Individual differences in alpha frequency are associated with the time window of multisensory integration, but not time perception.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abstract

Previous research provides some preliminary evidence to link the temporal binding window, the time frame within which multisensory information from different sensory modalities is integrated, and time perception. In addition, alpha peak frequency has been proposed to be the neural mechanism for both processes. However, these links are not well established. Hence, the aim of the current study was to explore to what degree, if any, time perception, the temporal binding window and the alpha peak frequency are related. It was predicted that as the width of the temporal binding window increases the size of the filled duration illusion increases and the alpha peak frequency decreases. We observed a significant relationship between the temporal binding window and peak alpha frequency. However, time perception was not linked with either of these. These findings are discussed with respect to the possible underlying mechanisms of multisensory integration and time perception.

Keywords: Temporal Binding Window, Occipital Alpha, Time Perception, Double-flash Illusion, Filled Duration Illusion, Multisensory Integration

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Introduction

Temporal sensitivity, the ability to detect time-based discrepancy between two stimuli, regulates temporal grouping of sensory information (Colonius & Diederich, 2004). The temporal binding window (TBW) is the time frame within which such grouping takes place and is highly variable across individuals (Cecere et al., 2015; Ferri et al., 2018; Haß et al., 2017). The most often used task to measure the width of the TBW can be argued to be double-flash illusion (for recent reviews see Hirst et al., 2020; Keil, 2020). This task involves simultaneous presentation of visual (flash) and auditory (beep) stimuli followed by the presentation of a second auditory (beep) stimulus after a variable delay. If the second beep occurs within the individuals` TBW then both beeps are integrated with the visual stimulus. This creates an illusion whereby participants report experiencing two flashes despite only one flash being presented. The delay at which an individual no longer perceives two flashes is taken as the width of their TBW, and acts as an index of their temporal sensitivity.

There is evidence suggesting that individual differences in temporal sensitivity are linked with individual difference in time perception. Fenner et al. (2020) measured the width of the TBW, using a simultaneity judgement task, and time perception, using the filled duration illusion. The filled duration illusion is a well-known means to explore time perception (Thomas & Brown, 1974; Wearden et al., 2007; Williams et al., 2019). This task consists of filled intervals that are filled with a continuous tone, and empty intervals that only have the onset and offset signalled with a tone. Evidence robustly shows that filled intervals are judged longer than empty intervals (Plourde et al., 2008), with this effect quantified by the difference in the slope between the filled and empty durations. Fenner et al. (2020) found a positive correlation between the width of the temporal binding window and the magnitude of the filled duration illusion.

If it is the case that individual differences in temporal sensitivity are linked with individual difference in time perception, it is plausible that these two processes also have a common underlying neural mechanism. One strong candidate for this would be the frequency of the occipital alpha peak. The power spectrum of human EEG decreases in amplitude as the frequency increases with an exception around the 10Hz range, where amplitude is increased (see Donoghue et al., 2020 for a comprehensive review). When measured over posterior electrodes, during an awake state, this peak is known as the occipital alpha peak. The precise frequency of this peak varies from one person to the next, normally within the range of 8Hz to 12Hz, but can be as low as 7Hz or as high as 14Hz (Mioni et al., 2020; Zhang et al., 2019).

Alpha oscillations have previously been linked to both the TBW (Cecere et al., 2015; Keil & Senkowski, 2017; Migliorati et al., 2020; Samaha & Postle, 2015) and time perception (Glicksohn et al., 2009; Horr et al., 2016; Mioni et al., 2020). In terms of TBW, individual differences in the alpha peak frequency have been shown to negatively correlate with the width of the TBW (Cecere et al., 2015; Keil & Senkowski, 2017; Migliorati et al., 2020). Moreover, neuromodulation of the alpha peak frequency alters the width of the TBW (Cecere et al., 2015). Namely, decreasing the alpha peak frequency increases the width of the TBW. In terms of time perception Glicksohn et al. (2009) found that the alpha peak frequency correlates with time perception and Horr et al. (2016) found that alpha power has been linked to time perception. In addition, it has been shown that time perception can also be modulated by tACS in the alpha frequency range (Mioni et al., 2020).

