

Thinking theta and alpha: Mechanisms of intuitive and analytical reasoning

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ABSTRACT

Humans have a unique ability to engage in different modes of thinking. Intuitive thinking (coined System 1, see Kahneman, 2011) is fast, automatic, and effortless whereas analytical thinking (coined System 2) is slow, contemplative, and effortful. We extend seminal pupillometry research examining these modes of thinking by using electroencephalography (EEG) to decipher their respective underlying neural mechanisms. We demonstrate that System 1 thinking is characterized by an increase in parietal alpha EEG power reflecting autonomic access to long-term memory and a release of attentional resources whereas System 2 thinking is characterized by an increase in frontal theta EEG power indicative of the engagement of cognitive control and working memory processes. Consider our results in terms of an example - a child may need cognitive control and working memory when contemplating a mathematics problem yet an adult can drive a car with little to no attention by drawing on easily accessed memories. Importantly, the unravelling of intuitive and analytical thinking mechanisms and their neural signatures will provide insight as to how different modes of thinking drive our everyday lives.

1. Introduction

The decisions we make on a daily basis range from fast, intuitive responses to slow deliberations. For example, while driving on an empty road we rely on automatic control to negotiate corners, stop when required, or follow well known directions. However, while driving on a busy highway we utilize cognitive resources when merging, navigating traffic, or listening to directions from our navigation system. Broadly, these two modes of thinking are classified as intuitive (e.g., System 1) and analytical (e.g., System 2) (Kahneman, 2011; Stanovich and West, 2000), respectively. Whereas System 1 thinking is fast, automatic, and effortless, System 2 thinking is slow, contemplative, and effortful (Kahneman, 2011; Stanovich and West, 2000; Evans and Stanovich, 2013a; Kruglanski and Gigerenzer, 2011). Kahneman (2011) described System 1 as the main operator of the brain that leads to our first impressions, heuristics, and associatively learned responses. However, when deemed necessary, Kahneman (2011) posited that System 2 interrupts System 1's automatic processing and exerts control to explore alternative decision options. As this latter mode of thinking requires significant mental effort, we rely on automatic processes whenever possible.

Although there is no clear consensus as to the cognitive mechanisms involved in these modes of thinking, the distinction between System 1 and System 2 have been attributed to autonomous processing versus the

engagement of high-level cognitive mechanisms, respectively (Evans and Stanovich, 2013b; Pennycook, 2017). These systems have been linked to cognitive control (Kahneman, 2011; Pennycook, 2017; Pennycook et al., 2015), attention (Kruglanski and Gigerenzer, 2011; Brush et al., 2017), working memory (Evans and Stanovich, 2013b), and long-term memory (Brush et al., 2017) – a diversity of processes in line with the proposition that these modes of thinking are comprised of cognitive networks (Evans and Stanovich, 2013b). Indeed, all of the aforementioned mechanisms are known to interact when doing everyday tasks (Meier et al., 2017), as evidenced by the electroencephalography (EEG) literature on theta and alpha brain rhythms. Specifically, the recruitment of cognitive control (Cavanagh et al., 2012; Cavanagh and Frank, 2014; Cavanagh and Shackman, 2015) and working memory (Jensen and Tesche, 2002; Raghavachari et al., 2001; Itthipuripat et al., 2013; Sauseng et al., 2010; Hsieh and Ranganath, 2014) have been linked to increased frontal theta activity (event-related synchronization), the recruitment of attention has been associated with decreased parietal alpha activity (event-related desynchronization) (Jokisch and Jensen, 2007; Klimesch, 2012), and the access to long-term memory (and other memory mechanisms) has been reflected by increased parietal alpha activity (Klimesch, 2012).

Demonstrating the interaction of cognitive processes, Cavanagh and colleagues (Cavanagh et al., 2012) found similarly increased frontal theta in response to novelty, conflict, punishment, and error – findings that

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Cavanagh and Frank (2014) later posited to reflect a cognitive control mechanism under environments of uncertainty. Similarly, theta activity increases systematically with the number of items to be remembered (Jensen and Tesche, 2002), with the maintenance (Raghavachari et al., 2001) and manipulation (Itthipuripat et al., 2013) of items, and with computational demands (Hsieh and Ranganath, 2014) – all components of working memory. In the other vein, decreased alpha activity occurs when task-relevant information is attended to and has been attributed to focused attention (Jokisch and Jensen, 2007; Klimesch, 2012; Mathewson et al., 2009, 2011, 2014). In contrast, increased alpha activity has been theorized to reflect the access of knowledge systems including long-term memory (Klimesch, 2012) – findings congruent with the notion that long-term memory is an automatic process (Brush et al., 2017; Klimesch, 2012). In sum then, System 1 functioning may reflect autonomous access to long-term memory and System 2 functioning may involve the recruitment of cognitive control, working memory, and focused attention.

