discrepancies can be additionally explained by the above-mentioned reason and other factors, such as difficulty of a task (Ogden et al., 2014).

However, it is important to note that in the present study, temporal performance was assessed by method of reproduction, in contrast to a majority of aforementioned studies, where the method of temporal production was the one most commonly used (e.g., Brown et al., 2013; Ogden et al., 2011). This is important to note, as recent studies indicate that there can be differences in the usage of various methods, especially regarding executive (Mioni et al., 2013) and, specifically, core executive function tasks (Ogden et al., 2014).

Present disruption of temporal performance can be interpreted within the internal clock model scope with an additional accent on the importance of the executive processes, e.g., such as modified attentional-gate model, an executive-gate model (AMG), proposed by Block et al. (2010), where the gate controlled by attention is replaced by the gate controlled by executive processes. As fewer executive resources are allocated to timing (due to recruitment of distractor executive task), lesser amount of hypothetical pulses is accumulated, leading to an under-reproduction of the to-be-timed interval. Moreover, such loss of pulses is more obvious in longer durations.

This is conceptually in line with nascent observations of the involvement of the prefrontal cortex in human timing (e.g., Allman et al., 2014; Wiener et al., 2010) and in executive functioning (Diamond, 2013; Miyake & Friedman, 2012). For instance, Wiener, Turkeltaub, and Coslett (2010), in their meta-analysis of the set of 446 activation foci across 41 neuroimaging studies of interval timing, in fact, found recruitment of cortical networks, such as prefrontal cortex in supra-second intervals, in comparison to the engagement of the subcortical networks in sub-second interval timing. In accordance, Lewis and Miall (2006) conducted a meta-analysis, revealing the recruitment of right hemispheric prefrontal and parietal cortices in cognitively controlled timing (characterized by a combination of factors, such as supra-second intervals; discontinuous, non-repeated and unpredictable fashion; and not defined by motor control). Furthermore, a more recent meta-analysis of neuroimaging studies conducted by Radua et al. (2014) provides an additional evidence that neural basis associated with the working memory and executive functions are, indeed, engaged during the time processing.

Furthermore, such neuroanatomical evidence is in line with conceptual suggestion proposed by Brown (2006) who stressed that "the conscious, intentional nature of prospective timekeeping, requiring continuous monitoring and updating of the passage of time, logically aligns time perception with executive functioning" (p. 1466).

However, regarding the proposed distinction of three core executive functions, in the present study, there were no significant differences in time processing across the three core executive load conditions (inhibitory control, cognitive flexibility, working memory). This pattern of results can be, in some sense, interpreted within the scope of the unity/diversity issue of executive functions. This issue questions the extent to which executive functions can be considered as a reflection of the same underlying mechanism (same common basis on a more general level) (Miyake & Friedman, 2012; Miyake et al., 2000). For instance, according to Miyake and Friedman (2012), common EF (the variance of which is explained by inhibition's variance) "is about one's ability to actively maintain task goals and goal-related information and use this information to effectively bias lower-level processing" (p. 11).

Additionally, absence of differences in duration reproduction between two control conditions (static and dynamic absence) indicates the importance of the mental effort in general, rather than perceptual and motor factors, in influencing human prospective timing. This pattern of results is in line with meta-analyses of neural studies delineated above (e.g., Lewis & Miall, 2006).

Therefore, regarding the present results and potential development of an executive-gate model (EGM), there is preliminary evidence, pointing out that there is no need for further fractionalization of executive resources in this model, differentiating three core executive resources in human prospective timing. However, for a definitive conclusion, a further deliberate investigation is needed.

Nevertheless, it is important to note that, regarding this issue, there exists a more parsimonious account, which conceptually rethinks the attention/executive gate model and proposes an explanation in line with the present findings. Phillips (2012, 2013) attributes passage of time to internal attention that "should be identified with mental activity within our non-perceptual stream of consciousness: conscious thinking in the broadest sense of the term" (p. 278), and, therefore, providing key measure of perceived duration not in terms of vague metaphorical "pulses", but in terms of concrete "thoughts", operationalized as a "number of changes in stream of thoughts, where thought is intended to cover all aspects of non-perceptual consciousness, including mental imagery and episodic memory" (p. 289). Therefore, "time may seem to pass quickly when a lot of processing is done to obtain a few solutions, but it may seem to pass slowly while one is performing a tedious task in which all the substeps are remembered" (p. 291) (for further discussion, see Phillips, 2012).

