NeuroImage 226 (2021) 117601

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Boosting working memory with accelerated clocks

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ARTICLE INFO

Keywords:
Time perception
Subjective timepassage
Working memory
Task engagement
Posterior alpha
Frontal theta
CDA

ABSTRACT

Our perception of time varies with the degree of cognitive engagement in tasks. The perceived passage of time accelerates while working on demanding tasks, whereas time appears to drag during boring situations. Our experiment aimed at investigating whether this relationship is mutual: Can manipulated announcements of elapsed time systematically affect the attentional resources applied to a cognitive task? We measured behavioral performance and the EEG in a whole report working memory paradigm with six items of different colors that each had to be reported after a short delay period. The 32 participants were informed about the current time after each 20 trials, while the clock was running at either 100% (normal), 120% (fast), or 80% (slow) of normal clock speed depending on the experimental block. The mean number of correctly reported colors per trial was significantly increased in the fast as compared to the slow and normal clock conditions. In the EEG, we focused on neural oscillations during working memory encoding and storage. As an electrophysiological correlate of task engagement, frontal theta power during the storage interval was increased in the fast clock condition. Also, the power of frontal theta oscillations predicted the number of correctly reported colors on a single-trial basis. This shows that a covert manipulation of clock speed can lead to an improvement in cognitive performance, presumably mediated by a higher allocation of attentional resources resulting from an adaptation of the subjective passage of time during an experiment.

1. Introduction

Our perception of time is highly subjective, showing strong intra-individual variability and dependence on a subject's affective and cognitive states. A large number of experimental studies have investigated and confirmed the common phenomena of slowed passage of subjective time in negative mood (Droit-Volet, 2013; Droit-Volet and Wearden, 2015; Wearden, 2015), depression (Bschor et al., 2004; Oberfeld et al., 2014; Thönes and Oberfeld, 2015), and boredom (Watt, 1991; Wearden et al., 2014) on the one hand, and its acceleration during situations of sustained attention (Zakay and Block, 1996) and flow-like experiences (Brown, 2008; Csikszentmihalyi and Csikszentmihalyi, 1992) on the other hand. Some recent studies aim at investigating whether this relationship between cognitive and affective processes and time perception is uni- or bi-directional (mutual) in nature (Christandl et al., 2018; Park et al., 2016; Tanaka and Yotsumoto, 2017; Thönes et al., 2018): Is it possible to systematically induce specific temporal cognitions / expectations, thereby modifying (improving) affective and cognitive processes, such as mood, motivation, and sustained attention. Therefore, in the present study, we developed an experimental design to investigate to what extent manipulated information about elapsed time can impact cognitive processes in a highly demanding working memory (WM) task. In addition to behavioral performance, we measured neural activity from the electroencephalogram (EEG) that is related to processes of attentional task engagement and WM storage.

Over the last decades, research in the field of time perception has provided a large body of literature on endogenous and exogeneous factors affecting our perception of duration and time passage (for recent reviews, see Grondin, 2010; Matthews and Meck, 2016). Most prominently, naïve theories and common sayings, such as 'time flies when you are having fun' or 'a watched pot never boils', have been investigated and confirmed empirically within theoretical frameworks comprising cognitive and affective factors that emphasize the importance of attentional and emotional processes in our experience of time. The cognitive pacemaker-accumulator models of time perception, for example, refer to the mental representation of duration (Gibbon et al., 1984; Treisman, 1963). Basically, these models propose an internal clock that consists of a pacemaker emitting pulses and an accumulator counting these pulses. The amount of counted pulses is positively correlated with the perceived duration of an event, i.e., the more pulses are accumulated, the longer the perceived duration. The clock device is integrated into an information-processing system that comprises attentional and memory components. In order to consider and conceptualize cognitive

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https://doi.org/10.1016/j.neuroimage.2020.117601
Received 26 October 2020; Accepted 23 November 2020
Available online 26 November 2020

processes, Block and Zakay (Block and Zakay, 1996), for example, propose an attentional gate between pacemaker and accumulator regulating the amount of pulses that can reach the accumulator (Lejeune, 1998). The gate's width is controlled by the amount of attentional resources allocated to time. The more attention is focused on other events or tasks, the narrower the gate, and the less pulses can reach the accumulator. Accordingly, the model accounts for the frequently reported underestimation of duration in situations when a subject is focused on a specific task (e.g., Conti, 2001), which clearly suggests that cognitive processes affect perceived time (e.g., Thönes and Hecht, 2017).

It remains widely uninvestigated, however, whether manipulating information about time passage may also affect cognitive processes. In fact, several past studies from different lines of research suggest that such a manipulation can succeed by providing the subject with rigged clocks in the lab environment (Craik and Sarbin, 1963; London and Monello, 1974; Park et al., 2016; Rotter, 1969) or simply by means of false instructions regarding elapsed or to be expected duration during an experiment (Christandl et al., 2018; Tanaka and Yotsumoto, 2017). Accordingly, when subjects are led to believe that more time had passed than actually did pass (e.g., by means of a fast running clock), they experience a discrepancy between the amount of time that passed subjectively and the amount of passed time as indicated by the rigged clock. This discrepancy in turn may lead to an adaptation of the subjective experience of time passage. The opposite effect can be observed when slowed clocks or other temporal cues are presented that understate (elapsed) duration (for a recent review, see Thönes et al., 2018). These manipulations have been reported to influence affective responses and motivational processes (London and Monello, 1974; Sackett et al., 2010), behavioral performance in simple cognitive tasks (McGrath and O'Hanlon, 1967; Nelson et al., 1984), and even physiological parameters, such as blood glucose level (Park et al., 2016; Schachter and Gross, 1968). A recent investigation by Christandl et al. (2018) has shown that false information about elapsed time during a cognitive task led to differences in flow experience, i.e. the motivating feeling of a mental state of complete concentration. It is therefore reasonable to assume that manipulated time announcements should affect the attitude towards an executed task and potentially the extent of cognitive resources a subject is willing to engage in it.

For the first time, in the present study, we have investigated the neural basis of the influence of manipulated time announcements on higher-level cognitive mechanisms. For this purpose, we measured the capacity of visual WM in a whole-report task that requires to store and subsequently report the colors of six visual stimuli. The color for each individual stimulus was drawn without replacement from a set of eight different colors. While this task clearly overstrains average WM capacity, it provides the possibility to measure the trial-by-trial variability in WM performance (Adam et al., 2015). In three separated experimental blocks, to each subject, we provided correct (block 1) and false announcements of time repeatedly understating (80%) or overstating (120%; counter-balanced block order between subjects) elapsed duration after a series of trials. We expected higher cognitive performance, that is, more correctly reported items, in the fast- relative to the slow-clock condition.

Moreover, the trial-by-trial measure of performance allowed for distinguishing between two alternative causes for the hypothesized impact of subjective time on WM: On the one hand, an effect on the average number of correctly reported colors might result from a modulation of the number of trials in which participants featured a complete attentional disengagement from the task (i.e., an attentional lapse) and were thus unable to encode and actively store any task-related information in WM (e.g., Rouder et al., 2008; Sims et al., 2012; Van den Berg et al., 2014). In this sense, a modulation of subjective time passage would bias the participants' motivation to allocate attentional resources on the task at hand. While decelerated clocks would increase the tendency to give up on the rather difficult task and, for example, get distracted by task-irrelevant thoughts (Smallwood and Schooler, 2006), accelerated clocks would decrease the prevalence of complete attentional disengagement. On the other hand, an experimental bias of subjective time passage might influence the attentional resources applied to the task in a more graded fashion, bringing about higher performance in the accelerated clock conditions due to overall increased attentional resources engaged on the task. Whereas a modulation of attentional lapses should be reflected primarily in the number of trials with extreme low performance (less than 2 out of 6 items correct; cf. Adam et al., 2015), a graded modulation should be evident in a uniform difference in the number of correctly reported items between the clock conditions.

In the EEG, we assumed effects on attentional and WM processes to be reflected in modulations of oscillatory power in the theta (∼4-7 Hz) and alpha frequency range (∼8-14 Hz). Previous research has indicated that the power of frontal theta oscillations is generally related to executive control processes (Cavanagh and Frank, 2014). More specifically, frontal theta power has been shown to be increased with higher WM load (Jensen and Tesche, 2002; Onton et al., 2005) or when retrieving or manipulating information stored in WM (Hsieh and Ranganath, 2014; Itthipuripat et al., 2013). In a six-item whole report task highly comparable to our experimental procedure, frontal theta power prior to the presentation of the memory array and during WM encoding and storage predicted the number of correctly reported items and was thus linked to the varying amount of attentional resources applied to the task (Adam et al., 2015).