The robust interconnectivity between cognitive control, working memory, attention, and long-term memory supports this premise (Meier et al., 2017; Sauseng et al., 2005, 2010; Klimesch, 2012; Mathewson et al., 2014). For example, Sauseng and colleagues (Sauseng et al., 2010) posited that increased theta reflects the cognitive control of working memory. Moreover, Mathewson and colleagues (Mathewson et al., 2014) demonstrated that top-down control processes were negatively associated with parietal alpha activity. In addition, Klimesch (2012) described the interaction between working memory and attentional mechanisms of long-term memory to represent a coupling of frontal theta and parietal alpha. A fronto-parietal theta and alpha network has also been proposed by Sauseng et al. (2005) who demonstrated increasing cognitive demand corresponded with enhanced long-range theta connectivity and diminished short-range alpha connectivity.

Assessing cognitive control, working memory, attention, and long-term memory within System 1 and System 2 framework, however, may not be simple. One way in which the evaluation of intuitive and analytical reasoning has been studied is with complex word problems. For example, Frederick (2005) developed a test utilizing reasoning problems that were designed to elicit an incorrect intuitive response that could be overridden by contemplation of the problem. An example is the Bat-and-Ball problem: “A bat and a ball cost \$1.10 in total. The bat costs \$1.00 more than the ball. How much does the ball cost?” (Frederick (2005), p.27). An intuitive response of 10 cents first rises, but contemplation of the problem leads to the correct answer of 5 cents (Frederick, 2005). Although these types of tasks are difficult to implement in neuroimaging research, a small cluster of EEG studies focusing on event-related potentials do exist (see Banks (Banks, 2017) for a review; see also Bago et al., 2018; Yin et al., 2018). Banks (Banks, 2017) has argued, however, that major methodological issues made the majority of these studies difficult to interpret and that their findings were often incongruent. Although semantic problems can provide important insights into intuitive and analytical thinking, a wealth of diverse tasks exist that can be used to evaluate the two distinct modes of thinking (Evans and Stanovich, 2013b; Evans, 2008, 2010). For example, a seminal pupillometry study by Kahneman and colleagues (Kahneman et al., 1968) manipulated thinking mode by having participants complete computations under a time pressure. Specifically, to the beat of a metronome that sounded every second, participants heard four digits and were tasked to either retain the digits in memory in one condition (add-zero condition; System 1 thinking) or add one to each of the four digits in another condition (add-one condition; System 2 thinking). Whereas the former would require little cognitive resources, the latter would recruit high-level mechanisms. They found that the pupil dilations between each condition diverged when hearing the numbers, peaked with mathematical computations, and merged when reporting their responses. They concluded that increased pupil size in the add-one condition was analogous to increased processing load and thus System 2 or analytical thinking.

Over the years it has been argued that pupillometry is an effective measure of mental effort (Beatty, 1982; Beatty et al., 2000; Mathôt, 2018; Laeng et al., 2012) and an indicator of System 1 and System 2 thinking (Kahneman, 2011). Moreover, it has been posited that varying pupil dilations reflect changing brain states (Laeng et al., 2012). These changes, thought to be guided by the noradrenergic system, may represent a process wherein top-down working memory mechanisms control attention (Laeng et al., 2012). Thus, the increased pupil dilation seen in Kahneman and colleagues’ (Kahneman et al., 1968) seminal study may have reflected the recruitment of additional cognitive systems. With that said, pupil dilation is also modulated by target detection, perception, learning, memory, and decision making thus demonstrating its inability to dissociate underlying cognitive mechanisms involved within intuitive and analytical thinking (Wang and Munoz, 2015). Alternatively, advances in neuroimaging have opened the way to more direct measures of brain activity and thus underlying cognitive mechanisms.