In conclusion, present results indicate that timing is moderated by executive processes, however, probably in general. Nevertheless, further and definitive conclusions should be drawn with caution because of the limitations of the current and former research. For instance, despite evidence for the existence of three core executive functions, this does not necessarily mean that they are the only executive functions, or "fundamental units of cognition" (Miyake et al., 2000, p. 89). Additionally, in spite of the present effort to take into account various important factors (various length of intervals, used methods, etc.), additional systematic incorporation of a plethora of deliberately chosen tasks, further manipulation of the difficulty of the tasks and attentional demands (as in Brown et al.'s, 2013 study) can be a fruitful invitation for future research. Furthermore, deliberate incorporation of a variety of widely used temporal tasks can be fruitful as well (Mioni et al., 2013; Ogden et al., 2014). Moreover, last but not least, analysis of bidirectional interference (mutual disruption of timing and executive tasks performance), which is beyond the scope of the present article, can, indeed, provide valuable insights into the nature of human timing resources (Brown, 2008; Brown et al., 2013; Ogden et al., 2011).

Conclusion

The present study aimed to further elucidate the issue of the involvement of three often postulated core executive functions (inhibitory control, working memory, and cognitive flexibility) in human prospective timing. First such attempts have emerged recently, however, ambiguity of results has occurred. Unfortunately, this ambiguity can be caused by a variety of factors. Therefore, some of them were taken into account in the present study, resulting in the creation of specific complex experimental procedure.

The interference effect, a disruption of timing performance due to the involvement of specific distractor tasks, was analyzed. An analysis revealed that prospective timing was disrupted by executive load. Specifically, there was a significant decrease of timing accuracy, reflected in under-reproduction of temporal intervals (shortening of perceived time – subjective time runs faster). However, timing impairment was similar across each of three core executive function tasks. This probably speaks to the unity/diversity issue, revealing the existence of some common shared executive resources in human prospective timing.

Furthermore, this timing impairment was not observed in the shortest interval condition and subsequently increased with the increment in duration of the to-be-timed interval, implying the involvement of cognitive resources especially in the reproduction of longer duration.

Present results are compared with empirical evidence and further discussed within the scope of an executive-gate model (EGM) and within an alternative explanation identifying underlying prospective timing mechanism in internal attention to the stream of conscious thoughts.

Nevertheless, a definitive conclusion from the present and former studies can be drawn only with caution due to the specific issues regarding timing and executive functions research (e.g., the impurity problem) and limitations of the present study. Further research, therefore, calls for taking into account specific nuances of executive functions and various factors responsible for impairing of prospective timing. Furthermore, additional analysis of bidirectional interference can provide further valuable insights into the nature of human prospective timing.

Received January 20, 2015

References

Allman, M. J., Teki, S., Griffiths, T. D., & Meck, W. H. (2014). Properties of the internal clock: First- and second-order principles of subjective time. *Annual Review of Psychology*, *65*(1), 743-771. http://dx.doi.org/10.1146/annurev-psych-010213-115117

Baudouin, A., Vanneste, S., Isingrini, M., & Pouthas, V. (2006). Differential involvement of internal clock and working memory in the production and reproduction of duration: A study on older adults. *Acta Psychologica*, *121*(3), 285-296. http://dx.doi.org/10.1016/j.actpsy.2005.07.004

Block, R. A., & Zakay, D. (1996). Models of psychological time revised. In H. Helfrich (Ed.), *Time & Mind* (pp. 171-195). Kirkland, Hogrefe & Huber Publishers.

Block, R. A., & Zakay, D. (2008). Timing and remembering the past, the present, and the future. In S. Grondin (Ed.), *Psychology of time* (pp. 367-394). England: Elsevier Publishers.