The conceptualization behind the link of alpha oscillations with time perception and TBW can be explained by considering internal clock model (a hypothetical mechanism that is driven by a neural pacemaker producing rhythm (Kononowicz & Van Wassenhove, 2016). Treisman (1963) proposed that alpha oscillations in the internal clock drive time perception. Treisman (1963) explained that when the event needing to be timed commences, a pacemaker begins sending pulses. These pulses are then taken as a subjective estimate of elapsed time. Treisman et al. (1994) took this argument further and proposed that the pulses of the pacemaker are driven by alpha oscillations. Similarity, Samaha and Postle (2015) proposed that alpha oscillations in the internal clock drive TBW. Researchers argued that perception depends on the temporal windows, which are clocked by the frequency of the alpha oscillations. Namely, fluctuations in the alpha oscillations predict temporal resolution of perception. A higher alpha frequency provides a narrower excitatory phase, and thus results in a higher temporal sensitivity. In other words, when stimuli are within the same alpha cycle they are perceived as single stimulus. Whereas if stimuli are in different alpha cycles they are perceived as separate. As higher temporal sensitivity gives rise to shorter width of the TBW (see Hirst et al., 2020; Keil, 2020 for recent reviews), this provides a clear link between alpha peak frequency and the TBW. Further support comes from the proposed involvement of alpha oscillations in producing perceptual cycles (Busch et al., 2009; Van Rullen, 2016), whereby the outcome of sensory processing is driven by the phase of alpha oscillations at the time of the presentation of the sensory information.

Despite there being some preliminary findings linking TBW, time perception and alpha oscillations robust conclusions cannot be made. Consequently, the aim of the current study was to investigate to what degree, if any, time perception, TBW and alpha oscillations are linked. Based on the findings described above, it was predicted that an increase in the width of the TBW will be associated with an increase in the size of the filled duration illusion (as in Fenner et al., 2020), and a decrease in alpha peak frequency.

Method

Participants

The sample consisted of 51 student volunteers from the University of Essex recruited via the University`s research advertisement websites. All participants had self-reported normal or corrected to normal vision and hearing to avoid these variables affecting the perception of the tasks. The local ethics committee approved the study, and participants gave their informed consent before taking part in the study. The study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and approved by the University of Essex`s Faculty Ethics Subcommittee (departmental reference no: AV1901).

Data Exclusion

All 51 participants took part in the study. The data sets that did not fit the psychometric sigmoid function (R^2 less than .4) or/and contained incomplete data were removed from further analysis. Twelve data sets in the double-flash illusion, two data sets in the filled-duration illusion and one data set in the EEG analysis were removed from the further analysis. Given that some of the participants` data sets were excluded from some tasks but not the others, this resulted in different sample sizes used for different comparisons. Comparison of alpha peak frequency and alpha power with TBW included 38 data sets, alpha peak frequency and alpha power with time perception included 48 data sets and TBW with time perception included 38 data sets.

Design

The study used correlational design with variables being the variability of time perception, the width of the TBW, alpha peak frequency and alpha power.

Apparatus/Materials

<u>Double-flash illusion (TBW measure)</u>

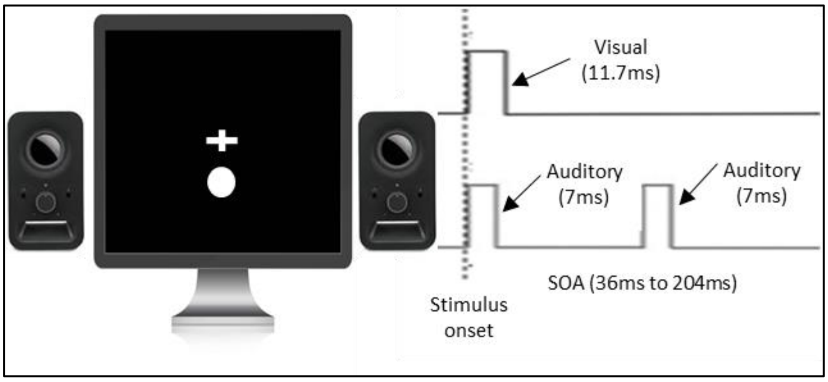

Figure 2.1: Paradigm of the double-flash illusion.