In the current study, we sought to replicate findings of Kahneman and colleagues’ (Kahneman et al., 1968) seminal research and incorporate modern neuroimaging techniques in order to explore the underlying mechanisms that drive System 1 and System 2 thinking. We elected to pair pupillometry measures with electroencephalography (EEG) due to their analogous high temporal precision and EEG’s more direct association with, and specificity of, brain function. Our decision was also grounded by the aforementioned work linking frontal theta power to cognitive control and working memory and parietal alpha power to attention and memory systems. Here, we sought to replicate Kahneman et al. (1968) with regard to pupil dilation and further that we would see increased frontal theta power and decreased parietal alpha power when employing System 2 relative to System 1 thinking strategies.

2. Methods

2.1. Participants

Thirty undergraduate students ($M_{age} = 22.8$ yrs [21.3 yrs, 24.3 yrs], 22 female, 8 male) from the University of Victoria’s Psychology department were recruited through the use of an online sign-up system. One of these participants was removed due to technical issues with data collection. All participants had normal or corrected-to-normal vision, no neurological impairments, and received extra course credit in a psychology course. All participants provided informed consent approved by the Human Research Ethics Board at the University of Victoria (protocol number: 16–428).

2.2. Apparatus and procedure

Participants were seated in a sound dampened room in front of a 19” LCD computer monitor with external speakers. As this task required participants to stare at a fixation cross while keeping their eyes open, the room lights were kept on to reduce strain elicited by screen illumination. They comfortably placed their forehead against an eye-tracking mount attached to the table where they were to complete an adaptation of the add-one task as described by Kahneman and colleagues (Kahneman et al., 1968). In the current experiment, we only included the condition in which participants were to verbalize their response (rather than think it). The task was written in MATLAB (Version 8.6, Mathworks, Natick, U.S.A.) using the Psychophysics Toolbox extension (Brainard, 1997).

On each trial, participants heard four numbers and were tasked to either simply repeat the numbers that they had heard (add-zero condition), or repeat the numbers after adding one to each of them (add-one condition). For example, if they heard the numbers 4-2-8-5 they would verbalize 4-2-8-5 in the add-zero condition or 5-3-9-6 in the add-one condition. Each trial lasted 26 s where the participants stared at a white fixation cross on a light grey background. A 70 dB metronome of 400 Hz sounded for 50 ms in 1 s intervals (i.e., one beat on each

second). On each trial, after 2 s (i.e., two beats of the metronome), the participants heard the instructions ‘say add one’ or ‘say add zero’ where each word was presented on one beat of the metronome. The instructions and numbers presented to participants were created using a neutral man’s voice from an online text to speech website (www.fromtexttospeech.com). After a 3 s delay, four auditory numbers were presented, one on each of the four proceeding beats. Participants were then to wait for 1 s before verbalizing their response. They were to verbalize each number, in order, on separate beats of the metronome, thus it took them 4 s. After they had verbalized their response, they waited for a 1 s delay, and verbalized the same response again. After four more seconds, the trial ended. During the experiment, participants were instructed to keep their eyes open to facilitate pupil area measures. As this would be difficult for some participants, we emphasized they keep their eyes open from the time they were presented the numbers to when they finished reporting their response. The experiment began with practice trials in order for participants to learn the pattern of the task (e.g., when to respond). Practice trials continued until both the experimenter and participant indicated that they had effectively learned to perform the task. Participants then underwent four blocks of 10 trials within which half were add-zero trials and half add-one trials, presented in random order. Between each block, participants were presented with a self-timed break.

2.3. Data acquisition and processing

In this study, auditory recordings, pupil area, and EEG data were collected. Auditory recordings were used in post processing to determine whether the participant performed each trial adequately and correctly. Trials that were deemed inadequate (e.g., did not report their responses in sync with the metronome) or where the participant reported incorrect digits (error trials) were marked in order to remove corresponding pupil and EEG data.

2.3.1. Pupil area

Pupil area data were recorded within MATLAB via an Eyelink II (SR Research Ltd., Ottawa, Ontario, Canada) device that was attached to a custom head mount. The Eyelink II data were synchronized with stimulus presentation via a direct Ethernet connection. Further, all processing was performed within MATLAB. One of the two cameras were used and was placed below the left eye, angled upwards, with a distance so that the entire eye completely filled the width of the camera. Between each trial, an experimenter ensured that the eye was in the camera frame before proceeding. Pupil area data were recorded at 500 Hz. Post-collection data were chunked into 1 s segments, corresponding to each metronome beat. Error trials were then removed. If a blink was detected within a second, the segment was removed and interpolated using a linear regression (de Gee et al., 2014) between the preceding and proceeding seconds. As there are known individual differences of pupil size, participant data were standardized (de Gee et al., 2014). This standardization was a z-score transformation across the two conditions for each participant. The data were then separated into the two conditions (add-zero and add-one) and all trials were averaged within the corresponding condition and second. A difference of the conditions was also calculated (add-one condition – add-zero condition) for each second. This facilitated grand averages in which each second and condition for all participants were averaged.