Likewise, posterior alpha power has been shown to vary with the amount of information stored in WM, but the direction of alpha power changes was rather inconsistent between different studies. Studies indicating an increase of posterior alpha power with WM load usually argue that alpha oscillations protect new memory content from interference by prior information or new sensory signals (Bonnefond and Jensen, 2012; Jensen et al., 2002; Wianda and Ross, 2019). On the contrary, the suppression of posterior alpha power relative to an oscillatory baseline has been shown to get stronger with increasing WM load. This effect has been linked to the need to individuate items during WM storage (Fukuda et al., 2015). In favor of the latter assumption, posterior alpha power was more suppressed during the delay interval for high performance trials in the whole report WM task by Adam and colleagues (Adam et al., 2015). Therefore, using a similar task procedure, we expected to find this relationship in the current experiment.

Furthermore, the contralateral delay activity (CDA) effect in the event-related potential (ERP) of the EEG has been related to the active storage of visuo-spatial information in WM (Vogel and Machizawa, 2004). The CDA appears as a sustained negativity at posterior electrodes contralateral to the position of information stored in WM and it increases in amplitude with the number of items stored until individual WM capacity is reached (e.g., Vogel et al., 2005). We therefore expected CDA amplitude to predict the number of correctly reported items in the whole report WM task. This assumption has also been supported in a whole report WM task similar to the current one (Adam et al., 2018).

With regard to our research question, we intended to link these electrophysiological indicators for high WM performance to the experimental manipulation of clock speed. If a modulated subjective experience of time passage led to differences in the attentional task engagement, this should accordingly be indicated by a frontal theta power increase in the fast clock condition and a decrease in the slow clock condition (relative to the normal clock). A difference in posterior alpha power and CDA between the clock conditions would furthermore indicate a modulation of the individual ability to keep a high number of items activated in WM.

2. Methods

2.1. Sample

A total of 32 participants was tested. They were compensated with 10 € per hour or course credit for their participation. Two participants were excluded from the analyses because they did not follow task instructions (participant 8 checked the time on a watch that had not been removed prior to the experiment; participant 10 responded on chance level). The remaining 30 subjects (16 females) were aged from 19 to 33 years (M = 23.67, SD = 3.34) and had normal or corrected-to-normal visual acuity. Color perception was ensured by means of the Ishihara Test for Color Blindness (Ishihara, 1917). In accordance with the Declaration of Helsinki, all participants gave their written informed consent and were debriefed after the experiment. The experimental procedure was approved by the local ethics committee of the Leibniz Research Centre for Working Environment and Human Factors.

2.2. Stimuli, task and procedure

The experiment took place in a soundproof and electrically shielded room. The stimuli were displayed on a 22-inch CRT monitor (100 Hz; 1024 × 768 resolution). Participants were seated at 145 cm distance from the screen. Before the experiment, participants filled out a demographic questionnaire (providing information about the subject's age and sex) and received detailed instructions about the whole report WM task (without mentioning the clock manipulation).

2.2.1. Working memory task

The WM task featured a memory array with 6 differently colored discs that were each presented with a diameter of 0.59° visual angle. The colored discs were either located on the left or the right side of the central fixation cross. Stimulus position was chosen from a total of 32 possible positions: In a hypothetical matrix with four columns and eight rows, stimulus positions were chosen randomly, with the pre-condition that the stimuli were not allowed to lie directly next to each other (in order to prevent a grouping/chunking of stimuli). The colors of the six items were randomly drawn from a set of eight colors without replacement (RGB values: red = 255/0/0; green = 0/255/0; blue = 0/0/255; magenta = 255/0/255; yellow = 255/255/0; cyan = 0/255/255; orange = 255/128/0; white = 230/230/230). The stimuli were presented on a grey background (RGB: 28/28/28; luminance: 10 cd/m^2). Additionally, 6 light grey stimuli were presented on the opposite side of the fixation cross. Again, stimulus positions were drawn randomly from a set of 32 possible positions. The luminance of these grey 'filler items' was matched to the average luminance of the colored discs (i.e., 50 cd/m^2). The two hypothetical matrices on the left and right side of fixation each measured 5.9° (height) x 2.95° (width) and their outer edges were at a distance of 4.425° from the fixation cross. The memory array stimuli were presented for 300 ms and followed by a 2000 ms delay period with only the fixation cross being displayed.

The subsequent memory probe display contained probe stimuli centered on the positions of the colored discs from the prior memory array. Each probe was composed of a 3 × 3 matrix with small squares that were each filled with one of the eight possible colors (the central position was displayed in the background color; cf. (Adam et al., 2015). Participants were instructed to use the computer mouse for choosing the color of each memory array item by clicking on the respective square within the probe stimulus. When clicking on a certain square, the whole probe stimulus turned into the respective color. The probe display remained for 200 ms after the last color had been chosen. The inter-trial interval was set to 3000 ms and started immediately after the last color report or when participants had not completed the task within 15 seconds. When participants had not completed the color assignment within this time limit, they were advised to complete the task faster (i.e., the text feedback 'bitte schneller reagieren' ('please respond faster') was displayed for 1000 ms at the center of the screen, followed by a 2000 ms inter-trial interval). A training block of 10 trials was run prior to the first experimental block. The real time of day was displayed after completing the training block.

2.2.2. Duration announcement and performance rating

After each 20 trials in the WM task, the subjects were asked to rate their current performance level (during the last 20 trials) on a 7-point-Likert scale from 1 ('sehr niedrig'; 'very low') to 7('sehr hoch'; 'very high'). Immediately after the subject had responded, a 'short break' followed for 10 seconds while the current time of day was announced visually by means of a digital clock display (hours and minutes based on a 24-hour clock) in the center of the screen. The purpose of the performance rating was less a crucial measure within the experiment but rather a cover story for the frequent breaks (time announcements). Importantly, in block 1, the time was announced correctly, whereas in block 2, and 3, the displayed time of day was false. That is, the displayed time was overstated or understated by 20%. The order of blocks 2 and 3 (120% vs. 80% clock) was counter-balanced between subjects. Half of the participants were assigned to the 80 %-clock speed condition first (and 120% second), while the second half received the two blocks in the 120%-80% order. The first experimental block was always run with a 100% (normal) clock, as we wanted to have a baseline condition undistorted by the experimental manipulation of clock speed. Prior investigations have shown that false temporal announcements can lead to carry-over effects on cognitive performance in tasks without a clock speed manipulation (see Christandl et al., 2018).

For example, a subject finished the first block (always 100%-clock speed) after 40 minutes. The time displayed after trial 160 (announcement number 8) was identical to the real time of day, for example 09:50. Given the subject was assigned to the block-order condition 100%-80%-120%, that is, the clock was decelerated in block 2, let us assume that it took the subject 5 (true) minutes to finish the first 20 trials of Block 2 and another 5 minutes to finish trials 21 to 40. Accordingly, the time displayed was 09:54 after trial 20 in block 2 (trial 180 with reference to the overall experiment), that is, seemingly 4 minutes (5 minutes in real time) had elapsed since the end of block 1. The time displayed after trial 40 in block 2 would be 09:58 (10:00 in real time). Assuming the subject to work constantly at this speed, the displayed time would be 10:22 when completing block 2. During the accelerated block 3, the time displayed would constantly approach and finally reach the real time of day (11:10). Therefore, the increasing and decreasing discrepancy between true and displayed duration is assumed to induce the impression of time slowing down, and speeding up during block 2, and 3, respectively.

Taken together, the experimental task comprised 540 trials (180 per block) plus 10 training trials.

2.2.3. Post-experimental questionnaire: Time passage and manipulation awareness

After the subjects had finished the experimental task, they were asked to work on a short questionnaire (paper and pencil). The first three questions were related to manipulation awareness. In order to check whether the subjects recognized that some of the duration announcements were false, we asked:

1 'Ist Ihnen bei der Bearbeitung der Aufgabe etwas Besonderes aufgefallen? Wenn ja, was?' ('Did you notice anything odd in general during the task? If so, what precisely?')
2 'Haben Sie bei der Bearbeitung der Aufgabe auf die Uhr geachtet?' ('During the task, did you attend to the clock displayed?')
3 'Ist Ihnen während des Versuchs aufgefallen, dass die Uhr unterschiedlich schnell gelaufen ist? Wenn ja, wie hat die Uhr ihre Geschwindigkeit verändert?' ('During the task, did you recognize that the clock ran at varying speed? If so, how did the clock change in speed?').

The subjects were asked to give binary responses ('yes' or 'no') to each of the three questions. In the case of a 'yes' - response to question 1 or 3, the subjects were asked to provide a short statement of clarification. Subsequently, based on 7-point Likert scales ranging between 1 ('sehr langsam'; 'very slow') and 7 ('sehr schnell'; 'very fast'), we asked our subjects to provide three retrospective judgments (ratings) of perceived passage of time, each relating to one of the blocks.

The whole procedure took about 3.5 hours, including the preparation of the EEG and the post-experimental questionnaire.

2.3. Data processing and analysis

As in each block the first (false) duration announcement has been provided after trial 20, a potential effect of clock speed may evolve (build up) from trial 21 on. Therefore, in our analyses, we focused on the data from trials 21 to 160 of each block.

