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1. Introduction

1.1 Iconic Memory

1.1.1 *Early Experiments on Iconic Memory*

Imagine for a moment, that you are walking outside during a dark, stormy night, with no external sources of light. Suddenly, everything is lit up by a lightning flash for just a moment. Despite the area around you only being illuminated for a fraction of a second, you are still able to recall quite accurately, what you have seen for a short period of time. This fleeting visual representation of the area around you can be thought of as an example for iconic memory (IM), a type of sensory memory that is able to store briefly presented visual stimuli for up to a second quite accurately, but decays rapidly. The term was first coined by Neisser (1967), and one of the first to investigate this memory domain was George Sperling (1960). He was curious, that observers of complex stimuli like numbers and letters, presented via a tachistoscope, often reported to have seen more than they could remember when asked to recall the stimuli. Thus, he developed a series of experiments to investigate the information available to observers following brief exposure to stimulus arrays that consisted of multiple rows containing letters and numbers, e.g., a 3x3 grid. In a first step, he estimated the amount of information that could be recalled when participants were asked to report the whole stimulus array, which amounted to ~4.2, or ~46% correctly reported items, mostly independent of the number, type and exposure duration of stimuli originally presented. This is consistent with the generally accepted estimated immediate memory span, or working memory limit in humans (e.g., Barton et al., 2009; Buschman et al., 2011; Cowan, 2001; Miller et al., 2018). Crucially though, Sperling (1960) also introduced another experimental condition where participants only had to report a subset of the array. For example, when a 3x3 grid was presented, subjects only had to report one of the rows (three items), indicated by a random, auditory post-cue. Due to the random nature of the cue, the total amount of information available to subjects could be sampled and estimated reliably by multiplying the average number of correctly reported letters with the number of equiprobable partial reports. In case of the 3x3 grid, this resulted in ~8.2 of 9 available letters, or ~91% hit rate, when the cue was presented almost immediately after stimulus presentation. This was about twice as high as the results from the whole-report conditions and suggested to Sperling, that there was more information available to participants than they were able to access, when asked to recall all stimuli. This ‘partial-report superiority’ constitutes a key element of IM. However, the effect was not stable over time but declined as

the delay between stimulus array and post-cue in the partial report condition increased. Once the delay reached a duration of ~ 1 s, partial report-performance was at about the same level as whole-report performance, indicating that IM representations decayed rapidly and were only available for a short amount of time. Furthermore, Sperling (1960) was also able to demonstrate that both partial- and whole-report performance were sensitive to visual interference following stimulus presentation, suggesting a reliance on persisting visual afterimages which could easily be erased or masked. Exposure duration of the stimuli, on the other hand, had little to no effect on performance. Additionally, a positional superiority effect was also found, i.e., a strong tendency for better performance when the top row had to be reported compared to other rows, which has since been replicated (Gegenfurtner & Sperling, 1993; Graziano & Sigman, 2008). Furthermore, a tendency for better performance in the right visual field and close to the horizontal median has also been found (Graziano & Sigman, 2008).

Following these early experiments by Sperling (1960), several other characteristics of IM have since been investigated further. For instance, the amount of time for which cues are presented also affects partial report performance, as was shown by Dixon et al. (1997) and Fenske & Stolz (2001) in partial-report paradigms using a bar-code task (i.e., one single stimulus is probed by a bar indicator). Both report an inverse relationship between cue duration and performance, meaning that an increased cue duration (> 50 ms) negatively affected performance. Interestingly though, this effect was mostly specific to peripherally presented cues, not for central ones.

More recently, some evidence supporting an alternative view of iconic memory decay has also been proposed. Contrary to the gradual decay theory, by using a computational modelling approach, Pratte (2018) was able to show that visual information corresponding to the colour and orientation of presented stimuli did in fact not decay exponentially with an increasing delay between stimuli and cue, but rather seemed to discretely vanish from memory during the first few hundred milliseconds following perception. Interestingly though, precision for items that managed to be retained was largely unaffected by the increased stimuli-cue delay, indicating that "[...] an item in iconic memory is maintained with high precision until it vanishes abruptly and completely" (Pratte, 2018, p. 881). However, evidence supporting this conception is rather scarce, as this is, to our knowledge, the only article to report such a sudden-death model of IM. Furthermore, the stimuli used in the experiment consisted only of

coloured squares and Gabor patches, calling into question whether information about the identity of number or letter stimuli would exhibit the same properties.

1.1.2 Visible & Informational Persistence

Prior to 1980, the predominant view of IM was that of a single-unit, high-capacity, pre-categorical, quickly decaying visible memory and it was assumed, that Sperlings' experiments, and tasks examining *visible persistence* (Coltheart, 1980), or *phenomenological persistence* (Turvey, 1978), were measuring the same underlying representations (Irwin & Thomas, 2008). Visible persistence here being the lingering phenomenal trace of a visual stimulus after its offset, much like the example I gave at the very beginning with a lightning flash illuminating the area around you very briefly. However, it is not only a visual representation that gets maintained after stimulus offset, but also information about the stimulus itself persists, something usually termed *informational persistence* (Coltheart, 1980; Turvey, 1978). In an extensive review, Coltheart (1980) argued that, even though both types of persistence might constitute what we refer to as IM, they are distinct from one another. There are several reasons for his assumption, for instance the estimated duration of visible persistence after stimulus offset (only ~100 ms) differs significantly from the timeframe during which information about the stimulus is available after offset (~ 500-1000 ms). Furthermore, Coltheart (1980) pointed out that the duration of visible persistence often decreases with increased stimulus presentation time in a variety of paradigms, whereas the persistence duration in partial-report experiments is usually unaffected by stimulus duration. Thus, Coltheart (1980) concluded that visible and informational persistence constitute two distinct phenomena, with visible persistence being the result of neuronal after-activity in the visual system and informational persistence relying on a memory system post-stimulus identification. Following this new approach, Irwins and Yeomans (1986), conducted a series of experiments aimed at disentangling the characteristics of informational persistence. They mostly investigated the effects of cue duration and masking of single letters in a partial report paradigm and proposed a model of informational persistence that consists of two separate elements: on one hand, a brief *visual analog representation*, which begins at stimulus offset and is subject to masking effects due to its visual nature, and on the other, a non-visual post-categorical component, i.e. *non-visual identity codes* that are immune to masking effects. To summarize, the current generally accepted conceptualization of visual sensory memory, or iconic memory, is one characterized by multiple components. First, the visual system generates a sensory response elicited by a visual stimulus. Visible persistence is thus the prolonged sensory response of the visual system that persists after

stimulus offset. However, as mentioned above, non-visible information also gets maintained via the visual analog representation, which is maskable but relatively precise regarding spatial information for ~150-300 ms, and the non-visual identity codes, which are immune to masking effects and contain pre-categorical information about the stimulus (see Irwin & Thomas, 2008 for an extensive overview).

1.1.3 Differentiation to Other Visual Short-Term Memory Stores

Besides IM, another well-studied type of short-term visual memory is visual working memory (VWM), a longer, more durable store that is mainly characterized by its limited capacity of around 4 items (e.g., Barton et al., 2009; Buschman et al., 2011; Cowan, 2001; Miller et al., 2018), as mentioned above. To distinguish between these two memory stores, it is beneficial to consider, how information is represented in each respective store. Regarding IM, as the name already implies, information is represented in an iconic format. But what exactly is an ‘icon’? Quilty-Dunn (2019) posit two principles that icons must obey to be considered iconic:

Parts: Parts of icons correspond to parts of what they represent.

Holism: Parts of icons represent multiple properties simultaneously.

