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Transition Zone: the influence of pause duration on temporal reproduction

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Contents

ABSTRACT

In contrast to the concept of objective time being continuous as described in classical physics, in psychology and cognitive neuroscience it has been discussed and studied since a long time whether subjective time has to be understood as being continuous or discrete. It has been demonstrated on the basis of different experimental conditions and with different research paradigms that subjective time does not match directly objective time. Different mechanisms of temporal processing have been disclosed in studies on the question how subjective time relates to objective time. One such mechanism is reflected in a low-frequency "time window" of 2 to 3 seconds which has been confirmed in many studies; it can be understood as a pre-semantic and automatic integration mechanism. One experimental paradigm in such studies is the temporal reproduction task. Previous studies mostly focused on how standard durations influence cognitive processing; the influence of pause durations for reproduction of temporal intervals has been neglected. Some preliminary research suggests, however, that in fact pause durations between stimulus presentation and its reproduction may play an important role. In the research presented here, the influence of pause duration was systematically investigaed with a behavioral paradigm and an EEG study. Experiment 1 used pause durations from 1 to 16 seconds as independent variable and investigated how various pause durations may effect the reproduction of a 2 second standard interval. Results showed that when pause durations were below 4 seconds, the reproduced durations increased and then levelled off. To further explore whether this effect only applied to 2 second standard intervals, a 3 and 4.5 second was added as standard stimulus in the second experiment. It was observed that the reproductions for different standards showed the same pattern, i.e., a transition zone of reproductions up to 4 seconds was observed, before a "plateau" or subjective set point of constant reproductions was reached. Experiment 3 employed longer pause durations by excluding short pause durations, and in this case no transition zone was observed which confirmed the critical role of pause duration for cognitive processing, and substantiates the existence of a low frequency time window of 2 to 3 seconds. Different standard and reproduced auditory stimuli were applied in experiment 4 to test a potential dependence of reproduction on stimulus characteristics; no such effect was observed supporting the notion of a generalized temporal reproduction mechanism for a 2 to 3 second time window. Experiment 5 using measurements with EEG examined possible neural

indicators for the pause duration effect. Precisely timed and intense low-beta activities in the EEG across the entire cortical mantle were observed in the reproduction phase only up to a 3 second pause duration. This observation suggests the neural entrainment of a very low frequency oscillation or temporal integration interval by the onset of the standard to be reproduced. Thus, the low-beta activity as a neural marker may indicate the representation of a temporal stimulus in working memory.

ZUSAMMENFASSUNG

Im Gegensatz zum Konzept einer objektiven Zeit, die als kontinuierlich in der klassischen Physik zu verstehen ist, wird in der Psychologie und den kognitiven Neurowissenschaften seit langem diskutiert und auch experimentell untersucht, ob die subjektive Zeit als kontinuierlich oder diskret verstanden werden muss. Auf der Grundlage verschiedener experimenteller Bedingungen mit unterschiedlichen Paradigmen konnte gezeigt werden, dass subjektive Zeit nicht direkt der objektiven Zeit entspricht. Verschiedene Mechanismen konnten in Untersuchungen über die Frage aufgedeckt werden, wie sich subjektive Zeit auf objektive Zeit bezieht. Ein solcher Mechanisms spiegelt sich in einem niederfrequenten "Zeitfenster" von etwa 2 bis 3 Sekunden wider, und dies wurde in vielen Studien bestätigt; der Mechanismus kann verstanden werden als ein präsemantischer und automatischer Integrationsprozeß. Ein experimentelles Paradigma für solche Studien ist der zeitliche Reproduktionstest. Frühere Studien haben sich darauf konzentriert, wie verschiedene Standarddauern kognitive Prozesse beeinflussen; was vernachlässigt wurde, das ist der mögliche Einfluß der Dauer einer Pause auf die Reproduktion von zeitlichen Intervallen. Einige vorläufige Studien haben gezeigt, dass die Dauer der Pause zwischen Stimulus-Präsentation und der Reproduktion der Dauer eine wichtige Rolle spielen könnte. In den hier dargestellten Untersuchungen wurde der Einfluss der Pausendauer mit einem einem Verhaltens-Paradigma und einer EEG-Studie systematisch untersucht. In Experiment 1 wurden Pausendauern von 1 Sekunde bis 16 Sekunden als unabhängige Variable genutzt, und es wurde geprüft, wie möglicherweise verschiedene Pausendauern die Reproduktion eines Standardintervalls von 2 Sekunden beeinflussen. Es ergab sich, dass dann, wenn die Pausendauern unter 4 Sekunden waren, die Dauer der Reproduktion anstieg, und danach konstant blieb. Um zu untersuchen, ob dieser Effekt nur bei der Dauer des Stimulus von 2 Sekunden vorkommen würde, wurden in Experiment 2 Reizdauern auch von 3 und 4.5 Sekunden untersucht. Es zeigt sich das gleiche Muster der Reproduktion; es wurde ebenfalls eine Übergangszone für Reproduktionen bis zu 4 Sekunden Pausendauern beobachtet, bevor ein "Plateau" gleichbleibender Reproduktionen erreicht wurde. In Experiment 3 wurde kürzere Pausendauern ausgeschlossen und nur längere Pausendauern geprüft, wobei in diesem Fall keine Übergangszone beobachtet wurde; dies bestätigt die kritische Bedeutung der Pausendauer für kognitive Prozesse, und der Befund unterstützt das Konzept eines