The double-flash illusion task (see Figure 2.1) used was the same as that in the study of Cecere et al. (2015). We chose to use this task, as it has previously been associated with individual differences in the EEG alpha peak frequency, and has also been successfully modulated by tACS and measures the width of the TBW implicitly (Cecere et al., 2015). E-Prime software (Psychology Software Tools, Pittsburgh, PA) and a 17 inch CRT monitor with a refresh rate of 85Hz (ViewSonic Graphics Series G90FB, refresh rate 85Hz) were used to present visual stimuli (flash). Visual stimuli were 11.7ms in duration and in the form of a white circle 1.32cm in diameter. Visual stimuli were located 1cm below the fixation cross that was positioned in the centre of the screen. Such characteristics of stimuli were chosen as it has been shown that tasks involving multisensory integration are optimised when visual stimuli are displayed in peripheral vision (Shams et al., 2002). Auditory stimuli were presented via two typical PC stereo speakers. In order to minimise the possible effect of the spatial cues on the perception of the task, speakers were placed at each side of the monitor and raised to align with the position of the visual stimuli (Macaluso et al., 2004). The auditory stimuli (beep) were presented for 7ms and consisted of a sinusoidal pure tone with a frequency of 3.5kHz and a sampling rate of 44.1kHz played at a constant volume. The above durations of the visual and auditory stimuli were chosen as they have previously been successfully employed to measure multisensory integration (Cecere et al., 2015; Ferri et al., 2018; Haß et al., 2017). The first auditory stimulus was aligned with the onset of the visual stimulus. The second auditory stimulus was presented in one of the possible inter-beep intervals. Inter-beep intervals ranged from 36ms to 204ms in 12ms steps. The above range of inter-beep intervals was chosen as Cecere et al. (2015) showed that such methodology not only captures but also extends beyond the time frame within which the double-flash illusion task is perceived in the general population. Each trial started with a white fixation cross in the centre of the monitor that remained on the screen throughout the trial. On each trial, visual and auditory stimuli were presented simultaneously, with the second auditory stimulus being presented in one of the possible inter-beep intervals randomly. Participants performed one block. Each inter-beep interval was presented 20 times, for a total 300 trials. Participants were instructed to always fixate on the fixation cross and report whether they perceived one or two flashes by pressing the key `1` or the key `2` respectively. Providing a response triggered the start of the next trial. The time interval between the beeps at which participants no longer stated they saw two flashes was calculated to be the width of their TBW.

Filled Duration Illusion (time perception measure)

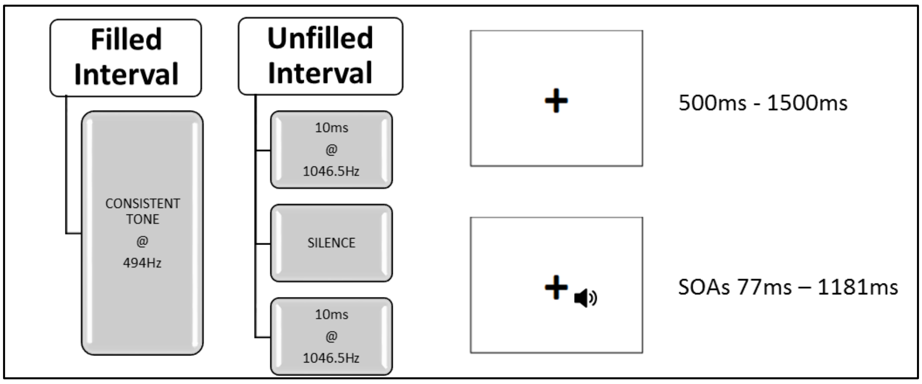

Figure 2.2: Paradigm of filled duration illusion.