2.3.1. Behavioral data

We defined the mean number of correctly reported items per trial (N_{CRI}) as the dependent variable. Separately for each block (clock-speed condition), we explored the mean individual N_{CRI} for potential outliers. According to the criterion proposed by Tukey (Tukey, 1977), there were no far outliers (individual mean >/< +/-3 SD relative to the samples' mean) in behavioral performance. We then analyzed the mean N_{CRI} by means of a repeated-measures analysis of variance (rm-ANOVA) including the within-subjects factor Clock speed (100%; 80%; 120%) and the between-subjects factor Block order (100%-80%- 120%; 100%-120%-80%) with Huynh-Feldt correction for the degrees of freedom (Huynh and Feldt, 1980). Note that Block order was considered for the purpose of experimental control only in order to rule out a moderating effect of time-on task (training or mental fatigue) on the assumed effect of clock speed, which would be evident in an interaction effect between both factors. Partial eta squared ($\eta_p{}^2$) is reported as a measure of association strength. Pairwise comparisons are based on three subsequent paired-samples *t*-tests with adjusted *p*-values according to the false discovery rate procedure proposed by Benjamini & Hochberg (Benjamini and Hochberg, 1995); the adjusted *p*-values (p_{adj}) are reported. We report Cohen's d_z (Cohen, 1988) as a standardized measure of effect size in a within-subjects design.

As an indicator of attentional lapses related to a complete attentional withdrawal from the task, we focused on the mean number of trials in which none or only one item had been reported correctly (Adam et al., 2015). According to the same protocol as applied to N_{CRI}, we analyzed mean N_{AL} by means of a rm-ANOVA.

Additionally, we run an rm-ANOVA on N_{CRI} including the within-subject factor Sub-block (24 levels: trials 1-20; 21-40; 41-60; 61-80; 81-100; 101-120; 121-140; 141-160; …; 461-480) in order to test for potential effects of training or fatigue in the task, which might mask or bias effects of clock speed.

2.3.2. Questionnaire data

In accordance with the behavioral data, the first performance rating (PR; immediately after trial 20) within each block was not considered in the analyses. By means of an rm-ANOVA following the same protocol as for the performance data, we analyzed PR and additionally considered Sub-block within each block (21-40; 41-60; 61-80; 81-100; 101-120; 121-140; 141-160) as a second within-subjects factor.

The retrospective judgments of perceived time passage (JTP) were also analyzed by means of an rm-ANOVA following the standard protocol as described above.

The subjects' binary (yes/no) responses to the three questions relating to manipulation awareness (anything odd in general?; attention to clock?; recognition of clock-speed manipulation?) and their related comments were explored in a descriptive fashion. We report frequencies of 'yes' and 'no' responses to each question and also explored a potentially moderating effect of recognition of clock-speed manipulation on N_{CRI} by means of an rm-ANOVA additionally considering Recognition of clock-speed manipulation (response to question 3: yes, no) as a between-subjects factor. An interaction effect between both factors would point to a dependency of the effect of clock speed on the subjects' believe in the clock's accuracy.

2.3.3. EEG recording and pre-processing

The EEG was recorded with 65 Ag/AgCl passive electrodes (Easycap GmbH, Herrsching, Germany) and based on an extended 10/20 scalp configuration. A 1000 Hz sampling rate and a 250 Hz low-pass filter were applied during recording with a NeurOne Tesla AC-amplifier (Bittium Biosignal Ltd, Kuopio, Finnland). Channel FCz served as reference during recording. Channel AFz was used as the ground electrode. Impedances were kept below 10kΩ.

Further analyses were performed using MATLAB and the EEGLAB toolbox (Delorme and Makeig, 2004). The data were down-sampled to 500 Hz and low- (30 Hz, 33.75 Hz cutoff, 0 to -6 dB transition window) and high-pass filters (0.1 Hz, 0.075 Hz cutoff, 0 to -6 dB transition window) were applied. A channel was rejected from further analyses if its kurtosis exceeded 5 SD (M = 1.47, SD = 1.5, range: 0-6). Afterwards, data were re-referenced to the average signal of all remaining channels. Before creating epochs from 1000 ms before to 2700 ms after memory array presentation, data were again high-pass filtered (1 Hz, 0.5 Hz cutoff, 0 to -6 dB transition window) for later independent component analysis (ICA). Prior research has shown that 1 Hz high-pass filtering prior to ICA produces better results in terms of IC classification accuracy, the dipole solution to the individual ICs (see below) and overall signal-to-noise ratio (Dowding et al., 2015). Before starting ICA, a statistical trial-rejection procedure was run (threshold: 500 µV, probability threshold: 5 SD, max. % of trials to reject per iteration: 5). The independent components (ICs) were classified by means of ADJUST (Mognon et al., 2011) and IC weights were transferred back to the whole dataset (0.1 Hz high-pass filter, 30 Hz low-pass filter, average reference, bad channels rejected). The DIPFIT plugin of EEGLAB was used for calculating single dipoles based on a 4-shell spherical head model for each IC. Further ICs were excluded from the data when residual variance of the dipole solution exceeded 50%. Additionally, by means of ADJUST, ICs were excluded when they had been labeled as vertical or horizontal eye movements, eye blinks or generic data discontinuities. These analyses were followed by a statistical trial rejection procedure (threshold: 1000 µV, probability threshold: 5 SD, max. % of trials to reject per iteration: 5) that led to a rejection of 162 trials on average (SD = 35, range: 93 – 250 trials). Finally, the channels rejected during pre-processing were replaced by a spherical spline interpolation of the immediately proximate channels. In all subsequent analyses, only those trials that featured a color specification for all of the six stimulus positions (i.e., a complete response by the participant) were considered.

2.3.4. EEG time-frequency analyses

Event-related spectral perturbations (ERSP; Delorme and Makeig, 2004) were computed by convolving 3-cycle complex Morlet wavelets with each epoch of the EEG data. Resulting time-frequency values consisted of 200 time points between -582 and 2282 ms relative to memory array onset. Frequencies ranged from 4 Hz to 30 Hz in 52 logarithmic steps. The pre-stimulus interval was used as spectral baseline. The number of cycles in the data window increased half as fast as the number of cycles used in the corresponding fast-fourier transformation (FFT). This led to 3-cycle wavelets at lowest frequency (i.e., 4 Hz) and 11.25-cycle wavelets at highest frequency (i.e., 30 Hz).

2.3.4.1. Oscillatory correlates of high WM performance. As prior research indicates a relation between oscillatory power at fronto-central and posterior sites and WM performance (e.g., Adam et al., 2015; Onton et al., 2005), we defined a fronto-central (F1, Fz, F2, FC1, FCz, FC2) and a posterior lateral electrode cluster near and including PO7/PO8 (PO7, PO8, PO9, PO10, P7, P8) and assessed to what extent oscillatory power averaged within these clusters predicted WM performance. This posterior cluster of channels was chosen, because prior research has shown that alpha suppression in response to a lateralized visual stimulus display is strongest over posterior lateral recording sites (e.g., Bacigalupo and Luck, 2019; Schneider et al., 2017). Single-trial ERSPs (with a single-trial pre-stimulus spectral baseline) were measured separately for each clock condition and for the fronto-central and posterior lateral cluster of electrodes. Subsequently, Spearman rank correlations were calculated across trials between each of the 200 (times) x 52 (frequencies) single-trial ERSP data points and the number of correctly reported items (separately for each clock condition). This resulted in three matrices (one for each clock condition) with 200 (times) x 52 (frequencies) x 30 (participants) correlation coefficients. These coefficients were Fisher-z transformed and subsequently averaged across clock conditions. In an additional step, the Fisher-z transformed correlation coefficients were tested against zero based on *t*-tests run for each data point and a cluster permutation statistical procedure was used to define time-frequency areas with a reliable correlation between oscillatory power and WM performance: Within 1000 permutation, the z-values were randomly intermixed with a matrix of zeros for each dataset and two-sided *t*-tests were calculated for all data points. This resulted in a $52 \times 200 \times 1000$ (permutations) matrix and the largest cluster of *p*-values < 0.01 was assessed for each permutation. A time-frequency cluster with $p < 0.01$ in the original 52×200 matrix of Fisher-z transformed correlation coefficients was considered as statistically significant when it was larger than the 95th percentile of the distribution of maximum cluster sizes. This procedure was run separately for the fronto-central and posterior lateral electrode clusters (Rösner et al., 2020; Schneider et al., 2020).

2.3.4.2. The effect of clock speed. As the prior analyses indicated a relationship between the level of posterior alpha power (PO7, PO8, PO9, PO10, P7, P8, ~8-14 Hz), fronto-central theta power (F1, Fz, F2, FC1, FCz, FC2, ~4-7 Hz) and WM performance, further analyses concentrated on potential effects of clock speed on these oscillatory parameters. Fronto-central theta power (F1, Fz, F2, FC1, FCz, FC2; 4-7 Hz average) and posterior alpha power (PO7, PO8, PO9, PO10, P7, P8; 8-14 Hz average) were calculated for each clock condition. Subsequently, the 100% (normal) clock condition was compared against the 120% (fast) clock condition and 80% (slow) clock condition, respectively. These analyses were run separately for fronto-central theta power and posterior alpha power and were based on the cluster-permutation statistics described above (here: based on the average oscillatory response in the two frequency ranges). The same statistical procedure was used to compare fronto-central theta power and posterior alpha power between the fast and slow clock conditions.