2.3.2. Electroencephalography

EEG data were recorded from 64 electrodes mounted in a standard ActiCAP (Brain Products GmbH, Munich, Germany) layout using Brain Vision Recorder software (Version 1.10, Brain Products GmbH, Munich, Germany). During recording, electrodes were referenced to a common ground, impedances were, on average, kept below 20 k Ω and data were sampled at 500 Hz using the ActiCHamp (Revision 2, Brain Products GmbH, Munich, Germany) with a 245 Hz antialiasing low-pass filter. A

DATAPixx processing unit (VPixx, Vision Science Solutions, Quebec, Canada) was used to ensure temporal accuracy. Specifically, the DATA-Pixx was used to synchronize the EEG markers with stimulus presentations. This is accomplished by loading the DATAPixx box with both the upcoming stimulus information (i.e., the next frame to be displayed) and the marker value. The display frame is then sent to the stimulus presentation computer at the same time that the marker is sent to the EEG amplifier.

Post processing was first conducted using Brain Vision Analyzer software (Version 7.6, Brain Products GmbH, Munich, Germany) and then using custom code in MATLAB. Excessively noisy and faulty electrodes were first removed. Data were down-sampled to 250 Hz, re-referenced to averaged mastoid electrodes, and filtered using a dual pass Butterworth filter with a passband of 0.1–60 Hz (order 4 roll-off) and a notch filter of 60 Hz. Epochs –1000 ms to 2000 ms on the onset of the metronome at each second were created to facilitate ocular correction via independent component analysis (ICA). A restricted infomax ICA with classic PCA sphering was used to extract components. Components containing eye blinks were selected manually via component head maps and an examination of the related factor loadings. The artifacts were then removed using ICA back transformation. Electrodes removed early during processing were interpolated using spherical splines. At this stage, data were exported to a MATLAB format. Within MATLAB, data were then reduced to 0 ms–1000 ms for each second of each condition, and run through artifact rejection where trials with an absolute difference of 200 μ V and/or 20 μ V/ms gradient violation were removed. We then conducted a Fast Fourier transform (FFT) using the standard MATLAB function similar to Cohen (Cohen, 2014; Cohen et al., 2008) (script can be found at www.github.com/krigolson). The FFT process did not involve tapering and the output was normalized. The FFT results were standardized and then averaged for each second in the corresponding conditions (add-zero, add-one).

This allowed us to explore the whole range of theta and alpha bands (i.e., our bands of interest). Through visual inspection of frequencies (theta: 4–8 Hz, alpha: 8–12 Hz) across the grand averaged trials, we found consistency in the 4–6 Hz range in theta, and in the 10–12 Hz range in alpha. This is consistent with Klimesch’s (Klimesch, 2012) (Box 2) proposition of an existing global frequency structure within the brain. Specifically, he poses that alpha is the dominant oscillation of the brain, and that optimal alpha-theta coupling would be within the 4–6 Hz range. Moreover, the 10–12 Hz range (i.e., high alpha) of alpha has been shown to reflect different cognitive processes than the 8–9 Hz range (i.e., low alpha) (Lopes da Silva, 2013; Klimesch, 1999). We then reprocessed the data in the same manner as explained above, however, with a 4–6 Hz (order 8 roll-off) passband filter for the theta analyses and a 10–12 Hz (order 8 roll-off) passband filter for the alpha analyses. Data for each second and each condition were then constrained and binned to these theta and alpha frequency bands. For all participants, differences of each second were created by subtracting add-zero trials from add-one trials. Grand averages of each second in each condition were created across participants.