The current study used the filled duration illusion (see Figure 2.2) as this method has been shown to be dependable and one of the most frequently used illusions in the time perception field since the beginning (Thomas & Brown, 1974; Wearden et al., 2007; Williams et al., 2019). Furthermore, this task has previously been used to investigate the relationship between time perception and TBW (Fenner et al., 2020). The filled duration illusion refers to the fact that participants experience a filled interval to be longer than an empty interval. A filled interval consists of a single (494Hz) tone presented for the duration of the target interval, and an empty interval encompassed two (1046.5Hz) tones of 10ms presented at the beginning and end of the target interval. The 10 target intervals were 77, 203, 348, 461, 582, 707, 834, 958, 1065 and 1181 in ms. Tones were presented via two typical PC stereo speakers. In order to minimise the possible effect of the spatial cues on the perception of the task speakers were placed at each side of the monitor and their position aligned horizontally with the position of the visual stimuli (Macaluso et al., 2004). Participants completed 5 blocks, each consisting of the 20 stimuli (10 filled and 10 empty) in random order for a total of 100 trials. Each trial was commenced by the participant pressing any button on the keyboard. This triggered the tone/tones. Participants were then asked to estimate the duration of the tone, or the gap between tones, in ms, using the keyboard number pad. Participants were reminded of how ms relate to s (0.5s = 500ms, etc.) and that responses should be within a range of 50ms to 1500ms. Where responses were beyond this range they were discounted and the participant reminded of the possible range.

EEG recording

To measure the alpha peak frequency and alpha power continuous EEG was recorded from 64 sintered Ag/AgCI electrodes mounted on an elastic cap (EasyCap) using a Brain Products BrainAmp DC system throughout the tasks. Left mastoid was used as a reference during recording.

Procedure

Participants were seated in a dimly lit room with their corporeal midline aligned with a centre of the computer screen located approximately 60cm away. Participants then signed a consent form and were given opportunity to enquire about the study. Thereafter participants performed flash-beep illusion task (10 minutes) followed by the filled duration illusion task (20 minutes) while EEG was recorded.

Data Analysis

TBW

To assess the width of the TBW, the time window in which the illusion was maximally perceived, the percentage of trials where two flashes were reported was first plotted as a function of the inter-beep delay. A psychometric sigmoid function was then fitted to the data. The sigmoid function was defined by the equation: $y = a+b/(1+\exp(-(x-c)/d))$ (a = upper asymptote; b = lower asymptote; c = inflection point; d = slope). For each participant, c was taken as the TBW, i.e. the point of decay of the illusion (Cecere et al., 2015).

Time Perception

To determine the variability in time perception, for each participant the regression between participants' estimated times and the actual intervals were calculated in the filled duration illusion task. The difference between the filled and empty slopes in filled duration illusion task was taken as a measure of the size of the filled duration effect, corresponding to the individual differences in time perception (as in Fenner et al., 2020).

Alpha Oscillations

For each of the two tasks, data were extracted in one second epochs corresponding to the second immediately prior to stimulus presentation. For eyes open and eyes closed resting data, the 120 second periods were divided into epochs of one second. Bad channels were removed by visual inspection. Noisy epochs were excluded using automatic artifact rejection in eeglab (Delorme & Makeig, 2004), with the joint probability parameter and kurtosis parameter set to 5, and amplitude threshold set to 5000. Independent component analysis in eeglab (Delorme & Makeig, 2004) was used to identify and remove eye blinks. A second round of artifact rejection was then completed with the joint probability parameter and kurtosis parameter set to 5, and amplitude threshold set to 2000. Each one second window was then multiplied by a Hanning taper, and zero-padded to 10s. Power was computed from 4Hz to 30Hz using a fast Fourier transform (FFT function in matlab). The resulting FFT had a frequency resolution of 0.1Hz. The power at each frequency was normalising by subtracting the mean power across the spectrum, and dividing by the standard deviation (see Singh et al., 2015 for a similar approach).

To determine alpha peak frequency, we found the maximum power between 8Hz and 14Hz. Based on previous studies, we extracted the alpha peak frequency averaged across 6 posterior electrodes (Oz, O1, O2, PO3, POZ and PO4). Here, we present only analysis from during the tasks, but analysis during rest with eyes closed and eyes open provides a similar pattern of the results. Data are available at: https://doi.org/10.17605/OSF.IO/VAW7D. Although we were primarily interested in alpha peak frequency, we additionally calculated alpha power. To do this we calculated the mean amplitude of the power spectrum between 8Hz and 14Hz over the pooled posterior electrodes (Oz, O1, O2, PO3, POZ and PO4).