According to Quilty-Dunn (2019), iconic representations are akin to a picture of the item that is held in memory. Imagine, for instance, that you hold the image of a large, pink elephant in your mind. In this example, Parts would be satisfied, because each part of the mental image corresponds to a specific part of the elephant. Holism would be satisfied, because each part of the image of a pink elephant simultaneously represents multiple properties, such as colour and spatial location. According to Quilty-Dunn (2019) and, more recently, Green and Quilty-Dunn (2021), representations held in VWM, on the other hand, are stored in a propositional, discursive manner. To keep with our elephant example, the propositional representation would be akin to a sentence such as this: “*This is a large, pink elephant*”. Here, both Parts and Holism criteria are not satisfied, because each symbol (i.e., word) is discrete and acts as a stand-in for individuals or features (Green & Quilty-Dunn, 2021) instead of corresponding to the whole scene. Interestingly, this difference in type of representation might explain the differences in capacity limits between IM and VWM. Iconic representations require less resources to encode items or scenes compared to propositional representations, due to obeying the Parts & Holism criteria. As Quilty-Dunn (2019) put it: “[...] an iconic representation of a scene could encode

a large array of letters or other items that appear in that scene without segmenting out individual items or sorting them into high-level categories” (p. 666).

Apart from IM and VWM, in recent years another type of visual short-term memory has been proposed: the fragile VSTM, which seems to be, temporally speaking, situated between IM and VWM (Landman et al., 2003; Sligte et al., 2008). By using a change-detection task with different types of cues as varied independent variables, Sligte et al. (2008) were able to accurately discern between IM, fragile VSTM and VWM. The types of cues used were either an iconic cue (right after memory array off-set), a retro-cue (1,000 ms after memory array off-set) or a post-cue (after on-set of the probe array). Additionally, the authors varied the strength of elicited afterimages, by either using white items on a black background (strong afterimage), or red items on a grey background (weak afterimage). Interestingly, in the iconic cue condition, participants performed significantly better (near perfect) when strong afterimages were elicited, compared to weak afterimages. This further strengthens the notion of Sperling (1960), that IM seems to, at least in part, rely on visually persisting afterimages. Furthermore, Sligte et al. (2008) found that both post-cue and retro-cue conditions were unaffected by the afterimage manipulation. Despite this, participants performed significantly better when presented with retro-cues compared to post-cues, suggesting a fragile memory store that exceeds the capacity of VWM but can be disentangled from IM. Importantly, by introducing masking conditions, the authors were further able to demonstrate that IM representations were easily wiped out by introducing a light mask that followed the stimulus array. Contrary to that, the posited fragile VSTM was unaffected by the light mask but could instead be overwritten by an irrelevant mask that included similar stimuli as the memory array and by doing so, reached the capacity level of VWM. Taking all of this into account, Sligte et al. (2008) propose a tri-partite division of VSTM stores:

- (1) Iconic Memory
- (2) Fragile VSTM
- (3) Robust VSTM (VWM)

As the authors point out, this distinction between two high-capacity VSTM stores that precede VWM is similar to the distinction drawn by Coltheart (1980) between visible persistence and informational persistence. Visible persistence here would constitute the traditional IM finding obtained by iconic cues and informational persistence could be equated to the fragile VSTM, as measured in the retro-cue condition. However, since the retro-cues

that were used by Sligte et al. (2008) were not presented in the traditional IM time window and, furthermore, since visible persistence and visual afterimages are traditionally thought of as two separate phenomena, since they are affected quite differently by stimulus duration and intensity and, also, exhibit different rates of decay (Di Lollo et al., 1988), this interpretation seems unlikely albeit not impossible. Nonetheless, the evidence presented by Sligte et al. (2008) favours the interpretation of a fragile VSTM store that can be distinguished from IM mostly by its immunity to light-masking, thus non-reliance on afterimages, and longer duration of ~ four seconds, compared to the traditional IM timeframe of ~ one second.

1.2 Neural Oscillations

Functionality of the human brain crucially depends on rhythmic, repetitive patterns of electrical activity that can be observed at multiple levels of hierarchical organization: microscopic (activity from single neurons), mesoscopic (activity of a group of neurons) and macroscopic (activity between different brain areas), see Haken (1996) for an extensive introduction. One of the first to discover these electrical patterns in humans was Hans Berger (1929), who is famously credited with recording the first human electroencephalography (EEG), a method by which one can measure meso- and macroscopic electrical brain activity by means of electrodes on the scalp. By applying spectral analysis methods, the rhythmic electrical signal that is picked up by the EEG can subsequently be divided into several distinct frequency bands that are each associated with various cognitive functions and characteristics. As Buzsáki and Draguhn (2004) lay out in their review, the frequency bands most commonly associated with cognitive processes are delta (~1–4 Hz), theta (~4–8 Hz), alpha (~8–13 Hz), beta (~13–30 Hz) and gamma (~30–100 Hz). For the sake of brevity, I will summarize the main findings on frequency bands that are most relevant to the current thesis: alpha and theta.

1.2.1 Alpha Oscillations

The oscillatory (spontaneous) alpha rhythm can be observed most prominently, when subjects are resting with their eyes closed, and has been traditionally associated with periods of cognitive inactivity, due to this (see Clayton et al., 2018 for an extensive review). For instance, regarding visual attention, it was shown multiple times that alpha power is significantly increased in the hemisphere contralateral to an attended stimulus, and significantly decreased in hemisphere processing the attended stimulus (Kelly et al., 2006;

Samaha et al., 2016). Furthermore, alpha has also been related to the general excitability of the visual cortex, as low alpha power indicates a susceptibility to both the appearance of visual phosphenes during magnetic stimulation of the visual cortex (Romei et al., 2008) and the perception of stimuli, even if none were presented (Iemi et al., 2017). More recently, Iemi et al. (2022) were also able to demonstrate that strong pre-stimulus alpha oscillations were not only associated with lower neuronal excitability, but also with reduced sensory encoding strength during an auditory categorization task.

Beyond its' more traditional, passive conceptualization as a marker for inactivity and low neuronal excitability, alpha also takes on a more functional role, by actively inhibiting and suppressing the processing of irrelevant stimuli, thus gating incoming information, and reducing cognitive load (see Jensen & Mazaheri, 2010 for a review). Interestingly though, considering the rhythmicity of oscillatory activity, inhibition of cognitive processing by means of alpha oscillations should thus also be rhythmic, or pulsed, in nature (Mathewson et al., 2011). This suggests that perception of visual stimuli is not constant, but rather wave-like or oscillatory due to alternating states of inhibition and exhibition, indicated by peaks and troughs in the alpha oscillation, respectively. This notion of rhythmic perception and processing will be expanded upon further in Section 1.3.

Another functional role of alpha also seems to be the maintaining of sensory information over time. By cross correlating the changing luminance values of a disc stimulus with its elicited EEG responses, one can obtain so-called echo functions, representations of the genuine brain response to the input sequence, which are characterized by high amplitude oscillations at ~ 10 Hz that are strongly correlated to the internal alpha rhythm of participants (VanRullen & Macdonald, 2012). Furthermore, by additionally introducing neuroimaging and binocular rivalry methods, it was discerned that these perceptual echoes originate in the primary (V1) and secondary (V2) visual cortex (Luo et al., 2021a) and can be elicited even without conscious perception, albeit with reduced power in that case (Luo et al., 2021b). Interestingly, decaying neural activity in V1 has recently also been proposed as a possible neural basis of IM in macaques (Teeuwen et al., 2021), suggesting that IM and perceptual echoes share the same neural origin and are possibly linked to each other.

1.2.2 Theta Oscillations

Theta oscillations have first been described in 1938, both as a spontaneous rhythm, as well as a reaction to painful stimuli in the hippocampus of rabbits (Jung & Kornmüller, 1938). Ever since this initial discovery, extensive research has been conducted on the functional role of theta oscillations in the human brain and has linked them to a broad range of cognitive, affective, and perceptual processes, such as sensory & motor processing, arousal, attention, navigation and, most relevant for the current thesis, memory (see Karakaş, 2020; Herweg et al., 2020 and Klimesch, 1999 for extensive reviews). For instance, event-related synchronization in the theta band is thought to reflect episodic memory, as it can reliably distinguish between good and bad performers in episodic memory tasks (Doppelmayr et al., 1998; Klimesch et al., 1994).