To facilitate visualization of the data, we also conducted wavelet analyses where data processing was the same as described above with the exception that a bandpass filter of 0.1 Hz–60 Hz, a notch filter of 60 Hz (order 4 roll-off), and an epoch of –200 to +1200 ms was used. The wavelet analyses were conducted on the epoched data by multiplying FFT-transformed EEG data with complex Morlet wavelets (Gaussian-windowed complex sine wave with a Morlet parameter of 6 and a frequency range of 1 Hz–50 Hz in 50 logarithmic steps; Cohen (Cohen, 2014; Cohen et al., 2008)) (script can be found at www.github.com/krigolson). The output was then normalized and averaged across trials for the add-zero and add-one conditions. The wavelets were standardized, difference wavelets were created by subtracting the add-zero condition from the add-one condition, and grand average wavelets were computed by averaging corresponding conditional and difference wavelets across all participants.

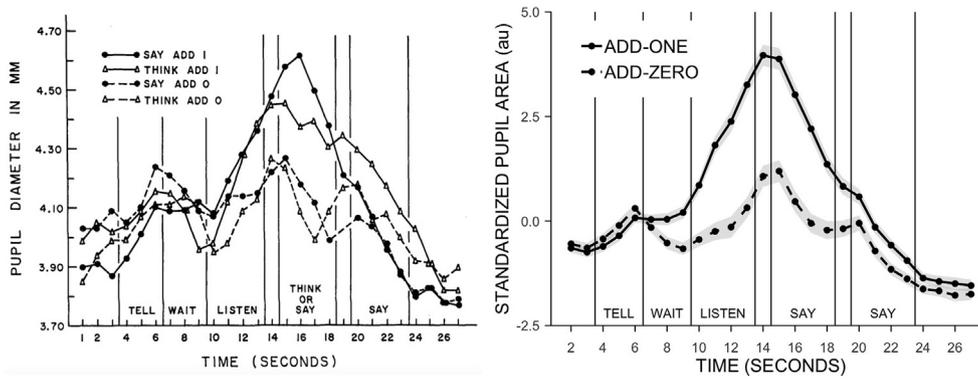


Fig. 1. Pupil dilation for both conditions across the task for the original (left) and the current study (right). The x-axis corresponds to 1 s intervals. Note that in the current study (right), data collection began a second later than the original study (left). Error bars represent 95% within subject credible intervals. Left figure reproduced with permission from Kahneman et al. (1968).

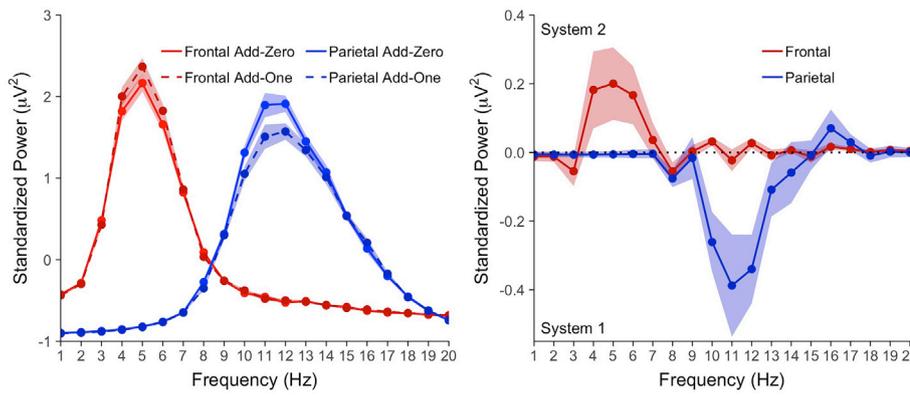


Fig. 2. Frequency line plots of the add-zero condition and the add-one condition for frontal (Fz) and parietal (CPz) electrode locations. Left: conditional line plots, right: difference line plots. In the right figure, negative values indicate enhanced power for the add-zero condition (System 1 processing) and positive values indicate enhanced power for the add-one condition (System 2 processing). Power values have been standardized. Frontal analyses were filtered with a band-pass consistent with theta (4–6 Hz), while parietal values were filtered with a band-pass consistent with alpha (10–12 Hz).