Results

Relationship of alpha peak frequency with TBW during double-flash illusion task.

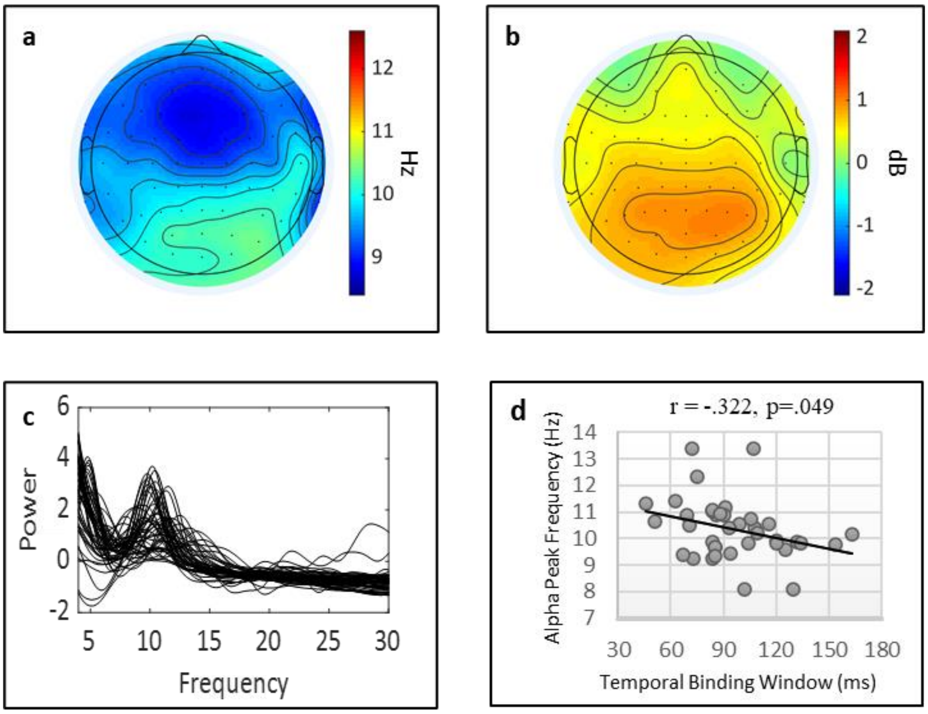

Figure 2.3: (a) Topographic distribution of the frequency of the alpha peak for each electrode during double-flash illusion task across all participants. The power spectrum has a lower peak at frontal electrodes, whereas over posterior electrodes this peak is at around 11Hz. (b) Topographic distribution of the alpha power, for each electrode during double-flash illusion task across all participants. (c) Power spectrum over posterior electrodes during the double-flash illusion task for each participant. (d) Scatterplot showing relationship between the alpha peak frequency and the temporal binding window. Alpha peak frequency decreases as the width of the temporal binding window increases.

The scatterplot (see Figure 2.3 d) indicated that there was a linear relationship between the alpha peak frequency (Hz) ($\alpha = 0.97$) and the width of the TBW (ms) ($\alpha = 0.99$). This was confirmed with a Pearson's correlation coefficient, $r(36)=-.32, p=.049$, which showed weak to moderate strength significant correlation. The slope coefficient for alpha peak frequency was -7.53, so the width of the TBW decreases by 7.53ms for each increase in Hz in alpha peak frequency. No association was found between alpha power (dB) ($\alpha = 0.97$) and the width of the TBW (ms) ($\alpha = 0.99$) during the double-flash illusion task, $r(36)=-.09, p=.600$. A sensitivity power analysis demonstrated that our sample had 80% power to detect moderate correlation of 0.44 or greater (α=.05, two-tailed).

Relationship of alpha peak frequency with time perception during filled duration illusion task.