When cluster permutation statistics indicated a reliable effect of clock speed, post-hoc ANOVAs on average oscillatory power within the respective time windows were run with the within-subject factors *clock condition* (normal, fast, slow) and *performance* (high: 4, 5 or 6 items correct vs. low: 0, 1 or 2 items correct; the median of the number of correctly reported items was three for all participants). Additionally, to assure that the normal clock condition was applicable as a baseline for interpreting the effects of manipulated clocks, the impact of 'time on task' on neural oscillatory parameters that featured a significant effect of clock speed was assessed. This was done because the first experimental block was always run with a 100% (normal) clock and differences in neural oscillatory patterns between this condition and the fast and slow clock conditions might thus be confounded by time on task. We thus calculated ERSPs separately for sub-blocks 2-4 (early) and sub-blocks 6-8 (late; see the blocks of 20 trials between each performance rating/clock display) within each clock condition. The 5th sub-block was not considered in order to have a comparable number of trials in the early and late sub-block conditions. The oscillatory power averaged across the time windows featuring significant effects of clock conditions was analyzed in a rm-ANOVA with factors for *time-on-task* (early vs. late sub-blocks) and *clock condition* (normal, fast, slow).

2.3.5. Lateralized ERPs

We calculated the contralateral and ipsilateral portions of the ERP at a cluster of posterior lateral electrodes (PO7/8, PO9/10, P7/8). This was done by averaging the signal of right-sided electrodes when targets were presented on the left side and left-sided electrodes when targets were presented on the right side (contralateral). The ipsilateral signal was calculated by averaging the signal of right-sided electrodes when targets were presented on the right side and left-sided electrodes when targets were presented on the left side. The contralateral minus ipsilateral difference was calculated separately for each clock condition and subsequently averaged across clock conditions. A time window of 40 ms centered on the first peak in the resulting contralateral minus ipsilateral difference in the average across all datasets was used for measuring N2 posterior contralateral (i.e., 230 – 270 ms after memory array presentation), an ERP effect linked to the attentional selection of lateralized information presented in a bilateral visual stimulus array (N2pc; see Luck and Hillyard, 1994). The CDA effect was measured as the mean amplitude in the contralateral minus ipsilateral difference waveform between 800 and 2300 ms after memory array presentation.

Mean amplitudes for N2pc and CDA were compared between high- and low-performance trials based on a median split and separate within-subject *t*-tests (high performance: 4, 5 or 6 items correct vs. low performance: 0, 1 or 2 items correct). Additionally, we analyzed the effect of clock condition on N2pc and CDA in separate rm-ANOVAs with the factor *clock condition* (normal, fast, slow). In case of a reliable clock condition effect, a post-hoc rm-ANOVA included the additional factor *time-on-task* (early vs. late sub-blocks; see above).

For all post-hoc analyses, the false discovery rate procedure as proposed by Cramer et al. (Cramer et al., 2016) was used to correct for a cumulation of Type 1 error within the ANOVAs. In these cases, adjusted critical p-values (p_{crit}) are provided. The false discovery rate procedure by Benjamini and Hochberg (1995) was used for correcting critical *p*-values (p_{adj}) in post-hoc pairwise comparisons.

3. Results

3.1. Behavioral data

For each clock-speed condition and across all 30 subjects, the total frequencies of trials with 0, 1, 2, 3, 4, 5, and 6 correctly reported items are depicted in Fig. 2.

Fig. 3 illustrates mean $N_{CRI,}$ and mean N_{AL} as a function of Clock speed and Block order. Irrespective of Block order, $N_{CRI,}$ was higher in the fast-clock condition relative to the normal- and the slow -clock condition. Corresponding differences in N_{AL} were weaker or absent.

The statistical analyses revealed a significant effect of Clock speed on N_{CRI}, $F(2, 56) = 4.880$, $\varepsilon > .999$, $p = .011$, $\eta_p^2 = .148$: N_{CRI} was significantly higher in the fast ($M = 3.172$, $SD = 0.338$) relative to the normal condition ($M = 3.076$, $SD = 0.336$; $t(29) = 2.584$, $p_{adj} = .030$, $d_z = 0.475$) and also higher as compared to the slow condition ($M = 3.102$, $SD = 0.305$; $t(29) = 2.459$, $p_{adj} = .030$, $d_z = 0.456$). N_{CRI} for slow clock speed did not differ from the condition with a normal clock, $t(29) = 0.807$, $p_{adj} = .426$, $d_z = 0.147$. The main effect of Clock speed was not significant for N_{AL}, $F(2, 56) = 2.392$, $\varepsilon > .999$, $p = .101$, $\eta_p^2 = .079$.

There were no effects of Block order (N_{CRI}: $F(1, 28) = 0.003$, $p = .959$, $\eta_p^2 < .001$; N_{AL}: $F(1, 28) = 0.110$, $p = .743$, $\eta_p^2 = .004$) and no interaction effects between Clock speed and Block order (N_{CRI}: $F(2, 56) = 3.043$, $p = .056$, $\eta_p^2 = .098$; N_{AL}: $F(2, 56) = 1.988$, $p = .147$, $\eta_p^2 = .066$). Across blocks, i.e., clock-speed conditions, the analysis on N_{CRI} including the within-subject factor Sub-block showed no differences between Sub-blocks, $F(23, 667) = 1.016$, $\varepsilon = .919$, $p = .441$, $\eta_p^2 = .034$, suggesting a constant level of performance from the beginning of the experiment and ruling out substantial effects of training or fatigue in the task.

3.2. Questionnaire data

The full descriptive data from the questionnaire are presented in Table 1 (self-rated performance) and 2 (time-passage judgments).

Table 1
Descriptive data (means and standard deviations) from the performance self-ratings (scale:1-'very low' to 7- 'very high').

Clock-speed	Trial	Block order 100-80-120		Block order 100-120-80		Mean	
		M	*SD*	*M*	*SD*	*M*	*SD*
100	40	4.067	1.163	3.600	1.121	3.834	1.142
100	60	4.200	1.265	3.933	1.033	4.067	1.149
100	80	3.867	1.125	3.533	1.187	3.700	1.156
100	100	3.867	1.125	3.533	1.060	3.700	1.093
100	120	3.333	1.047	4.067	1.335	3.700	1.191
100	140	3.867	1.187	3.800	0.862	3.834	1.025
100	160	3.667	1.345	3.533	0.990	3.600	1.168
100	Mean	3.838	1.180	3.714	1.084	3.776	1.132
80	40	4.267	1.28	3.733	1.335	4.000	1.308
80	60	4.600	1.404	3.533	1.246	4.067	1.325
80	80	4.067	1.335	4.00	1.414	4.034	1.375
80	100	4.067	1.223	3.667	1.447	3.867	1.335
80	120	4.200	1.320	3.600	1.454	3.900	1.387
80	140	4.200	1.082	3.400	1.502	3.800	1.292
80	160	3.867	1.187	3.267	1.280	3.567	1.234
80	Mean	4.181	1.262	3.600	1.383	3.891	1.322
120	40	4.467	1.356	3.533	1.187	4.000	1.272
120	60	4.467	1.125	3.600	0.986	4.034	1.056
120	80	3.933	1.438	3.800	1.373	3.867	1.406
120	100	4.067	1.486	3.267	0.961	3.667	1.224
120	120	3.933	1.486	3.467	1.125	3.700	1.306
120	140	3.933	1.580	3.600	0.986	3.767	1.283
120	160	3.600	1.682	3.600	1.502	3.600	1.592
120	Mean	4.057	1.450	3.552	1.160	3.805	1.305
Mean	Mean	4.026	1.297	3.622	1.209	3.824	1.253

Table 2
Descriptive data (means and standard deviations) from the time passage ratings (scale:1-'very slow' to 7- 'very fast').

Clock-speed	Block order 100-80-120		Block order 100-120-80		Mean	
	M	*SD*	*M*	*SD*	*M*	*SD*
100	4.267	1.58	4.400	1.454	4.334	1.517
80	3.800	1.265	4.330	1.543	4.065	1.404
120	3.333	1.780	4.467	1.125	3.900	1.453
Mean	3.800	1.542	4.399	1.374	4.100	1.458

3.2.1. Performance ratings

Self-rated performance was clearly not affected by Clock speed, $F(2, 56) = 0.343$, $\varepsilon = .983$ $p = .707$, $\eta_p^2 = .012$, and Block order, $F(1, 28) = 1.414$, $p = .244$, $\eta_p^2 = .048$. Less importantly, there was a significant effect of Sub-block, $F(6, 168) = 2.554$, $\varepsilon > .999$, $p = .022$, $\eta_p^2 = .084$, with Helmert contrasts indicating larger mean PR after trial 60 relative to the mean PR later within each block, $F(1, 28) = 10.462$, $p = .003$, $\eta_p^2 = .272$. None of the interaction effects reached statistical significance (all p-values > .1).