2.4. Data analysis

A two-tailed repeated-measures t-test was conducted on accuracy to determine any difference in performance across conditions. As previously stated, pupil diameter and FFT processing each resulted in two conditional averages (add-zero, add-one) across the 26 s. Kahneman (2011) indicated that the effect of processing (i.e., computations in the add-one condition) was most pronounced after hearing the last of the four digits, thus we focused our analyses to this time window (i.e., the 1 s interval in

which they heard the last number). Particularly, we conducted two-tailed repeated measures t-tests for each measure at this time point. All measures of error represent 95% within subject credible intervals (Nathoo et al., 2018). The assumption that data were normally distributed was tested for all variables using the Shapiro-Wilk test of normality, however, as paired sample t-tests are robust to violations of normality, no corrections were made when normality was violated (the accuracy data were found to violate this assumption). All statistical analyses were conducted in R (R Core Team, 2016) (version 3.3.0) using native functions of R

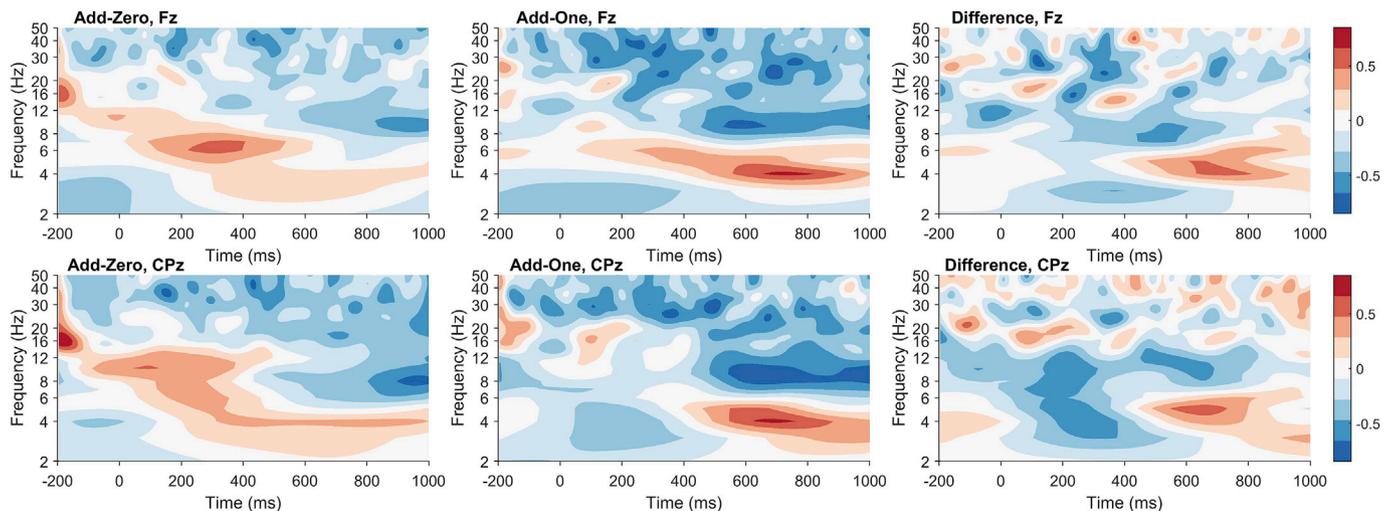


Fig. 3. Wavelet surface plots of the add-zero condition, the add-one condition, and the difference (add-one minus add-zero) for frontal (top) and parietal (bottom) sites of the scalp. All values are in units of standardized power. This data has a passband filter of 0.1–60 Hz and a notch filter of 60 Hz.