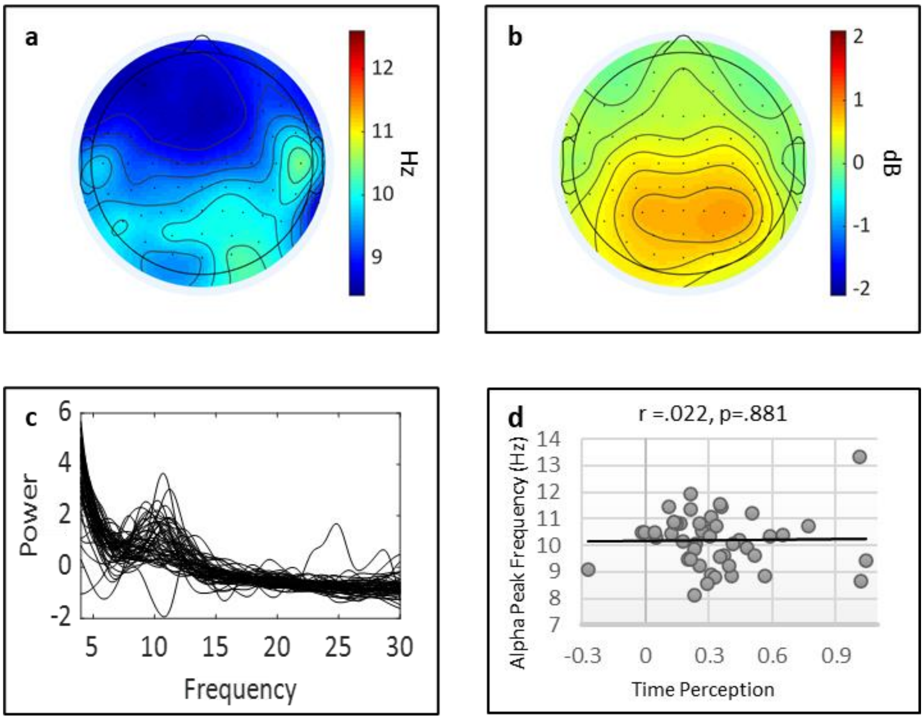

Figure 2.4: (a) Topographic distribution of the frequency of the alpha peak for each electrode during filled duration illusion task across all participants. The power spectrum has a lower peak at frontal electrodes, whereas over posterior electrodes this peaks at around 10 Hz. (b) Topographic distribution of the alpha power, for each electrode during filled duration illusion task across all participants. (c) Power spectrum over posterior area during filled duration illusion task for each participant. (d) Relationship between the alpha peak frequency and the time perception. Alpha peak frequency and time perception have a non-significant relationship. (The time perception represents the magnitude of the filled duration illusion effect by displaying the difference in filled and empty slopes. A positive value indicates that the filled slope was steeper than the empty slope and vice versa.).

The scatterplot (see Figure 2.4 d) indicated that there was no apparent relationship between the alpha peak frequency (Hz) (α = 0.97) and time perception (the difference in slopes between the filled and empty duration estimates). This was confirmed with a Pearson's correlation coefficient, *r(46)=.02,p=.881*, which showed non-significant correlation. No association was found between alpha power (dB) (α = 0.97) and time perception (α = 0.98) during the filled duration illusion, *r(46)=.16,p=.264*. A sensitivity power analysis demonstrated that our sample size had 80% power to detect moderate correlation of 0.39 or greater (α=.05, two-tailed).