3.2.2. Time-passage ratings

With regard to the retrospective judgments of perceived time passage, there were neither significant main effects of Clock speed, $F(2, 56) = 0.708$, $\varepsilon > .999$, $p = .497$, $\eta_p^2 = .025$, and Block order, $F(1, 28) = 3.335$, $p = .078$, $\eta_p^2 = .106$, nor an interaction between both factors, $F(2, 56) = 0.939$, $p = .397$, $\eta_p^2 = .032$.

3.2.3. Indices of manipulation awareness

Based on our subjects' responses to the three questions relating to manipulation awareness, most subjects ($N = 21$; 70%) did not notice 'anything odd in general during the experiment'. Almost all subjects ($N = 27$; 90 %) affirmed to having paid attention to the duration announcements. One third ($N = 10$) stated to having noticed a manipulation of clock speed after having been asked explicitly. However, based on the statements of clarification (in the cases of yes- responses to question 1 and/or 3), none of the subjects described the manipulation in a correct way.

Considering Recognition of clock-speed manipulation as a between-subjects factor in an additional rm-ANOVA on N_{CRI} did not indicate any moderating effect of the indicator of manipulation awareness on the effect of Clock speed (there was no significant interaction between Clock speed and Recognition of clock-speed manipulation: $F(2, 56) = 1.038$, $\varepsilon > .999$, $p = .361$, $\eta_p^2 = .036$).

3.3. EEG results

3.3.1. Neural oscillations

3.3.1.3. Oscillatory correlates of high WM performance. As can be seen in Fig. 4, both the fronto-central and the posterior lateral electrode cluster featured significant single-trial correlations between oscillatory power following memory-array presentation and the number of correctly reported items. While for the fronto-central cluster the oscillatory power in the theta frequency range (~4-7 Hz) predicted WM performance (more correctly reported items with higher theta power in the delay phase), the posterior electrode cluster featured a reliable negative correlation between oscillatory power in the alpha frequency range (~8-14 Hz) and the number of correctly reported items in the probe array (more correctly reported items with lower alpha power in the delay phase).

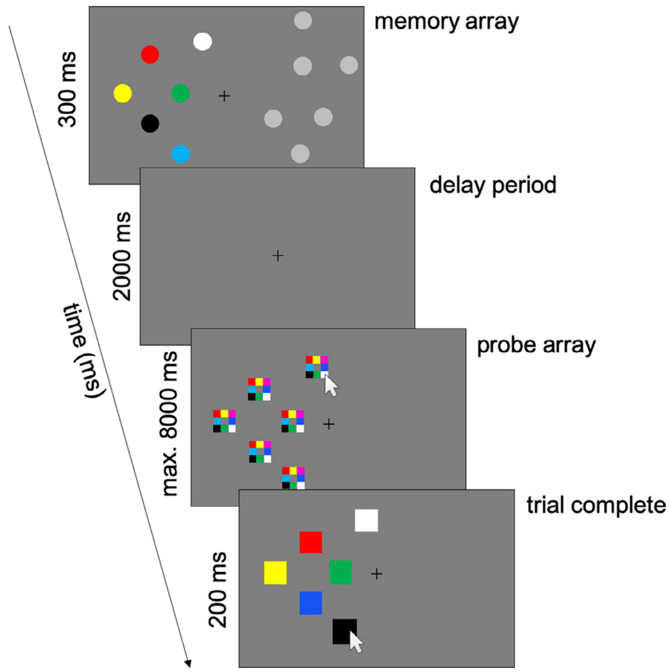

Figure 1. Experimental design of the working memory task. Participants remembered six colors presented at six different locations and subsequently chose the respective color from a matrix of eight colors presented on the prior stimulus positions.

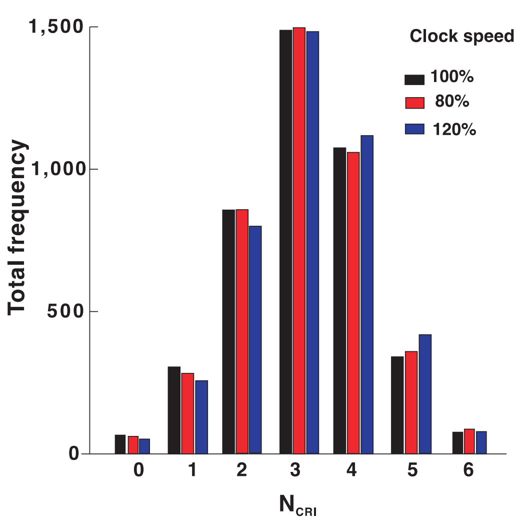

Figure 2. Total frequency of trials with 0, 1, 2, 3, 4, 5, and 6 correctly reported items as a function of Clock-speed (based on the final sample of N = 30 subjects).

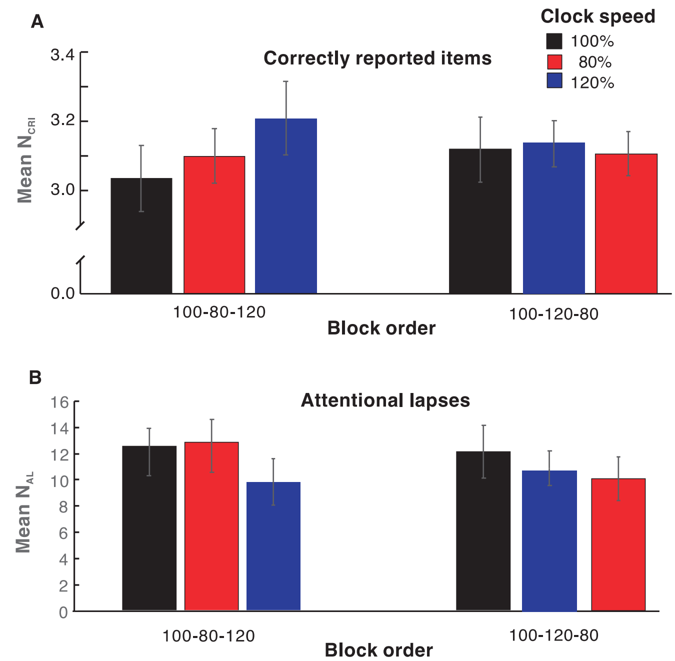

Figure 3. Behavioral measures. Mean number of correctly reported items per trial (NCRI; panel A) and mean number of attentional-lapse trials per block (NAL; panel B), as a function of Clock speed and Block order.

3.3.1.4. The effect of clock speed. While WM performance independent from the manipulation of clock speed was related to both posterior alpha power and frontal theta power during the delay phase, the varying speed of the clocks only affected frontal theta power. As can be seen in Fig. 5, fronto-central theta power (F1, Fz, F2, FC1, FCz, FC2) following memory-array presentation featured a statistically significant effect of clock condition: Theta power during the delay phase of the WM task was higher for the fast clock condition compared to the normal (see black dotted horizontal line) and slow clock conditions (see red dotted horizontal line). The slow clock condition did not significantly differ from the normal clock condition in this regard.

Furthermore, there was a strong suppression of alpha power following memory-array presentation. The respective scalp topography suggested the strongest suppression over posterior lateral electrodes. However, no cluster of time points with a statistically significant difference between the clock conditions was observable in this regard (see Fig. 5).

Post-hoc analyses addressed how the observed modulation of frontal theta power by clock condition was further influenced by WM performance and time-on-task. As to be expected and illustrated in Fig. 6, the mean theta power from 870 - 1526 ms following the memory array (i.e., the cluster with a significant difference between the fast and slow clock conditions; see the red dotted line in Fig. 5) was modulated by clock condition, $F(2, 58) = 4.957$, $\varepsilon = .989$, $p = .012$, $p_{crit} = .05$, $\eta_p^2 = .146$ (highest in the fast clock condition), and differed between high and low performance trials, $F(1, 29) = 5.35$, $p = .028$, $p_{crit} = .033$, $\eta_p^2 = .146$ (higher in high performance trials). There was no interaction between these two factors, $F(2, 58) = 0.004$, $\varepsilon > .999$, $p = .995$, $p_{crit} = .017$, $\eta_p^2 < .001$. The respective scalp topographies revealed a frontal maximum of the theta power difference between the high and low performance trials. In an additional analysis step, we measured mean frontal theta power within each clock condition in an early time window (the 870 - 1526 ms interval used for the prior analyses) and a late time window (1526 ms up to last ERSP data point at 2282 ms) during the delay interval and calculated correlations between them (Pearson correlation). This was done to assure that the slightly different time windows indicated by the single-trial correlations and the analyses of clock condition still captured the same (or a highly related) theta power effect. For all clock conditions, high correlations were observed (100% clock: r=.813, p_{adj}<0.001; 80% clock: r=.902, p_{adj}<0.001; 120% clock: r=.818, p_{adj}<0.001).