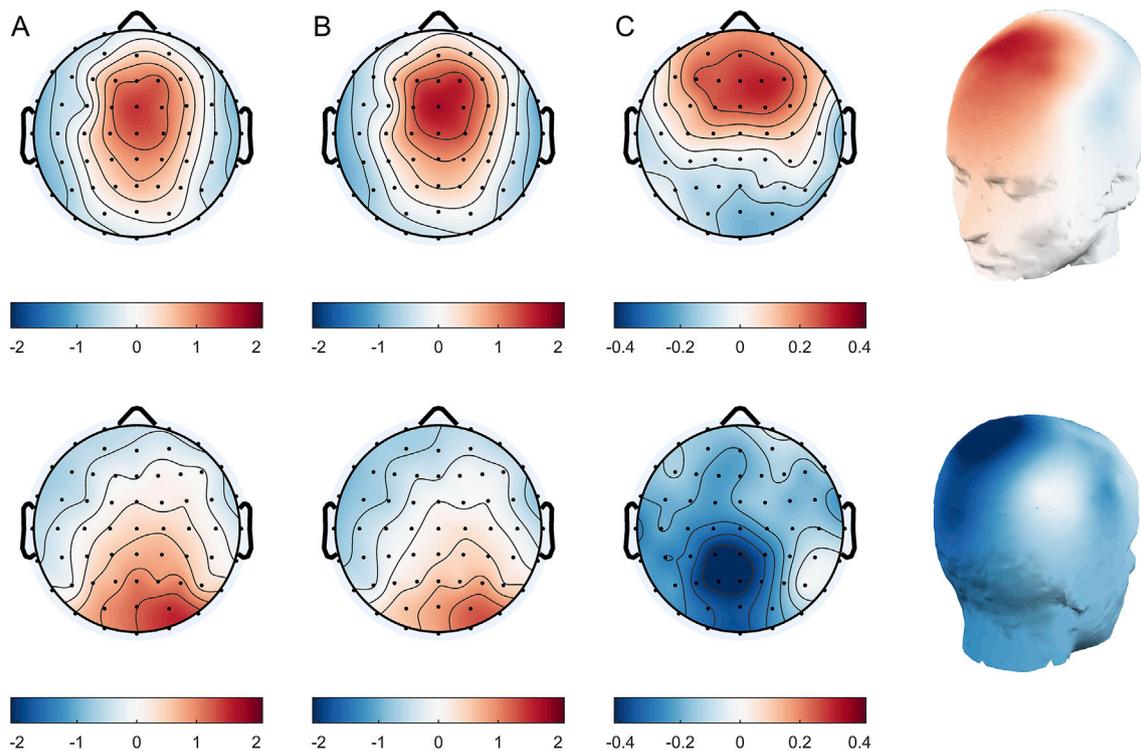


Fig. 4. Topographic headmaps of theta (top) and alpha (bottom). A: Add-Zero condition, B: Add-One condition, and C: 2D and 3D topographic maps of the difference between the conditions (add-one minus add-zero). Each electrode is a pool of up to five electrodes surrounding it. The electrode of interest for theta is Fz and for alpha is CPz. Power values have been standardized.

Studio (RStudio 2016) (version 1.1.383), with the exception of Cohen's D measures which utilized the R package 'effsize' (Torchiano, 2017). Figs. 1 and 2 were produced using the 'ggplot2' R package (Wickham, 2016) and Figs. 3 and 4 were produced using native MATLAB functions and EEGLAB (Delorme and Makeig, 2004), respectively.

3. Results

First, we analyzed measures of accuracy and pupil area to determine whether the add-one condition (System 2) was more difficult than the add-zero condition (System 1). Performance was worse in the add-one condition (74% [72%, 77%]) than in the add-zero condition (92% [89%, 94%]), $M_d = -18\%$ [-20%, -15%], $t(28) = -5.79$, $p < .0001$, $d = -1.08$. The pupil area and EEG analyses focused on the time segment in which the last number was presented to the participant – the time point at which the difference between System 1 and System 2 processing is at its peak (Kahneman, 2011; Kahneman et al., 1968) (see Fig. 1). Our analysis revealed pupil area was larger for the add-one condition in comparison to the add-zero condition, $M_d = 2.94$ au [2.69 au, 3.18 au], $t(28) = 9.97$, $p < .0001$, $d = 1.85$.

Next, we investigated whether thinking mode (System 1 versus System 2) impacted frontal theta band power and parietal alpha band power (see Figs. 2 and 3). Peak theta and alpha topographic head maps can be seen in Fig. 4 – we observed maximal theta power over frontal central regions and maximal alpha power over parietal central regions of the scalp. Frontal theta power was larger for the add-one condition than the add-zero condition, $M_d = 0.18 \mu\text{V}^2$ [0.12 μV^2 , 0.25 μV^2], $t(28) = 2.31$, $p = .0287$, $d = 0.42$, at electrode Fz (see Figs. 2 and 3). Conversely, the add-one condition elicited smaller parietal alpha power than the add-zero condition, $M_d = -0.33 \mu\text{V}^2$ [-0.42 μV^2 , -0.24 μV^2], $t(28) = -3.13$, $p = .0040$, $d = -0.58$, at electrode CPz (see Figs. 2 and 3).