Furthermore, considering that theta has also been closely linked to the process of long-term-potentialiation (Larson et al., 1986; Maren et al., 1994; Stäubli & Fang, 1995), which refers to the strengthening of synapses in order to facilitate transmission between neurons and serves as a core mechanism underlying learning and memory, some have proposed that hippocampal theta activity might reflect the encoding of newly arriving information (Klimesch, 1999). This view is supported by several studies that demonstrate an increase in theta power during the encoding of various categories of items, such as lexical or visuospatial, in working memory tasks (Sederberg et al., 2003; Sauseng et al., 2004; Jaiswal et al., 2010). More recently, Xie et al. (2021), extended this to audiovisual stimuli and demonstrated, that not only oscillatory theta power, but also interregional connectivity via theta activity across multiple cortical regions was significantly enhanced during the encoding of multisensory items. Additionally, harkening back to the notion of rhythmic perception and processing mentioned above, memory encoding, retrieval and concomitant eye movements were all shown to be guided, or dependent on the phase of the hippocampal theta cycle (Douchamps et al., 2013; Hasselmo et al., 2022; Kragel et al., 2020; Newman et al., 2013).

1.3 Perceptual Cycles

1.3.1 Neurophysiological Evidence

When we experience the world around us, it usually seems as though we are continuously taking in and processing information. Despite this, as mentioned above, an increasing amount

of recent evidence suggests, that we instead perceive and process external and internal information in a more discrete manner, akin to a movie that consists of multiple frames, even though to us it looks like a continuous stream of images. Early evidence supporting this idea can be found in a study by Nunn and Osselton (1974), who investigated the interaction between subjects' EEG alpha rhythm and the detection of briefly presented stimuli. By using the Galvanic Skin Response (GSR) amplitude as an indicator for perception and concurrently measuring EEG, they were able to demonstrate that participants only perceived stimuli, if they were presented during certain phases of the underlying alpha rhythm, suggesting alternating periods of enhanced detection performance and diminished detection performance (Nunn & Osselton, 1974). In a similar fashion, albeit more recent, Busch et al. (2009) presented participants brief flashes of light at the luminance threshold (50% detection rate) and concurrently recorded EEG. By subsequently comparing the phases associated with hits and misses respectively, Busch et al. (2009) report significant phase concentrations for hits and misses at different phase angles in the alpha and theta frequency bands, which accounted for ~16% of detection performance variability. In other words, alpha and theta phase could reliably predict detection performance on a single trial-basis and, as the authors put it: “[...] the visual detection threshold fluctuates over time along with the phase of ongoing EEG activity” (Busch et al., 2009, p. 7869).

Similar phase-dependency effects have since been reported across a variety of sensory, cognitive, and perceptual modalities, such as the auditory detection threshold (Neuling et al., 2009), the persistence of EEG alpha entrainment (Otero et al., 2020), episodic memory performance (Cruzat et al., 2021) and spatial memory performance (Bauer et al., 2021). Crucially though, these perceptual cycles, as they were termed by VanRullen et al. (2016), can not only be investigated by neurophysiological methods, but also solely behavioural ones. This can be achieved by densely varying time intervals between presented stimuli and cues, analysing performance as a function of this delay and, finally, investigating the spectral composition of the resulting time courses (VanRullen et al., 2016).

1.3.2 Behavioural Evidence

One of the first to report evidence for perceptual cycles by solely behavioural methods were Landau and Fries (2012) in a change detection paradigm. Here, participants had to monitor two simultaneously presented stimuli (drifting gratings) and, after a variable delay, a visual flash was presented to reset attention to one of the stimuli. After the attentional reset,

which allowed the investigation of the underlying temporal structure, performance was found to fluctuate rhythmically between 4 and 10 Hz. Interestingly, a flash in the right visual field (RVF) revealed oscillations at 4 Hz, whereas a flash in the left visual field (LVF) revealed a 7 – 10 Hz rhythm. The authors reason that there might exist a general attentional sampling rhythm at around 8 Hz, which can be reset and oriented by a RVF flash and thus become apparent as an alternating 4 Hz rhythm for both stimuli/locations in antiphase. Regarding the LVF flash, it seems as though the attentional reset was only partially successful, and attention was variably allocated to either location, making the 8 Hz attentional rhythm apparent as 7-10 Hz oscillations (Landau & Fries, 2012). In line with this, more recent studies have also reported attentional sampling rhythms in similar frequency ranges, such as a 7 Hz attentional rhythm during a difficult visual search task (Dugué et al., 2015), an alternating 4 Hz rhythm for two stimulus locations in an orientation-discrimination task (Senoussi et al., 2019) and an 8 Hz rhythm for feature-based attention on a single object, which also became apparent as two alternating 4 Hz rhythms for two objects (Re et al., 2019).

Similarly, behavioural periodicities regarding informational sampling itself have also been reported. For instance, Blais et al. (2013) systematically modulated the signal-to-noise ratio (SNR) of visual facial stimuli to investigate its influence on identification performance and report significant correlations between 10 Hz and 15 Hz frequencies (synchronized with stimulus onset) and performance, indicating an informational sampling rhythm in the alpha frequency range. Furthermore, Drewes et al. (2015) also report behavioural oscillations in a scene recognition paradigm at a frequency range of ~5 Hz. More recently, and importantly for my thesis, behavioural oscillations have also been investigated in memory domains, more specifically in the working memory domain. For instance, by employing a dense sampling working memory paradigm, Pomper and Ansorge (2021) were able to demonstrate that two visual templates that were concurrently held in WM, alternated in antiphase to each other at a frequency of ~ 6 Hz, which thus became apparent as ~ 6 Hz fluctuations in their performance.

Taking the above presented evidence into account, it seems reasonable to conclude that most, if not all, of our cognitive and perceptual processes operate rhythmically, and not continuously. Furthermore, as VanRullen (2016) point out in their extensive literature review, the most commonly reported frequencies for perceptual cycles lie in the alpha and theta frequency bands, with alpha (~ 10 Hz) being mostly associated with a sensory sampling rhythm and theta (~ 7 Hz) being mostly associated with attentional sampling.

1.4 Research Question & Hypothesis

Given the amounting evidence for perceptual cycles, it seems plausible to consider that iconic memory performance might also exhibit behavioural periodicities, much like working memory performance. It might be the case that these periodicities have not been reported as of yet, because the temporal resolution of iconic memory experiments (i.e., the amount of time variation between stimuli and cue) is usually not high enough, with only a few select timepoints (e.g., Sperling, 1960; Lu et al., 2005; Yeomans & Irwin, 1985; Chow, 1985; Graziano & Sigman, 2008). By thus employing a behavioural, densely sampled, high temporal resolution iconic memory paradigm (i.e., more timepoints between stimuli and cue), we set out to reveal possible underlying behavioural oscillations. Considering the role of alpha oscillations as a way of maintaining sensory information over time (VanRullen & Macdonald, 2012), their origin in V1 and V2 (Luo et al., 2021a) and their general association with sensory processing and sampling, we hypothesized that behavioural periodicities in IM performance might become apparent as fluctuations in the alpha frequency range. It should be noted that we still expected IM performance to worsen, i.e., the IM contents to decay, as the interval between stimuli and cue increased, but that this decay might exhibit rhythmic properties.

2. Methods

2.1 Participants

25 participants were recruited via the university-internal LABS recruitment system and participated either in exchange for course credits or monetary compensation. One participant had to be excluded due to a misunderstanding of the instructions, resulting in 24 participants that were considered for data analysis (5 male; mean age = 22.9 years; range = 19-32). This sample size was based on previous studies, commonly investigating behavioural oscillations with 14-38 participants (e.g., Cruzat et al., 2021; Drewes et al., 2015; Dugué et al., 2015; Landau & Fries, 2012; Re et al., 2019; Pomper & Ansorge, 2021). All had normal or corrected-to-normal vision, were naïve to the purpose of the experiment, gave written informed consent prior to data collection and were debriefed, when the experiment was finished.