Furthermore, theta power did not differ between early and late sub-blocks within the three clock conditions, $F(1, 29) = 0.314$, $p = .58$, $p_{crit} = .017$, $\eta_p^2 = .011$, and there was no interaction between time-on-task and clock condition, $F(2, 58) = 0.975$, $\varepsilon > .999$, $p = .383$, $p_{crit} = .033$, $\eta_p^2 = .033$. As could be expected, based on the chosen time window, also this analysis revealed a main effect of clock condition on delay phase theta power, $F(2, 58) = 8.241$, $\varepsilon = .89$, $p = .001$, $p_{crit} = .050$, $\eta_p^2 = .221$.

3.3.2. Lateralized ERPs

While N2pc amplitude differed between low- and high-performance trials, $F(1, 29) = 19.83$, $p < .001$, $\eta_p^2 = .406$, we could not replicate the

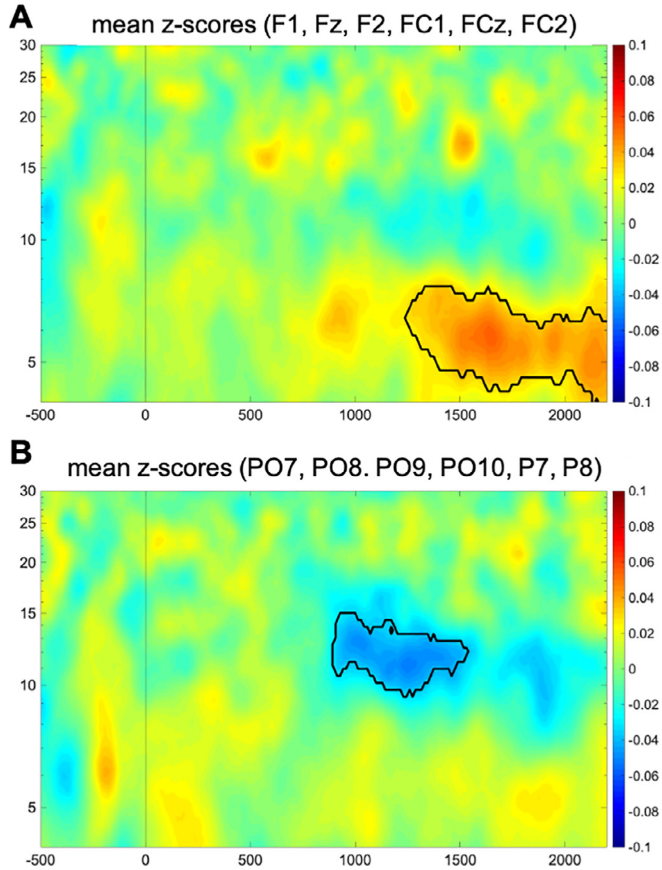

Figure 4. Single-trial correlations between oscillatory power and working memory performance. Each time-frequency value reflects the average Fisher-z-transformed correlation coefficients (averaged across clock conditions). The vertical line indicates the onset of the memory array. The outlined areas indicate clusters with a significant single-trial correlation. 4A depicts the correlations for fronto-central electrode positions, with a reliable effect in theta frequency range (~4-7 Hz). The single-trial correlations at posterior lateral channels can be seen in 4B, with a statistically reliable correlation in alpha frequency range (~8-14 Hz).

prior finding that CDA amplitude predicted the number of correctly reported colors in the whole-report WM paradigm (see Adam et al., 2018), $F(1, 29) = 0.001$, $p = .979$, $\eta_p^2 < .001$. However, the opposite pattern was found for the effect of clock speed on lateralized ERPs: There was a reliable effect of clock speed on the CDA effect, $F(2, 58) = 4.165$, $\varepsilon = .994$, $p = .021$, $\eta_p^2 = .126$, but not on prior N2pc, $F(2, 58) = 0.689$, $\varepsilon = .878$, $p = .489$, $\eta_p^2 = .023$ (see Fig. 7). Subsequent pairwise comparisons showed that the slow clock condition featured lower CDA amplitudes than the fast clock condition, $t(29) = 2.777$, $p_{adj} = 0.029$, $d_z = .507$. There was also a trend towards a lower CDA amplitude in the slow compared to the normal clock condition, $t(29) = 1.932$, $p_{adj} = 0.095$, $d_z = .353$. The fast and the normal clock condition did not differ in this regard, $t(29) = .859$, $p_{adj} = 0.398$, $d_z = .157$.

A post-hoc rm-ANOVA showed that the effect of clock speed on CDA amplitude did not differ between the early and late sub-blocks of the experiment, $F(2, 58) = .749$, $\varepsilon = .975$, $p = .474$, $p_{crit} = .033$, $\eta_p^2 = .025$. There was also no main effect of *time-on-task* on CDA amplitude, $F(1, 29) = 1.75$, $p = .196$, $p_{crit} = .05$, $\eta_p^2 = .057$, ruling out that the clock speed effect on CDA amplitudes resulted merely from a comparison with the first experimental block (normal clock speed).

4. Discussion

In the present study, we investigated the potential effects of manipulated time announcements on cognitive processes in a highly demanding whole report WM task. In addition to behavioral performance, we measured neural oscillatory activity and lateralized ERP effects in the EEG that are related to processes of attentional engagement and WM storage (frontal theta, posterior alpha oscillations and CDA). We hypothesized that the impression of accelerated vs. decelerated passage of time as induced by manipulated (overstating vs. understating) time announcements during the task leads to increased behavioral performance. Our behavioral data provide clear evidence in favor of this hypothesis. Task performance, that is, the mean number of correctly reported items in the WM task was significantly higher during the experimental block with increased clock speed as compared to both the blocks with normal and slow clock speed (see Fig. 2 and 3). Importantly, this effect was clearly not driven by between-block differences in the frequency of attentional lapses, i.e., trials with extreme low performance, but due to a graded modulation of correctly reported items between the clock conditions. Having established this, it is of course important to point out what could be the basis of such an influence of manipulated clocks on WM performance: The number of correctly reported items was not biased by effects of block order or time on task. The subjects reached a constant level of behavioral performance within the first block of the task (normal clock speed), and between-subject differences as a function of the order of blocks with fast vs. slow clocks were negligible. The pattern of behavioral results thus supports the notion of an improvement in the subjects' WM performance by faster clocks in terms of a gradual increase of engaged (attentional) resources across trials.

A possible explanation for such an attentional modulation would be a change of attitude towards the experimental situation depending on clock speed. In general, task engagement is assumed to be regulated by a resource-management system that maximizes the fitness benefit and minimizes the fitness cost of action (Kurzban, 2016). The cost function this system is based on has been described as the cost-benefit ratio of a task (Boksem and Tops, 2008), as the opportunity costs of the respective behavior (Kurzban et al., 2013), or as the tradeoff between intrinsically and extrinsically motivated activities (Kool and Botvinick, 2014). All these mechanisms proposed would be sensitive with respect to the subjective evaluation of a task. In the current experiment, participants perceived the time announcements during the experimental blocks (27 out of 30 participants stated to have perceived the time announcements) and the resulting cognition about elapsed time should have led to a discrepancy with their internal representation of elapsed time. The fact that participants did nevertheless not accurately report about the experimental manipulation (see further comments on the self-report measures below) suggests that they did not question the wrong time announcements. Thus, an adaptation of the subjective passage of time will not be attributed to the manipulated time announcements, but to the processing of the experimental task. Just as the degree to which we deliberately focus our attention on specific stimuli or on a given task affects our perception of duration and time passage (Brown and Merchant, 2007; Matthews and Meck, 2016; Phillips, 2012; Thönes and Hecht, 2017), a faster clock could thus lead to a more positive evaluation of an intrinsically boring task and consequently increase the allocation of attentional resources (Thönes et al., 2018). An earlier investigation by Christandl et al. (2018) supports this relation between clock manipulation, subjective time passage and attentional engagement. The authors made use of a manipulation of clock speed to bias the subjective passage of time ('time flies' vs. 'time drags' group). Participants in the 'time flies' group featured a higher flow experience (i.e., the motivating feeling of a mental state of complete concentration) and this factor mediated the positive influence of faster clock speed on performance in a subsequent cognitive task without clock manipulation.