4. Discussion

Here, we demonstrate that cognitive control, working memory, attention, and long-term memory are mechanisms involved in System 1 and System 2 thinking. We found that intuitive (System 1) thinking involved increased parietal alpha activity and decreased frontal theta activity suggesting a recruitment of autonomic long-term memory mechanisms and a release of cognitive control, working memory, and attention. Alternatively, we found that analytical (System 2) thinking elicited greater frontal theta activity and reduced parietal alpha activity suggesting the recruitment of cognitive control, working memory, and focused attention without need to access long-term memory. This is congruent with existing literature that theorizes System 1 thinking to rely on automatic or routine systems of the brain and System 2 thinking to recruit cognitively heavy systems (Kahneman, 2011; Stanovich and West, 2000; Evans and Stanovich, 2013a, 2013b; Kruglanski and Gigerenzer, 2011; Stanovich and Toplak, 2012; Kahneman and Frederick, 2001; Evans, 2011; Varga and Hamburger, 2014).

These findings adhere to network science (Börner et al., 2007) which advocates for research to assess the functional relatedness of a set of mechanisms rather than mechanisms in isolation (Bressler, 1995; Bullmore and Sporns, 2009; McIntosh, 2000). For example, McIntosh (2000) posited that cognition arises from the activation of cognitive networks that span the brain. Others have further specified that short-range neural connections reflect highly specialized processes while long-range neural connections correspond to integrative processes (Bullmore and Sporns, 2009; Bassett and Bullmore, 2006; Sporns and Zwi, 2004). Analogously, we found a concomitant relationship between frontal and parietal neural activity during different modes of thinking. Further, our findings indicate that this fronto-parietal network may involve a variety of mechanisms including cognitive control, working memory, attention, and long-term

memory. Thus, we believe that System 1 and System 2 thinking encompasses a range of interrelated cognitive mechanisms.

This is consistent with the three-staged framework of System 1 and System 2 proposed by Pennycook and colleagues (Pennycook et al., 2015). Within this model, intuitive responses accessed from long-term memory are first generated – a notion compatible with Klimesch's (Klimesch, 2012) theory that desynchronized alpha activity represents access to an autonomic knowledge system. Within this stage there is no need for working memory or executive functioning. Next, these intuitive responses are assessed to determine whether any conflict between them exists (see also Bago et al., 2018; Yin et al., 2018). Analogous to Cavanagh and Frank's (Cavanagh and Frank, 2014) theory of the mechanism driving frontal theta, if conflict exists, cognitive control mechanisms are employed. Finally, a chosen intuitive System 1 response is either adopted (if no conflict was detected) or engaged cognitive control mechanisms recruit higher-level mechanisms (e.g., working memory and attention (Meier et al., 2017; Sauseng et al., 2010; Klimesch, 2012)) to produce an analytically driven System 2 response (if conflict was detected).

There may be constraints, however, to the conclusions that we can draw from our findings. Here, we investigated measures associated with cognitive control, working memory, attention, and long-term memory. These processes, however, were not isolatable by the experimental task, and we were therefore unable to discern their individual influences on System 1 and System 2 processing. For example, frontal theta activity has been shown to reflect both cognitive control and working memory. It could be that one or the other mechanism caused the observed change in theta activity, that they both did in an additive manner, or that they both did in an interactive manner. But here we cannot know. Moreover, simultaneous involvement of attention and long-term memory in parietal alpha activity prevents us from determining the contribution of each mechanism. For example, diminished alpha activity may indicate focused attention but it may also simply indicate the release of long-term memory (Klimesch, 2012). Just as it is with frontal theta activity, we are unable to determine each mechanism's contribution to the observed parietal alpha activity. This research then sets the groundwork for cognitive mechanisms that may be further explored. With this, future research must utilize tasks that are able to systematically control for these proposed mechanisms in order to discern the involvement each mechanism has in System 1 and System 2 thinking and how they may interact. Furthermore, it will be important for future research to generalize these findings by evaluating these neural measures and mechanisms in a variety of other tasks thought to involve System 1 and System 2 thinking.

In summary, we manipulated the reasoning states of our participants. We found that System 1 thinking enhanced parietal alpha power and diminished frontal theta power. Conversely, System 2 thinking increased frontal theta power while decreasing parietal alpha power. We proposed that this indicates System 1 functioning to require autonomic access to long-term memory without the need for cognitive control, working memory, and focused attention, and System 2 functioning to be driven by the employment of cognitive control which recruits working memory and focused attention mechanisms without need to access long-term memory knowledge systems.

Declarations of interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuroimage.2019.01.048>.

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