Block, R. A., Hancock, P. A., & Zakay, D. (2010). How cognitive load affects duration judgments: A meta-analytic review. *Acta Psychologica*, *134*, 330-343. http://dx.doi.org/ 10.1016/j.actpsy.2010.03.006

Brown, S. W. (2006). Timing and executive function: Bidirectional interference between concurrent temporal production and randomization tasks. *Memory and Cognition*, *34*, 1464-1471. http://dx.doi.org/10.3758/BF03195911

Brown, S. W. (2008). Time and attention: Review of the literature. In S. Grondin (Ed.), *Psychology of time* (pp. 112-125). England: Elsevier Publishers.

Brown, S. W. (2010). Timing, resources, and interference: attentional modulation of time perception. In A. C. Nobre & J. T. Coull (Eds.), *Attention and time* (pp.107-121). Oxford: OUP. ISBN-13: 9780199563456

Brown, S. W., Collier, S. A., & Night, J. C. (2013). Timing and executive resources: Dual-task interference patterns between temporal production and shifting, updating, and inhibition tasks. *Journal of Experimental Psychology. Human Perception & Performance*, *39*(4), 947-963. http://dx.doi.org/10.1037/a0030484

Church, R. M. (1984). Properties of the internal clock. *Annals of the New York Academy of Sciences*, *423*(1), 566-582. http://dx.doi.org/10.1111/j.1749-6632.1984.tb23459.x

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135-168. http://dx.doi.org/10.1146/annurev-psych-113011-143750

Dutke, S. (2005). Remembered duration: Working memory and the reproduction of intervals. *Perception & Psychophysics*, *67*(8), 1404-1413. http://dx.doi.org/10.3758/BF03193645

Eriksen, B. A., & Eriksen, C. W. (1974). "Effects of noise letters upon identification of a target letter in a non-search task". *Perception and Psychophysics*, *16*(1), 143-149. http://dx.doi.org/10.3758/BF03203267

Fortin, C., Schweickert, R., Gaudreault, R., & Viau-Quesnel, C. (2010). Timing is affected by demands in memory search but not by task switching. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(3), 580-595. http://dx.doi.org/10.1037/a0017639

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent variable analysis. *The Journal of Experimental Psychology: General*, *133*(1), 101-135. http://dx.doi.org/10.1037/0096-3445.133.1.101

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. In J. Gibbon & L. G. Allan (Eds.), *Annals of the New York Academy of Sciences: Timing and time perception*. New York: New York Academy of Sciences, *423*, 52-77. http://dx.doi.org/10.1111/j.1749-6632.1984.tb23417.x

Gil, S., & Droit-Volet, S. (2011). "Time flies in the presence of angry faces"…depending on the temporal task used! *Acta Psychologica*, *136*(3), 354-362. http://dx.doi.org/10.1016/j.actpsy.2010.12.010

Grondin, S. (2008). Methods for studying psychological time. In S. Grondin (Ed.), *Psychology of time* (pp. 51-75). England: Elsevier Publishers.

Grondin, S. (2010). Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception &Psychophysics*, *72*(3), 561-582. http:/ /dx.doi.org/10.3758/APP.72.3.561

Hancock, P. A., & Block, R. A. (2012). The psychology of time: A view backward and forward. *American Journal of Psychology*, *125*, 267-274. http://dx.doi.org/ 10.5406/amerjpsyc.125.3.0267

Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends in Cognitive Sciences*, *16*(3), 174-180. http://dx.doi.org/10.1016/j.tics.2012.01.006

Irvy, R. B., & Schlerf, E. J. (2008). Dedicated and intrinsic models of time perception. *Trends in cognitive science*, *12*(7), 273-280. http://dx.doi.org/10.1016/j.tics.2008.04.002

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*, 1-12. http://dx.doi.org/10.3389/fpsyg.2013.00863

Lewis, P. A., & Miall, R. C. (2006). Remembering the time: A continuous clock. *Trends in Cognitive Sciences*, *10*(9), 401-406. http://dx.doi.org/10.1016/j.tics.2006.07.006