2.2 Experimental Setup

The experiment was presented via OpenSesame (Mathôt et al., 2012) on LCD monitors with a resolution of 1.280 x 1.024 pixels (px) and a refresh rate of 100 Hz. The operating system used was Windows 7. During the experiment, participants sat in a dimly lit room with their head on a chin and forehead rest 57 cm away from the centre of the screen.

2.3 Procedure

See Figure 1 for a visual illustration of the experimental paradigm. Each trial started with a fixation cross that was presented for 1.5 seconds at the centre of the screen. Then, an array of nine single digit numbers (3x3 grid; 1-9; random positions; 40 px size) was presented for 150 ms. Afterwards, a varied target-to-cue delay, or stimulus-onset asynchrony (SOA), consisting of a blank screen, took place. The duration of this delay was varied in 10 ms steps between 50 ms and 850 ms, resulting in 80 possible delay intervals. Subsequently, a post-cue was presented for 50 ms at one of six different positions (top row (TR), middle row (MR), bottom row (BR); left column (LC), mid column (MC), right column (RC)). The cue consisted of two arrows (pen width: 3 px; head width: 25 px; body/head proportions: 0.7 to 0.3) enclosing and indicating the row or column that had to be reported afterwards. Responses were given on a multiple-choice-like screen with four columns, one for each possible number position (i.e., left/middle/right for rows; top/middle/bottom for columns) and one to indicate the number of items, that were guessed (= inverse confidence rating). Participants were instructed to report the cued numbers position-dependent and to guess, if they were not able to recall a number. Once an answer was given in every column, they could press 'Next', and the subsequent trial began.

As there were six possible cue positions and 80 possible SOAs, each combination was probed either two times (N=7; 960 trials total) or three times (N=17; 1440 trials total). Please note that this difference is due to the fact, that after the initial data collection of 960 trials, we re-invited a subset of the participants to a third session, because we suspected that the original signal-to-noise ratio with only two sessions was not sufficient to detect possible behavioural oscillations.

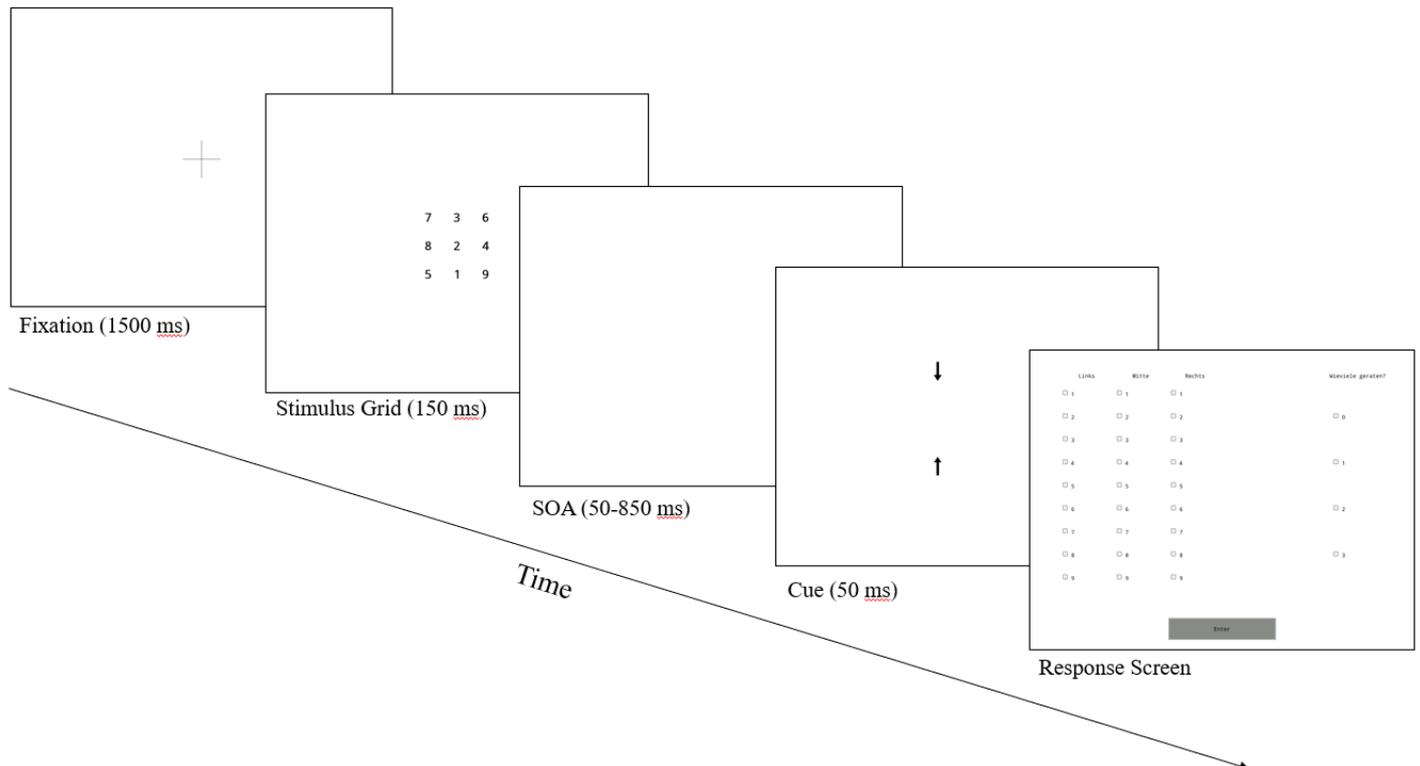


Figure 1. Experimental procedure. Participants were presented a 3x3 stimulus grid containing numbers. After a variable delay (SOA) they had to report the row/column indicated by a post-cue on a multiple-choice-like response screen. Additionally, they were instructed to indicate the number of guessed items.

Each session consisted of 480 trials, split into ten blocks with 48 trials each and took place on separate days. At the beginning of each session, a short training block consisting of 24 trials also had to be completed but was omitted from the data analysis. Following each block, participants received feedback on the percentage of correct answers during the most recent block and had the possibility to take a break for a few minutes. Although they were not forced to do so, they were strongly encouraged by the experimenter beforehand. Additionally, at the end of each session, they also received feedback on their performance for the whole session.

2.4 Data Analysis

All analyses were conducted with MATLAB (Version 2021; The MathWorks, Natick, MA) and the CircStat toolbox (Version 1.21; Berens, 2009). As a first step, we investigated whether performance was modulated by cue position by means of a traditional one-way analysis of variance (ANOVA) using the variables cue position (TR vs. MR vs. BR vs. LC vs. MC vs. RC) and performance. Following this, we discerned which cue position conditions differed significantly from each other by means of a post-hoc Tukey-Test.

Next, the mean hit rates of participants were computed as a function of the SOA. To that end, all trials were sorted according to the duration of the SOA. Then, we used a moving-window approach with a 10 ms step size to compute hit rates within bins of five consecutive SOAs (i.e., within 50 ms). Thus, we first computed the hit rates within 50-100 ms SOAs, then shifted the window by 10 ms, computed hit rates within 60-110 ms and so on, until the whole SOA duration was covered. We then removed underlying non-linear trends from the resulting hit rate time courses by subtracting the second order polynomial fit and subsequently estimated their spectral composition by means of a fast Fourier transformation (FFT). Doing so yielded power and phase values within 21 frequency bins from 0 to 25 Hz.

Statistical significance of peaks in the resulting power spectrum, i.e., the presence or absence of a rhythmic modulation at a specific frequency, was assessed via a nonparametric resampling procedure. Data was reshuffled across all SOAs within each participant and subsequently, the same analysis as described above was conducted on the reshuffled data and repeated 10.000 times. Thus, distributions of 10.000 power and phase values for each frequency bin were created and used to determine statistical thresholds ($p = .05$) which were corrected for multiple comparisons by means of a false discovery rate (FDR) function. In simpler terms, only spectral peaks that exceeded 95% of the surrogate peaks were considered significant. All the analysis steps described above were also performed for confidence ratings and performance position-independent (Performance PI).