The current experiment did not include a direct measurement of the subjects' attitude towards the task or experienced flow. The reason for this was that we wanted to keep the probability of a detection of the within-subject manipulation of clock speed as low as possible. Nevertheless, our electrophysiological results are clearly in favor of the notion that the manipulated clock has affected attentional engagement during

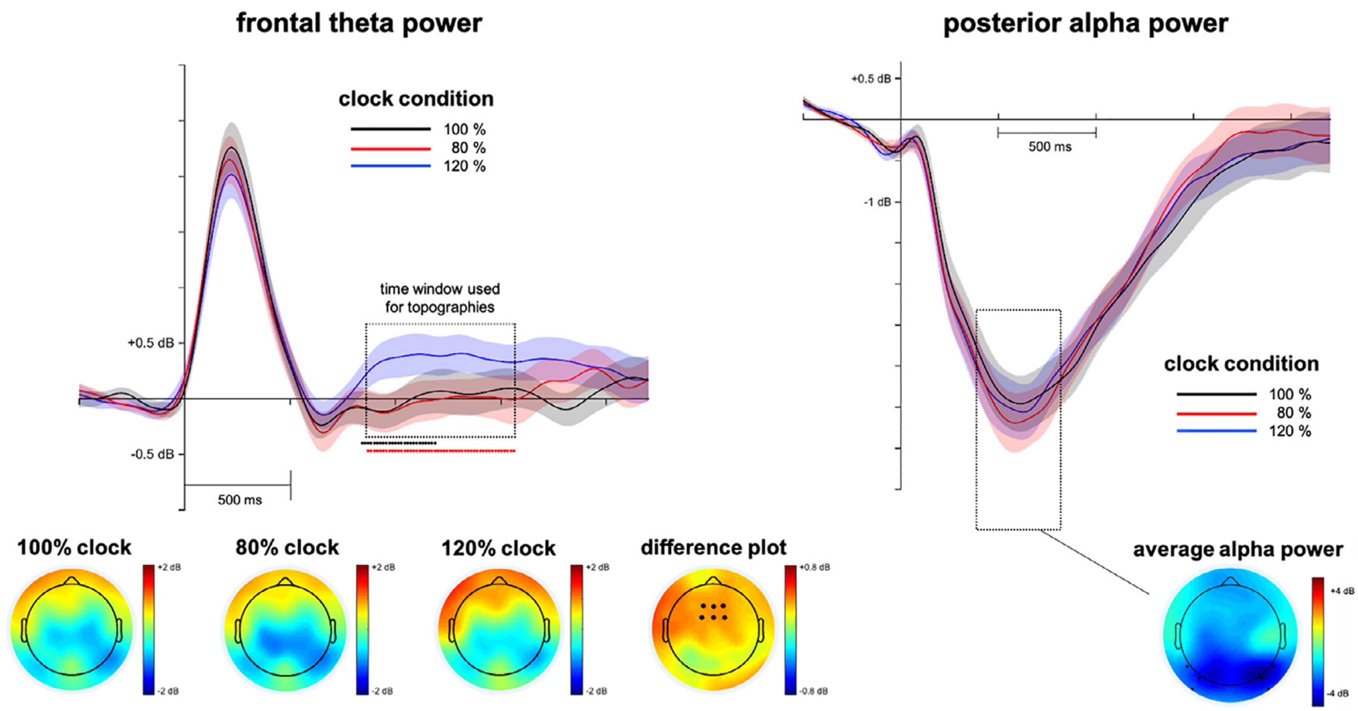

Figure 5. The effect of clock condition on frontal theta (4-7 Hz) and posterior alpha power (8-14 Hz). The line plots reflect the oscillatory power in theta (left) and alpha frequency range (right), with time point zero on the x-axis indicating the onset of the memory array. The shaded areas around the lines reflect the standard error of the mean. The red dotted line below the x-axis indicates a cluster of time points with a statistically significant difference between the 120% (fast) and 80% (slow) clock condition. The black dotted line reflects the interval with a statistically significant difference between the 100% (normal) and 120% (fast) clock condition. The theta power difference topography was calculated by subtracting the mean oscillatory power in the 100% and 80% clock conditions from the oscillatory power in the 120% clock condition (870 – 1562 ms). The fronto-central and posterior lateral channels used for analyses are marked within the topographic plots.

the WM task. In support of a general connection between frontal theta and posterior alpha oscillations and WM processes, frontal theta power during encoding and storage of the memory array was positively and posterior alpha power negatively related to WM performance (see also Adam et al., 2015). Here, we showed that these relationships could also be depicted by means of the oscillatory response on the single-trial level (see Fig. 4). With respect to frontal theta power, this is in line with earlier findings indicating that oscillatory activity in the theta range is generally linked to the extent of attentional resources engaged during a cognitive task (Cavanagh and Frank, 2014). In this respect, it is plausible that the covariation of theta power and performance was not only observable during the encoding and storage phases, but also during processing of the memory array and in preparation for WM retrieval (or the presentation of the probe array; see also Adam et al., 2015; Onton et al., 2005). Alpha oscillations, on the other hand, have been shown to get the more suppressed the more items are stored in WM (Fukuda et al., 2015). This may be related to the need to individuate each WM item in order to enable its selective retrieval. During encoding and storage, each item might be represented in alpha oscillations of a certain neuronal cluster, differing in phase compared to the items presented at other locations in order to exclude ambiguity in WM (Siegel et al., 2009). Thus, the more information can be stored, the lower the overall alpha power measured at the scalp.

However, we could not confirm earlier findings showing that also CDA amplitude varied with the number of correctly reported items in a whole-report WM task (Adam et al., 2018). Rather, N2pc amplitude proved to be a reliable predictor for a high number of correctly reported colors (see Fig. 7). This might suggest that participants did not consistently rely on the visuo-spatial representation of the individual stimuli (e.g., by generating a verbal representation or by chunking the stimuli presented – e.g., “warm” vs. “cold” colors) for accomplishing the task, turning it impossible to predict task performance by means of CDA amplitude. N2pc, however, reflects the selective processing of the laterally presented visual information (Eimer, 1996; Luck and Hillyard, 1994) (and potentially its encoding into WM) and thus predicted WM performance irrespective of the type of information stored.

Importantly, with regard to our clock manipulation, frontal theta power was significantly increased in the fast clock block relative to the normal and slow clock blocks, while posterior alpha power did not systematically differ between clock conditions. Thus, the clock speed conditions had an impact on frontal theta power as well as on task performance. Likewise, higher task performance was linked to increased frontal theta power during the delay period. Of course, this does not clearly prove that the impact of manipulated time announcements on WM performance was directly based on the theta power modulations. It is possible, for example, that clock speed had an impact on task performance and that the increase in frontal theta power in the fast clock condition was a mere byproduct of the higher number of items stored in WM, not its cause. In this case, however, we would expect to also observe an influence of the manipulated clocks on posterior alpha power in the delay phase of the WM task, since this oscillatory effect also predicted task performance on a single-trial level. We propose that the stronger increase in frontal theta power observed in the fast clock condition reflects a more pronounced allocation of attentional resources. As additional analyses showed that theta power was highly correlated during the delay phase of the WM task, such higher resources might have been applied for all processing stages ranging from WM storage to the preparation for probe display processing and WM retrieval. This is in line with earlier investigations showing an increase of frontal theta power as a function of performance independent from task demands (Meyers et al., 2019; Mussel et al., 2016; Onton et al., 2005; Umemoto et al., 2019).

It is furthermore interesting to note that also CDA amplitudes varied as a function of clock condition, with a higher contralateral negativity for the fast compared to the slow clock condition (see Fig. 7). In terms