Lindgren, M., Stenberg, G., & Rosen, I. (1996). Effects of nicotine in visual attention tasks. *Human Psychopharmacology*, *11*, 47-51. http://dx.doi.org/10.1002/(SICI)1099-1077(199601)11:1<47::AID-HUP743>3.0.CO;2-1

Matthews, W., & Meck, W. (2014). Time perception: The bad news and the good. Wiley Interdisciplinary Reviews. *Cognitive Science*, *5*(4), 429-446. http://dx.doi.org/10.1002/wcs.1298

Mioni, G., Mattalia, G., & Stablum, F. (2013). Time perception in severe traumatic brain injury patients: A study comparing different methodologies. *Brain and Cognition*, *81*(3), 305-312. http://dx.doi.org/10.1016/j.bandc.2012.12.005

Mioni, G., Stablum, F., Mcclintock, S., & Grondin, S. (2014). Different methods for reproducing time, different results. *Attention, Perception & Psychophysics*, *76*(3), 675-681. http://dx.doi.org/10.3758/s13414-014-0625-3

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8-14. http://dx.doi.org/10.1177/0963721411429458

Miyake, A., Friedman, N., Emerson, M., Witzki, A., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100. http://dx.doi.org/10.1006/cogp.1999.0734

Ogden, R. S., Salominaite, E., Jones, L. A., Fisk, J. E., & Montgomery, C. (2011). The role of executive functions in human prospective interval timing. *Acta Psychologica*, *137*(3), 352-358. http://dx.doi.org/10.1016/j.actpsy.2011.04.004

Ogden, R. S., Wearden, J. H., & Montgomery, C. (2014). The differential contribution of executive functions to temporal generalisation, reproduction and verbal estimation. *Acta Psychologica*, 152, 84-94. http://dx.doi.org/10.1016/j.actpsy.2014.07.014

Phillips, I. (2012). Attention to the passage of time. *Philosophical Perspectives*, *26*(1), 277-308. http://dx.doi.org/10.1111/phpe.12007

Phillips, I. (2013). XII—Perceiving the passing of time. In *Proceedings of the Aristotelian Society, 113*(3), 225-252. http://dx.doi.org/10.1111/j.1467-9264.2013.00353.x

Radua, J., del Pozo, N. O., Gómez, J., Guillen-Grima, F., & Ortuño, F. (2014). Meta-analysis of functional neuroimaging studies indicates that an increase of cognitive difficulty during executive tasks engages brain regions associated with time perception. *Neuropsychologia, 58*, 14-22. http://dx.doi.org/10.1016/j.neuropsychologia.2014.03.016

Rammsayer, T. H. (1999). Neuropharmacological evidence for different timing mechanisms in humans. *The Quarterly Journal of Experimental Psychology: Section B, 52*(3), 273-286. http://dx.doi.org/10.1080/713932708

Ulbrich, P., Churan, J., Fink, M., & Wittmann, M. (2007). Temporal reproduction: Further evidence for two processes. *Acta Psychologica*, *125*(1), 51-65. http://dx.doi.org/10.1016/j.actpsy.2006.06.004

Wiener, M., Turkeltaub, P., & Coslett, H. B. (2010). The image of time: A voxel-wise meta-analysis. *Neuroimage*, *49*(2), 1728-1740. http://dx.doi.org/10.1016/j.neuroimage.2009.09.064

Zakay, D., & Block, R. A. (1995). An attentional-gate model of prospective time estimation. In M. Richelle, V. De Keyser, G. d'Ydewalle, & A. Vandierendonck (Eds.), *Time and the dynamic control of behavior* (pp. 167-178). Liège, Belgium: Universite de Liège.

Zakay, D., & Block, R. A. (2004). Prospective and retrospective duration judgments: An executive-control perspective. *Acta Neurobiologiae Experimentalis*, *64*(2), 319-328. http://dx.doi.org/10.3758/bf03209393

Zakay, D. (2012). Experiencing time in daily life. *Psychologist*, *25*(8), 578-581.