Additionally, phase coherence between subjects for performance, position-independent performance and confidence was calculated in the alpha frequency range and tested for significance using Rayleigh tests for non-uniformity of circular data ($p = .05$).

3. Results

3.1 Cue Position

Figure 2 shows mean performance (position-dependent) across all participants for all possible cue positions. Overall, participants correctly report about half of the stimuli ($M = 1.55$). However, they were significantly less accurate on BR trials ($M = 0.76$; $p < .05$) and significantly more accurate on MR trials ($M = 2.42$; $p < .05$), as expected when considering the positional superiority effect mentioned in Section 1.1.1 (Sperling, 1960; Gegenfurtner & Sperling, 1993; Graziano & Sigman, 2008).

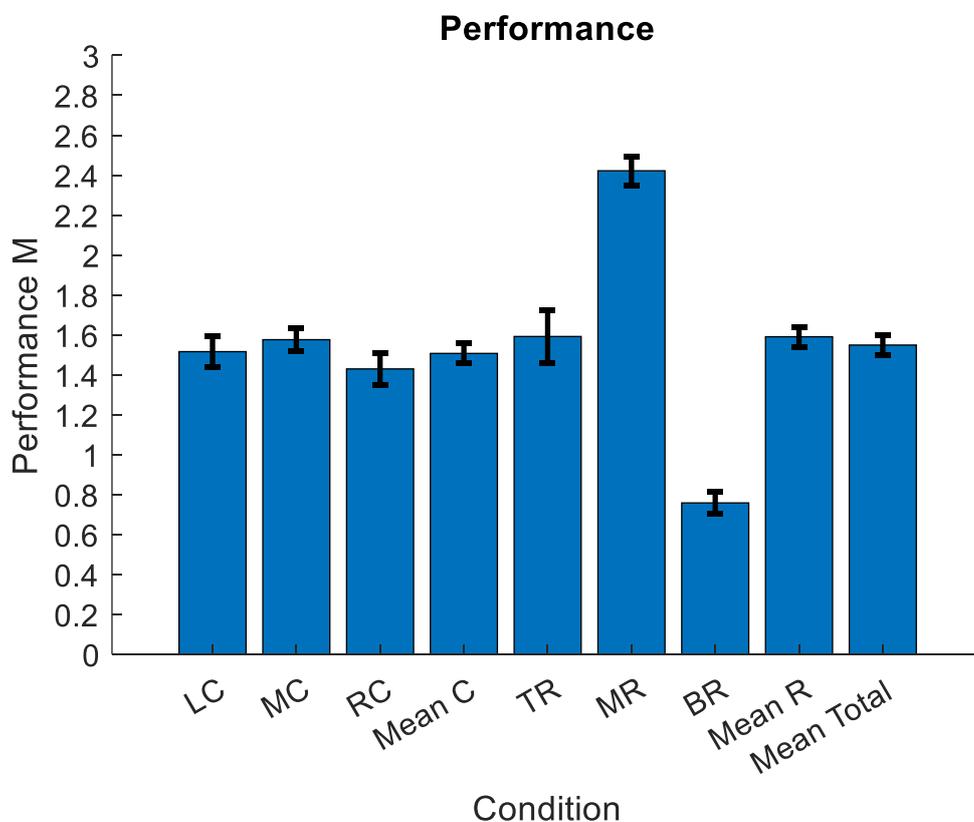


Figure 2. Overall results regarding cue positions. The mean amount of correctly reported items (out of 3 maximum) is shown for cue position, column average, row average, and total average. LC = left column; MC = middle column; RC = right column; Mean C = all columns; TR = top row; MR = middle row; BR = bottom row; Mean R = all rows. Stars indicate conditions that exhibit significantly better or worse performance compared to the other conditions.

3.2 Hit Rate and Confidence Time Courses

Plotting performance and confidence as a function of the varied SOA reveals grand-average time courses across participants. Figure 3 illustrates the resulting performance and

confidence time courses. Note that we did not observe the expected performance decay with increasing SOAs.

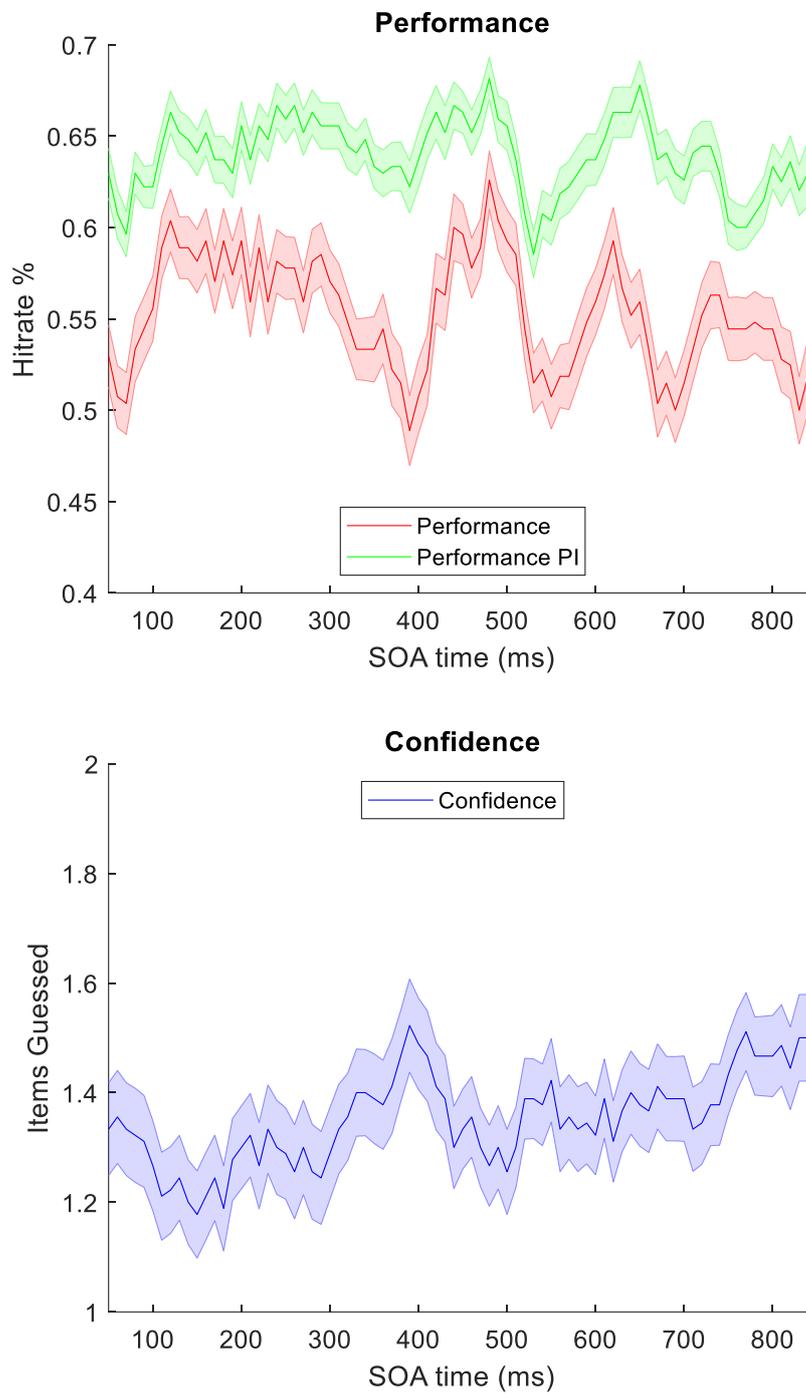


Figure 2. Performance and confidence time courses. Red: performance position-dependent; Green: performance position-independent; Blue: confidence. Shaded areas indicate the mean standard error.

Figure 4 illustrate the above performance and confidence time courses after removing underlying trends in the data and thus normalizing them.