Relationship between temporal sensitivity and time perception

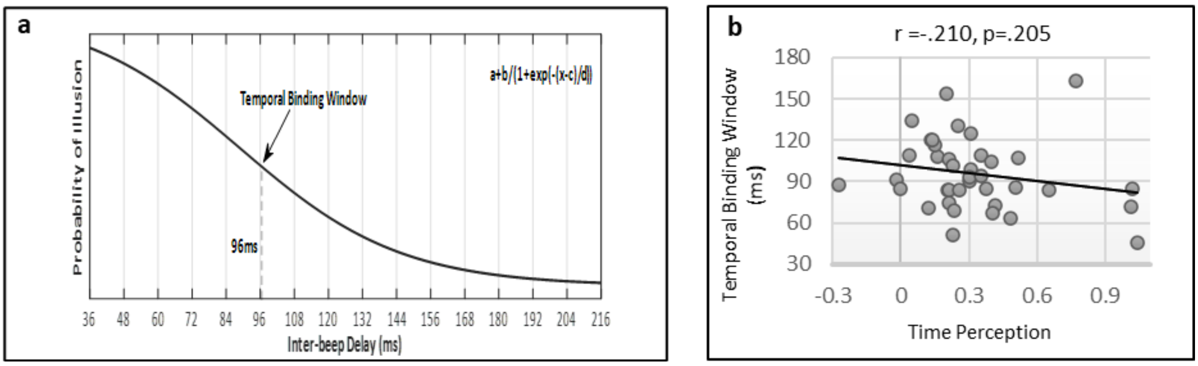

Figure 2.5: (a) Across-participants average probability of perceiving the double-flash illusion plotted as a function of inter-beep delay. The curve represents the sigmoid fit determining the point of decay of the illusion, corresponding to the width of the TBW. (b) Relationship between temporal sensitivity and time perception. Temporal sensitivity and time perception are shown to have non-significant relationship.

The scatterplot (see Figure 2.5 b) showed that there was no apparent relationship between the width of the TBW (ms) (α = 0.99) and the time perception (α = 0.98). This was confirmed with a Pearson's correlation coefficient, *r(36)=-.21,p=.205*, which showed non-significant correlation. A sensitivity power analysis demonstrated that our sample had 80% power to detect moderate correlation of 0.44 or greater (α=.05, two-tailed).

Discussion

Findings

The key aim of the current study was to investigate the relationship between temporal sensitivity, time perception and alpha peak frequency. It was predicted that an increase in the width of the TBW would be associated with an increase in the size of the filled duration illusion and decrease in alpha peak frequency. However, the results showed a significant relationship (negative correlation) only between the width of the TBW and the alpha peak frequency. Additionally, the current study explored relationship of alpha power with the temporal sensitivity and time perception, with the results indicating non-significant relationship between these processes.

Link with previous literature

Given the above results it is evident that the current study supports previous findings (Cecere et al., 2015; Keil & Senkowski, 2017; Migliorati et al., 2020; Samaha & Postle, 2015) indicating that the TBW and the alpha peak frequency are related. However, only one study (Cecere et al., 2015) with a very small sample size (12 participants) have showed causal evidence (the alpha peak frequency modulates the width of the TBW). As the current study is the only study since Cecere et al. (2015) that has investigated this phenomenon, it provides the opportunity to reaffirm these findings with more confidence. Additionally, the current study found no association between the TBW and alpha power. These findings support previous literature regarding relationship between alpha peak frequency and alpha power. Alpha peak frequency and alpha power have been shown to be somewhat related overall, but when investigated in detail (i.e. independent component analysis) only very few aspects were shown to be associated (Benwell et al., 2019). Hence the above, taken together with the current results concerning relationship of alpha peak frequency and alpha power with TBW, further supports the notion that alpha power and alpha frequency are distinctive. Moreover, these findings allow to conclude that TBW is linked to alpha peak frequency but not alpha power.

However, the current study contradicts findings of Fenner et al. (2020), demonstrating a relationship between the TBW and the time perception, as well as findings of Glicksohn et al. (2009), Horr et al. (2016) and Mioni et al. (2020), suggesting that time perception is related to the alpha peak frequency and alpha power.