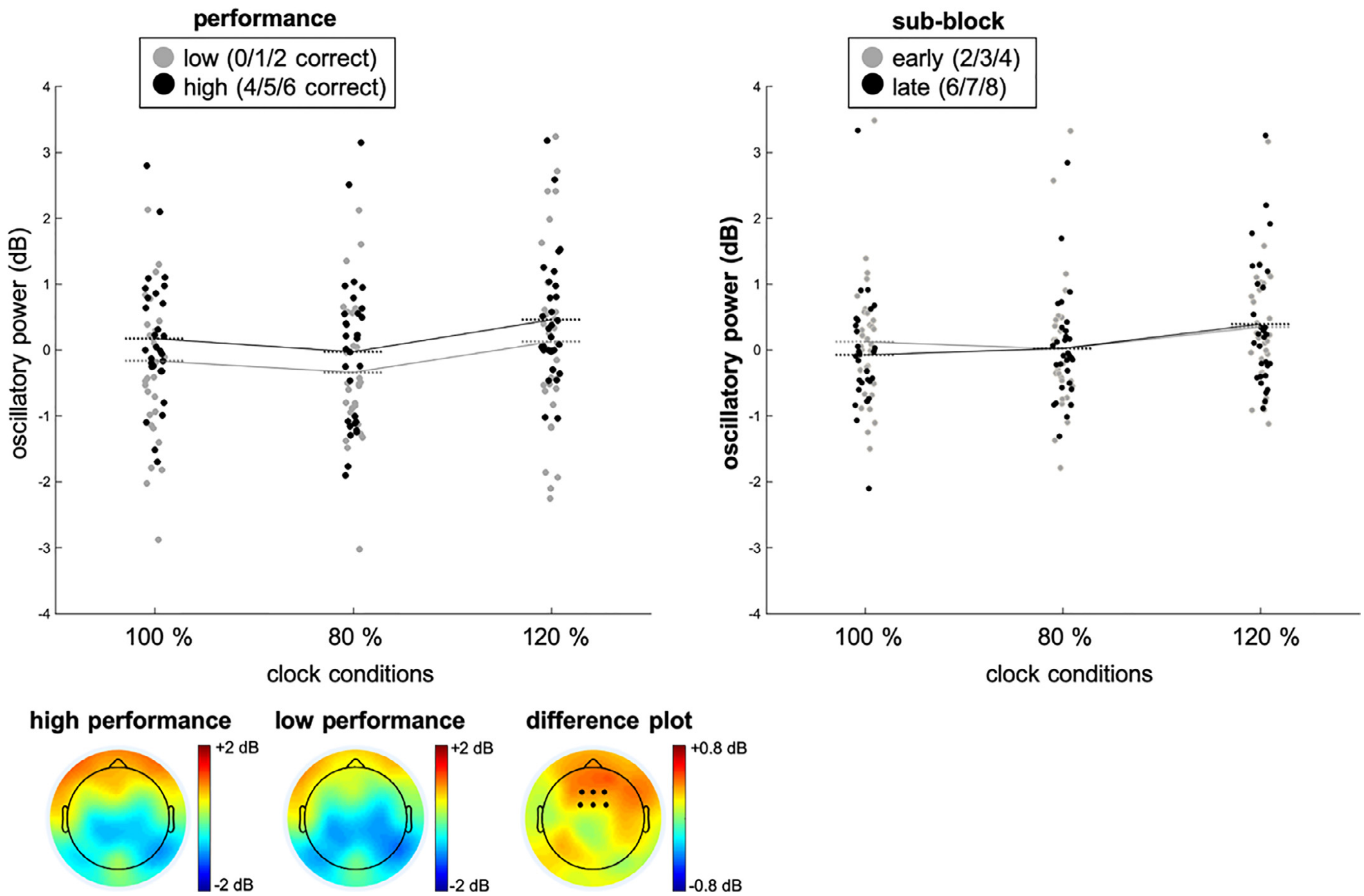

Figure 6. Frontal theta power depending on working memory performance, time on task (sub-blocks) and clock condition. The scatter plots indicate the mean fronto-central (F1, Fz, F2, FC1, FCz, FC2) theta power from 870 - 1562 ms following memory array presentation for each participant as a function of working memory performance and clock condition (left plot) and sub-block and clock condition (right plot). The scalp topographies reflect mean theta power from 870 to 1562 ms for the high vs. low performance conditions. The cluster of fronto-central channels is marked in the difference plot.

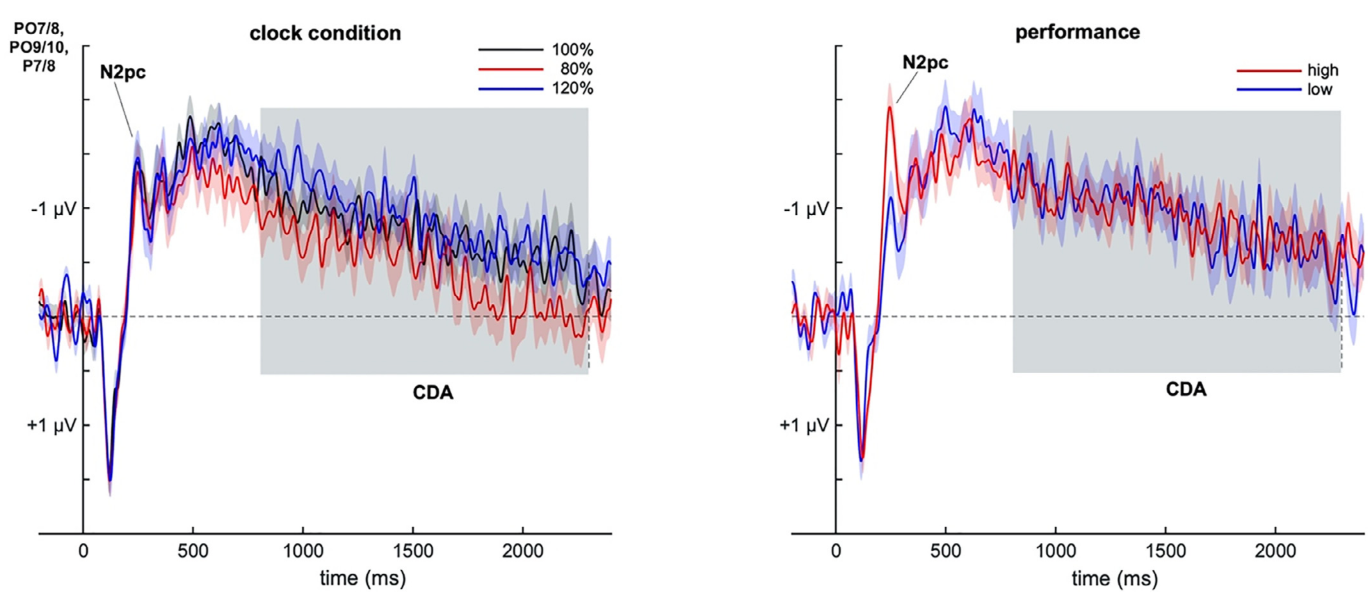

Figure 7. Lateralized posterior ERP effects (N2pc and CDA) dependent on clock condition and task performance. Each curve shows the contralateral minus ipsilateral difference wave within the respective condition. The vertical striped line indicates the onset of the probe array.

of the already mentioned interpretation of the influence of clock manipulation on WM performance, this would argue for a more efficient storage of visuo-spatial information through a stronger engagement of attentional resources on the task at hand. However, as the CDA amplitude did not vary as a function of the number of correctly reported items, the visuo-spatial storage process reflected by this lateralized ERP effect could not have been involved in mediating the effect of clock manipulation on working memory performance.

Summarized, on the behavioral as well as on the EEG level, the differences between clock speed conditions were driven by the accelerated rather than by the decelerated clock, suggesting that an accelerated subjective passage of time leads to a stronger allocation of attentional resources to the task, reflected in an increase of the power of frontal theta oscillations (see Fig. 5 & 6). This effect occurred clearly in terms of a gradual influence and cannot be explained by an "all or nothing" (complete task engagement vs. disengagement) principle.

With regard to the self-report measures, first, we did not observe any systematic effects of clock speed on self-rated performance. The data only indicate a slight decrease in rated performance in the second half of each block. It has to be noted that these results are of no specific relevance, as the performance rating did not represent a crucial measure in the experiment but was applied rather as a story to cover the frequent displaying of the (manipulated) time of day. At least, the weak but systematic effect of sub-block suggests that our subjects responded to the question seriously and not at random. Second and more important, while 90 % of our subjects reported to having paid attention to the time announcements and one third stated to have noticed that the clock was somehow incorrect (after having been asked explicitly), not a single subject was in fact able to correctly indicate in what way the time announcements were wrong. Third, the retrospective ratings of speed of time passage within each of the three blocks did not differ between clock speed conditions. This latter result needs to be viewed with caution because a retrospective judgment of perceived time passage referring to 'blocks ago' may lack the reliability needed (for a recent discussion on the validity of self-report measures, refer to Dang et al. (2020)). While prior research has indicated the importance of real-time data capture regarding the reliability of self-reports (Schwarz, 2007), we refrained from obtaining the time-passage judgment right after each block as such a procedure (explicit reference to time during the task) might interfere with our aim of keeping the manipulation of clock speed concealed. In this regard, future studies need to develop methods for measuring subjective time passage that are both sensitive and 'non-invasive' at the same time. Nonetheless, based on the self-report data obtained in our study, we conclude that (manipulated) clocks or time announcements in general are widely being attended and considered as valid by the participants. At the same time, without becoming aware of the manipulation, participants nevertheless seem to 'feel that something is odd'. However, this impression does not seem to be directly associated with the behavioral effects related to clock speed, as in our experiment these effects did not differ between subjects that mentioned doubts regarding the clock's accuracy and those that did not. It should be noted that this specific comparison is purely post-hoc and of limited validity. Future studies may extend the experimental design by adding a 'control group' that has been informed about the manipulation prior to the experiment.

5. Conclusion

In the present study, we showed for the first time that a simple temporal cue, i.e., an accelerated clock running at a speed of 120 %, can significantly improve cognitive performance in a highly demanding WM task. While WM performance was predicted by the power of frontal theta and posterior alpha oscillations (see Fig. 4) as well as the amplitude of N2pc after memory array presentation (see Fig. 7), the only EEG effect both associated with performance in the WM task and influenced by clock manipulation was frontal theta power (see Fig. 5), an established index of attentional engagement during a cognitive task (Adam et al., 2015; Mussel et al., 2016). This pattern of results can be explained in terms of an increase in the engaged attentional resources during the WM task, potentially mediated by a more positive evaluation of the experimental situation when 'time has flown'. Our data thus provide clear evidence for a complex interweaving of time perception, attentional engagement and higher-level cognitive mechanisms in the human mind.

6. Data and Code Availability Statement

Data and code will be made publicly available on the Open Science Framework (OSF) platform from the time of publication. https://osf.io/k3h98/?view_only=3b91544af822406ebfa8e9813349fe4c

Credit authorship contribution statement

Sven Thönes: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Stefan Arnau:** Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Edmund Wascher:** Conceptualization, Writing - review & editing. **Daniel Schneider:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration.

Acknowledgments

The co-authors would like to thank Sven Thönes, who unfortunately passed away recently, for the pleasant time spent together at the IfADo and for his essential contributions to the success of the research published here.

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