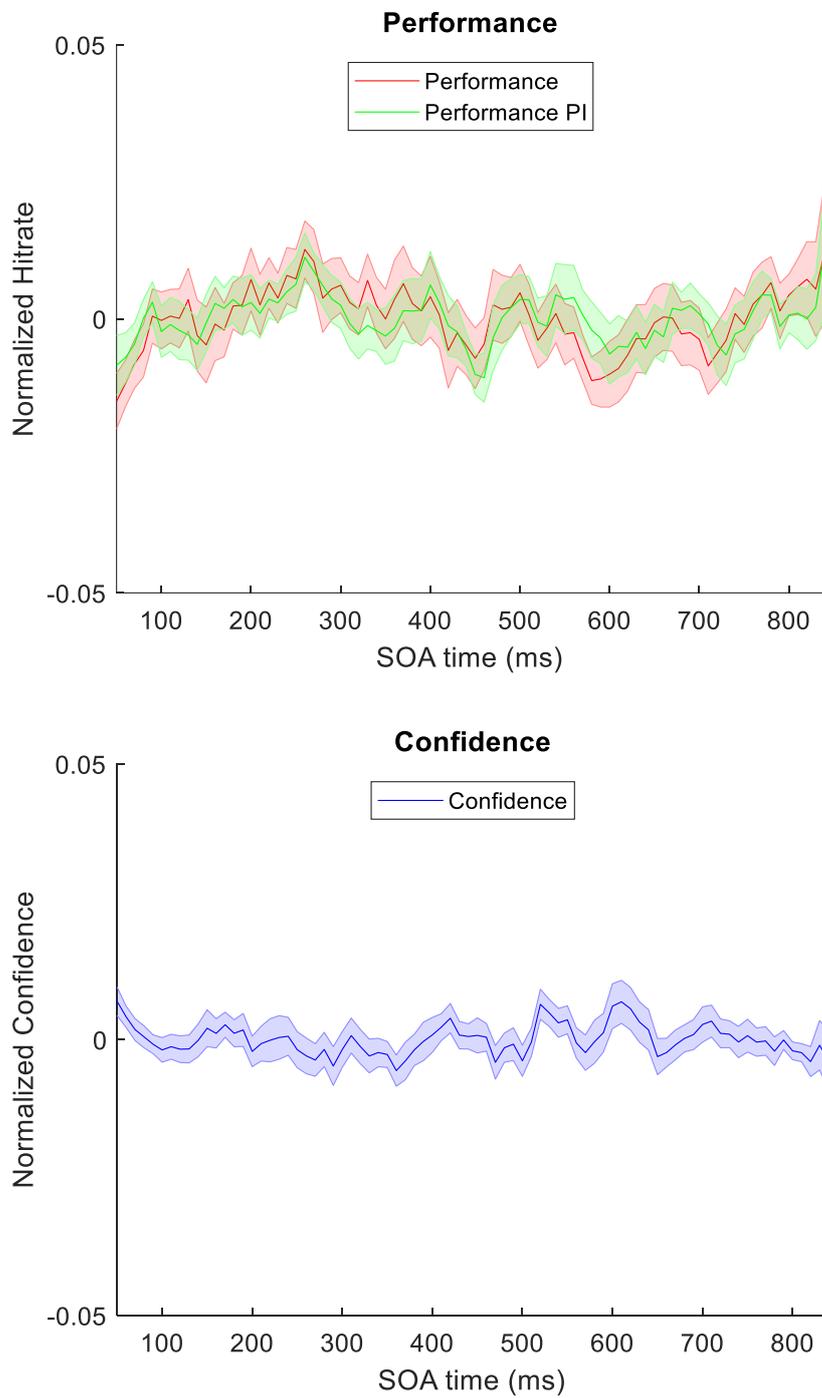


Figure 4. Normalized performance and confidence time courses. Red: performance position-dependent; Green: performance position-independent; Blue: confidence. Shaded areas indicate the mean standard error.

3.3 Practice Effects

Figure 5 shows performance of participants (position-dependent) across the first 800 trials. Note that performance seems to plateau around 100-200 trials and only marginally improves afterwards.

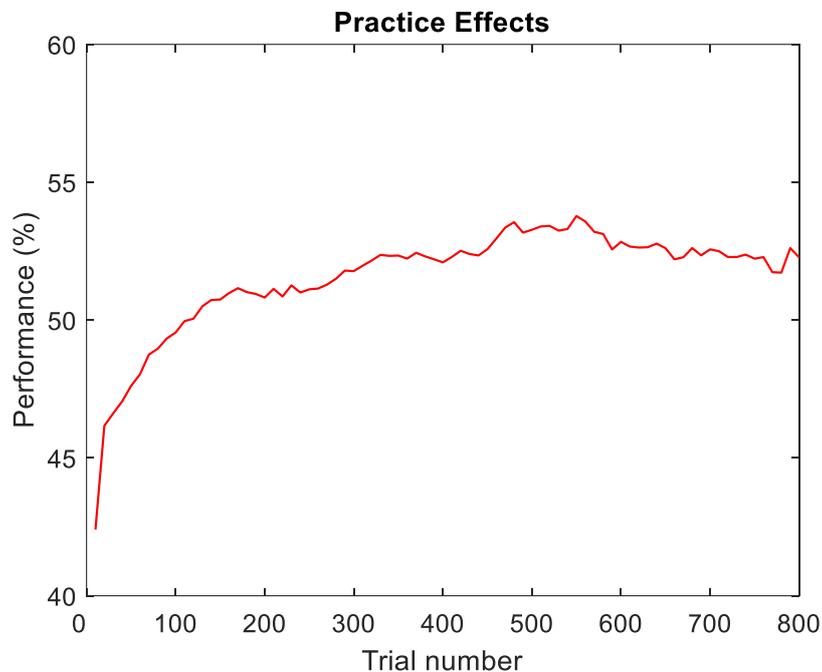


Figure 5. Performance progression and practice effects across the first 800 trials for all subjects.

3.4 Spectral Analysis

Figure 6 shows the spectral composition of the normalized time courses from Figure 4 obtained via the FFT procedure. None of the observed peaks visually exceeded the threshold for significance obtained from surrogate data. The small visual peak close to the threshold for performance at a frequency of 13.75 Hz did not reach significance ($p = .73$).