In terms of the discrepancy between the current results and those of Fenner et al. (2020) it seems that methodology, in particular the tasks used, may be the possible reason for the conflicting results obtained. Both Fenner et al. (2020) and the current study examined time perception using filled duration illusion where participants were asked to estimate in ms how long a sound is played for (the filled interval), or what the interval was between two sounds (the empty interval). This resulted in conscious thinking about time. However, the two studies used different tasks to assess the width of the TBW. Namely, Fenner et al. (2020) used the simultaneity judgement task whereas current study used the double-flash illusion task to assess the width of the TBW. The simultaneity judgement task and the double-flash illusion task both employed simple stimuli (flashes and beeps). Such stimuli result in integration only across modalities and hence allow for accurate and reliable investigation of across modalities integration. Similarly, both tasks used various time delays between the stimuli. In the simultaneity judgment task participants are presented with either a flash leading followed by the beep with various time delays or vice versa. In double-flash illusion task participants were presented with two beeps separated by various time intervals and a flash aligned with the first beep. TBW is the time frame within which stimuli are integrated and hence various intervals between the stimuli are needed to allow the assessment of the integration of the stimuli and consequently the width of the TBW. On the surface it seems that both tasks assess the width of the TBW similarly.

However, one difference between the tasks is the processes involved in responding to the question of the task. More precisely, in the simultaneity judgement task participants need to decide whether the two stimuli occur at the same time or not. The time interval at which participants perceive the two stimuli to be occurring at different times is said to be the person`s TBW. In the double-flash illusion task participants are required to decide whether they saw one or two flashes. The time interval between the beeps at which participants no longer stated they saw two flashes is used to measure the width of their TBW. As stated before, to provide a response to the simultaneity judgement task participants must decide whether the two stimuli (flash and beep) occurred at the same time. Hence, it is likely that during the judgement, not only the implicit process of integrating multisensory information is involved, but also the more explicit process of time perception is involved. More specifically, in the simultaneity judgement task an implicit process of integrating multisensory information occurs due to stimuli (flash and beep) being integrated if within the TBW. More explicit processing of temporal structure also occurs in this task as participants are directly instructed to determine whether or not flash and beep occur at the same time, resulting in participants consciously thinking about time between the stimuli. Hence, it seems that the simultaneity judgement task used to assess the width of the TBW and filled duration illusion used to assess the time perception both involve a common underlying process, namely thinking about time. If the above is to be true it perhaps could explain why there was a relationship found between TBW and time perception in Fenner et al. (2020) study.

In contrast, to provide response to the double-flash illusion task only implicit process of integration of multisensory information seems to occur. Namely, here participants must rely on this process solely as they are asked to only concentrate on the number of the flashes perceived and hence no conscious thinking about time is involved. Given the above, it seems that the relationship between time perception and the temporal binding window observed in Fenner et al. (2020) might be in part due to the fact that the two tasks shared a common underlying process, where both tasks required explicitly thinking about time. When one of the measures are assessed implicitly, as in the current study assessing the width of the TBW with double-flash illusion, this association seems to be less observable. Future research should explore this possibility in more detail. Additionally, different time perception and TBW tasks also should be investigated. Different tasks potentially could measure different phenomenon as shown above (i.e. explicit vs implicit).

With respect to the link between the time perception and the alpha oscillations, it is evident that the data does not align with the existing literature. The current findings contradict results obtained by Horr et al. (2016) and Glicksohn et al. (2009) suggesting relationship between time perception and alpha oscillations. The study by Glicksohn et al. (2009) used much longer time intervals (up to 32s) than those employed in the current study (up to 1181ms), which raised the possibility that participants used chronometric counting. Hence it could be argued that the relationship between the alpha peak frequency and time perception is being mediated by the chronometric counting (Bizo et al., 2006) in Glicksohn et al. (2009) study. While Horr et al. (2016) used similar intervals to those employed in the current study, these intervals were filled with regularly spaced tones, whereas we used either entirely filled or empty durations. Further research is required to fully understand why this difference might be crucial to the correlation with alpha oscillations, but one possibility is that the task in Horr et al. (2016) triggers neural entrainment that can drive distortions in time perception (Matthews et al., 2014), and that these in turn might be mediated by alpha oscillations.

Conclusions and significance of the results

The aim of the current study was to investigate to what degree, if any, time perception, the TBW and the alpha peak frequency are linked. We found no evidence to support a link between time perception and the TBW or alpha peak frequency. Despite the above findings contrasting with existing literature, they provide significant and novel conclusions upon which to build further studies. In line with previous research, we found evidence in support of the link between alpha peak frequency and the TBW. This finding confirms the role of alpha oscillations in driving the time window of sensory integration.

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