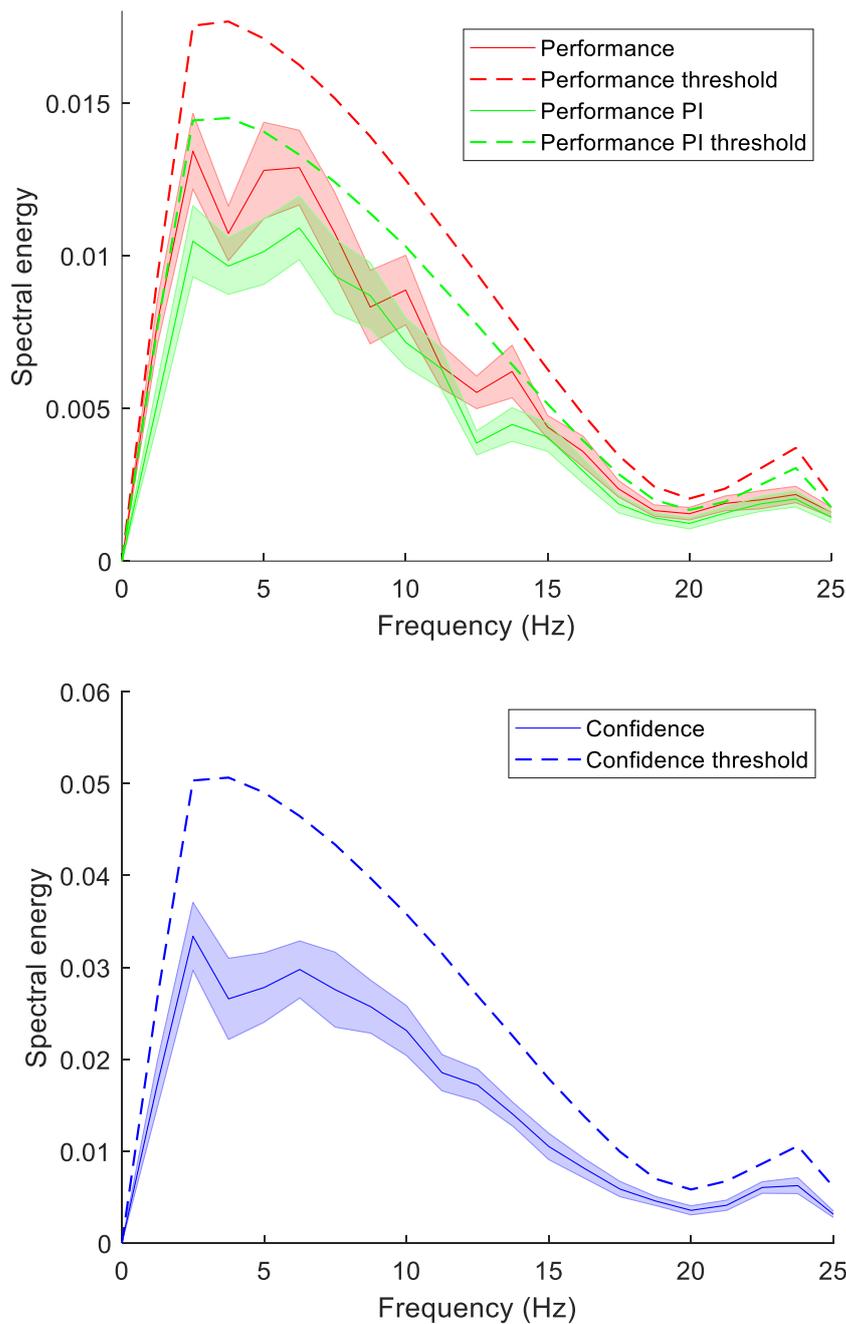


Figure 3. Spectral energy representation of performance (top, red), position-independent performance (top, green), and confidence (bottom, blue) time courses. Solid lines represent empirical data, dashed lines represent the resampled surrogate data.

3.5 Phase Analysis

We finally also investigated phase coherence across subjects for performance, position-independent performance, and confidence across participants in the alpha frequency range, as this was the range, we were most interested in. Please note that this analysis was conducted

despite none of the visual peaks in the spectral analysis being significant and should thus be considered purely exploratory. Regarding position-dependent performance, we observed no significant phase coherence across subjects (see Appendix, Table 1). Interestingly though, phase angles for position-independent performance at a frequency of 13.75 Hz were significantly biased towards one direction (see Figure 7) when tested against the surrogate data ($p = .04$, see Figure 8). Furthermore, we also observed phase coherence across subjects for confidence at frequencies of 8.75 Hz and 11.25 Hz (see Appendix, Table 1).

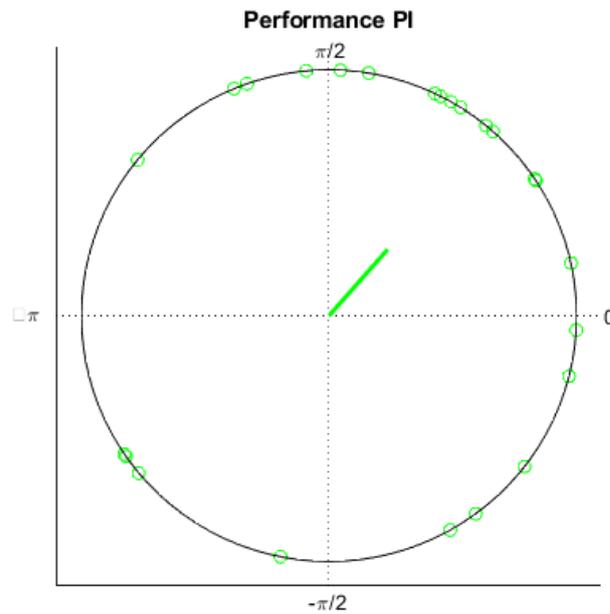


Figure 4. Phase angles of position-independent performance at 13.75 Hz. Coloured dots indicate phase angles of individual participants, and the vector represents the mean phase across participants.

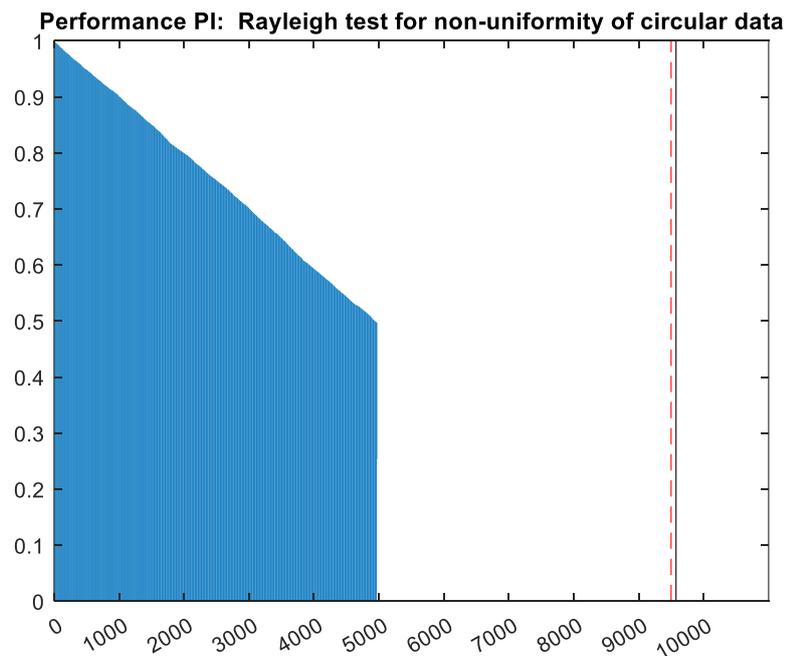


Figure 5. Rayleigh test for non-uniformity of circular data for position-independent performance at a frequency of 13.75 Hz. Blue lines represent surrogate data. Dashed red line indicates significance threshold. Black line indicates empirical data.

4. Discussion & Limitations

In summary, our results do not support the hypothesis that iconic memory representations, and thus iconic memory performance, are subject to rhythmic fluctuations. Despite this, our finding of significant phase coherence across subjects for position-independent performance at a frequency of 13.75 Hz might still be very cautiously interpreted as an indication that there might exist a shared sensory sampling rhythm in the high alpha/low beta frequency range that was phase reset by the appearance of our stimulus grid and thus aligned across participants but did not exhibit sufficient power to become significant in our spectral analysis. However, the absence of significant phase coherences for performance and position-independent performance in any other frequency bin in the alpha range suggests that this might have simply been an incidental finding. The significant phase coherences for confidence at frequencies of 8.75 Hz and 11.25 Hz should thus also only be carefully, if at all, interpreted.

Also, the fact that we did not observe the well-replicated traditional decay of IM performance with increased SOAs (see Figure 3) begs the question if what we investigated was truly IM or another type of memory store. By multiplying the average number of correctly reported trials with the number of equiprobable partial reports, one can obtain an estimate of items retained in IM, as described in Section 1.1.1. In our case ($M = 1.55$), this calculation would suggest that 4.65 out of 9 items were retained, which is below what would be expected for the high-capacity IM store but fits rather nicely into the commonly accepted span of working memory (see Section 1.1.1). This might be an indication, that our task did not probe IM, but rather WM. Possible reasons for this and general design issues are discussed below. Many of the following points were suggested by colleagues during personal communication after we obtained our rather unusual results, which we are very grateful for.

4.1 Stimulus Design, Salience and Masking

One thing that might have interfered with our IM task is the possibility that our stimulus items were not salient enough to produce sufficient visible persistence, a key component of IM. Furthermore, our cue stimuli were comparatively rather thick and prominent, as well as spatially close to the target items, a combination that might have resulted in the cue display metacontrast-masking the item display for trials with short SOAs, where usually the best performance would be expected (Coltheart, 1980; Di Lollo et al., 1974; Di Lollo et al., 1988;

Enns & Di Lollo, 2000; Sperling, 1960). On a similar note, the duration of visible persistence has been shown to be inversely related to, among other factors such as duration and proximity, stimulus intensity (Coltheart, 1980; Di Lollo & Bischof, 1995; Spalek & Di Lollo, 2022). Given that, unfortunately, due to miscommunication in our lab, the experimental screen brightness and contrast settings were set to the maximum, we might have accidentally presented stimuli with high intensity, thus reducing the duration of the already quite fragile visible persistence even more and making it more susceptible to masking and overwriting.

Even though no metacontrast-masking should be expected for longer SOAs, the appearance of a new display containing visually prominent items (i.e., cues) could have still overwritten the fragile iconic memory representation of the item display, leading to participants having to rely on the lower-capacity WM store, as the high-capacity IM store has been wiped and only items that have already been transferred into WM remain. This would explain the overall performance level being around the estimated capacity limit for WM and not higher as would be expected. There also exists recent evidence suggesting that certain groups of forms are processed in the same cortical visual system, such as lines and angles, and therefore can mask each other strongly (Lo & Zeki, 2014). It might be the case, that our arrow-shaped cues activated the same cortical regions as the numerical items did, thus interrupting processing and wiping the iconic representation on cue-onset. Noteworthy would be, that in our experimental design, we included a wide range of SOAs in order to achieve a high temporal resolution across the whole supposed timeframe of IM. However, as was laid out in Section 1.1.1, performance would be expected to decrease exponentially with an increasing SOA. Our subjects thus experienced many trials, where the cue would not have been very useful in the first place. This could have led to them not recognizing the overall utility of the cue and adopting a strategy of first filling their WM and attending to the cue afterwards.

The points considered above, and the present data would suggest that our design failed to induce an iconic representation of the number array, whether it be due to masking effects or overwriting in general. Instead, it seemingly prompted subjects to quickly fill their WM with as many of the 9 numbers as possible. attending to the cue afterwards and subsequently recalling the items they remembered. This could have led to an average performance level in the range of WM, instead of the higher performance level expected for IM tasks, especially for short SOAs.

4.2 Training

The possibility of our subjects not utilizing the cue until they have filled their WM storage could have further been exacerbated by the fact that our design did include few practice trials (24 at the beginning of each session). As Gegenfurtner and Sperling (1993) lay out in their extensive work on information transfer in iconic memory experiments, there seem to exist two transfer processes that are involved in visual short-term memory: non-selective transfer and selective transfer. Regarding IM tasks, the goal should be that subjects first non-selectively transfer items into a more durable store until the cue appears (biased towards the middle row in a 3x3 matrix) and then selectively transfer the cued items (Gegenfurtner & Sperling, 1993). However, literature suggests that a minimum of 100 practice trials seems to be necessary for participants to actually adopt this strategy and show the expected large-capacity IM finding (Chow, 1985). Unfortunately, our high temporal resolution experimental design already necessitated a large number of trials that were spread out over three separate days. Thus, due to feasibility reasons and time constraints, we opted to only include a short practice session of 24 trials before each session. This could have led to our subjects never really grasping the utility of the cue and only employing a non-selective strategy which would have been appropriate for long SOAs but inappropriate for short SOAs, resulting in an overall performance level worse than we would have been expected, especially for short SOAs. Some authors also used separate days just for practicing and training their participants for multiple hours (Gegenfurtner & Sperling, 1993), however as can be seen in Figure 5, our data suggests that participants reached somewhat of a plateau in their performance after 100-200 trials and only marginally improved afterwards. Thus, such extensive training would probably not have made a difference in our paradigm.

4.3 Future research

We of course also must consider that IM might simply not exhibit similar rhythmic properties as other memory modalities due to its unique fragility and rapidly decaying nature. However, even though we found no evidence that iconic memory is subject to rhythmic fluctuations, considering the methodological problems discussed above it seems premature to come to this conclusion, as what we investigated was probably not iconic memory in the first place. Since this was our first time working on the subject, mistakes are bound to happen. Nonetheless, these mistakes may still serve to make possible pitfalls and necessary

considerations for future research apparent. To summarize, given a hypothetical follow-up experiment, we would address and adapt the following points in our paradigm:

- (1) More practice trials to facilitate usage of the desired strategy and cue
- (2) Include a pre-cue practice condition to further facilitate cue usage
- (3) Consider adaptive practice sessions with increasing memory items
- (4) Use more salient items and less salient visual cues to avoid masking and overwriting
- (5) Consider using auditory cues to completely avoid masking and overwriting
- (6) Include a full-report condition to further verify whether we are dealing with IM
- (7) Make sure stimulus intensity (i.e., brightness and contrast) is at a moderate level

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5. Appendix

Table 1

p-values for phase coherence across subjects in the alpha frequency range; stars indicate significance

	8.75 Hz	10 Hz	11.25 Hz	12.5 Hz	13.75 Hz
Performance	.57	.53	.23	.29	.61
Performance PI	.99	.60	.97	.46	.04 *
Confidence	.03 *	.46	.04 *	>.05	.42

English Abstract

An increasing amount of recent evidence suggests that many of our cognitive, sensory, and perceptual abilities are in fact not operating continuously, but rather fluctuate over time. These fluctuations, or oscillations, can be investigated by a variety of methods ranging from purely neurophysiological to purely behavioural and have already been shown in multiple cognitive mechanisms, such as working memory (WM). However, as of writing this thesis, none have investigated possible behavioural oscillations in iconic memory (IM) yet. Thus, we recruited 25 university students to investigate whether the fidelity of iconic memory is modulated rhythmically by the amount of time between a to-be memorized 3x3 number array and a visual cue that is presented after the array. Our data does not support the hypothesis of rhythmic fluctuations in iconic memory performance and, furthermore, did not exhibit the traditional performance decay characteristic for partial-report experiments. Possible reasons

and implications for future research are discussed. Despite non-significant results, the current thesis still holds value by demonstrating the complexities and possible pitfalls one must avoid and handle, when dealing with iconic memory.

Deutsches Abstract

Immer mehr Forschungsergebnisse legen nahe, dass viele unserer kognitiven, sensorischen und perzeptuellen Fähigkeiten nicht kontinuierlich ablaufen, sondern stattdessen über die Zeit hinweg schwanken. Diese Schwankungen, oder Oszillationen, kann man mit unterschiedlichsten sowohl mit neurophysiologischen Methoden untersuchen, aber auch nur mit Verhaltensdaten. Es gibt bereits mehrere kognitive Mechanismen, für die solche Schwankungen gezeigt werden, wie beispielsweise das Arbeitsgedächtnis. Da bisher keine möglichen Verhaltensoszillationen im Rahmen des ikonischen Gedächtnisses untersucht wurden, haben wir 25 Universitätsstudenten rekrutiert, um zu untersuchen ob die Genauigkeit des ikonischen Gedächtnisses durch die Zeitspanne zwischen der Präsentation eines 3x3 Nummerngitters und einem Cue, der nach dem Gitter präsentiert wird, rhythmisch moduliert wird. Unsere Daten sprechen gegen eine rhythmische Modulierung des ikonischen Gedächtnisses. Allerdings beobachten wir auch nicht den traditionellen exponentiellen Verfalls des ikonischen Gedächtnisses mit länger-werdendem Abstand zwischen Stimulus und Cue. Mögliche Ursachen und Implikationen für zukünftige Forschung werden diskutiert. Trotz nicht-signifikanter Ergebnisse ist die vorliegende Arbeit relevant und macht mögliche Probleme und Komplexitäten, mit denen man umgehen muss, wenn man das ikonische Gedächtnis untersucht, sichtbar.