niederfrequenten Zeitfensters von 2 bis 3 Sekunden. In Experiment 4 wurden verschiedene Stimuli für den Standardreiz und seine Reproduktion verwendet um zu prüfen, ob spezifische Reizcharakteristiken für die Reproduktionsweisen entscheidend sind; ein solcher Effekt wurde mit diesem Paradigma nicht beobachtet, was das generelle Konzept eines Zeitfensters von 2 bis 3 Sekunden stützt. In Experiment 5 wurde mit Hilfe von EEG-Aufzeichnungen geprüft, ob sich ein neuronaler Indikator für den Effekt der unterschiedlichen Pausendauern finden lässt. Es ergab sich, dass eine zeitlich präzise und intensive Aktivität von Beta-Wellen im niederen Frequenzbereich ("low beta") über den ganzen corticalen Mantel zu beobachten war, doch dieses nur bei den Reproduktionen von Pausendauern bis zu 3 Sekunden. Diese Beobachtung weist darauf hin, dass durch den Reizauftritt eine neuronale Synchronisation eines zeitlichen Integrationsprozesses beziehungsweise einer stark niederfrequenten Oszillation angestoßen wird, was sich entscheidend auf die Reproduktion auswirkt. Die selektive Beta-Aktivität kann möglicherweise somit als ein neuronaler Indikator für die Repräsentation von Zeit-Stimuli im Arbeitsgedächtnis angesehen werden.

1. Introduction

Whenever talking about time, people find that time is ubiquitous – from casual chatting to large-scale sports matches, from necessary foraging to unique human abilities, like enjoying or playing music. Although temporal perception is one of the intrinsic features of cognitive functions, and precise temporal information processing is an essential prerequisite for perceptual and cognitive activities, there is no clear evidence of how temporal information is processed in the human brain: how the brain registers the order of events, to specify something that has already happened, what we are doing now, and things will or will not occur in the future.

1.1   History: objective time and subjective time

As an abstract notion, it is difficult to tell what exactly time is, like the famous quotation in the eleventh book of the Confessions by Augustinus: "Quid est ergo tempus? Si nemo ex me quaerat, scio; si quaerenti explicare velim, nescio." (What, then, is time? If nobody asks me, I know, but if I have to explain it to somebody, I don't know.) According to the Cambridge dictionary, time is "….the part of existence that is measured in minutes, days, years, etc., or this process considered as a whole". Physically speaking, time is a dimension to measure the changes in matter and can be quantified on a clock, as described by the famous scientist Isaac Newton (1687), "Absolute, true, and mathematical time by itself and by its own nature flows equably without relation to anything external."

The topic of time in psychology was established around 150 years ago (Fechner, 1860), and scientists have been working on time estimation or questions concerning temporal duration to understand how our brain experiences time since then. If, dating back from the 19th century, Karl Ernst von Baer (1861) pointed out that the sense of information probably needs different moments (from the external clock) to deal with. This led to the concept of the present. The question of 'what is a moment or how long is a moment' became an exciting topic of discussion and research. The Austrian physicist Ernst Mach (1865) employed the technology already available at that time and found that durations under 40 milliseconds (ms) were experienced as a 'time point' for humans, which means that for a duration of less than 40ms, one cannot experience time passing. This

was perhaps the first time that someone tried to discriminate different time durations. One of the milestones in psychology was the use of the simple choice-reaction time by Karl Donders (1969), which has been applied for almost one and a half centuries. This method measures how long the nervous system needs to respond to a stimulus and allows researchers to investigate some complex and dynamic cognitive processing. While the above-mentioned researchers were interested in short-time durations based on some tens or hundreds of a millisecond, the German scientist Karl von Vierorth (1868) raised the question of how humans behave when reproducing several seconds of temporal duration. He found that short intervals were reproduced longer than the stimulus and long intervals were reproduced shorter, and this effect has become known as the "Vierordt effect".

In contrast to the continuous passage of time described in physics, psychologically perceived time does not conform to real time. From personal experience we know that we have entirely different perceptions of time passing in different situations. For example, when standing in a checkout line, people always feel bored and impatient that a minute feels like half an hour. However, when on an exciting roller coaster, three minutes seems like three seconds. Here, one minute or three minutes is real time or objective time, while the over-emphasized half an hour or three seconds is subjective time reflecting human experience. This leads to the important question: when the same objective (physical) time has passed, however, under different situations, how can the human brain produce such different subjective times. Psychologists have been puzzling over this question for years.

1.2   Methods in time-perception studies

Studies about temporal perception can be roughly divided into two parts: temporal order perception and duration perception; the former refers to the time domain of some tens or hundreds of milliseconds, while the studies on duration perception refer to intervals of seconds or longer.

1.2.1   Temporal-order perception

Temporal-order perception is mostly about the simultaneity and succession of events. In this kind of task, at least two stimuli are presented in physical order and subjects are

asked to report the discontinuity, succession, or the order of the stimuli. If distinguishing order the paradigm is refered to as temporal-order judgement (TOJ). When investigating the temporal-order threshold (TOT), the duration is measured with which subjects differentiate the order of two successive stimuli with usually 75% accuracy. The threshold is an essential indicator of temporal-order perception. Researchers initially focused on the bottom-up mechanism and investigated the physical characteristics of stimuli and biological features like the modalities vision, audition, and touch, as well as the TOT across modalities (Fraisse, 1984). More recently, psychologists have attempted to discover the effects of emotion and culture on TOT, which is a top-down mechanism (Pan & Huang, 2018).

1.2.2   *Temporal-duration perception*

Temporal-duration perception is mainly about the human perception of time intervals lasting several seconds or longer. Studies have found that factors like the present situation, the intensity of the stimulus, or even emotions can affect time perception. Four paradigms are generally used in time-perception experiments:

1) Temporal estimation. In this method a stimulus of a pre-defined duration in physical time is presented, and the subjects are asked to estimate how long (in physical time) the interval lasted.
2) Temporal comparison. Two durations are presented in sequence, and the subjects are requested to tell which one was longer.
3) Temporal production. The subjects have to produce a duration of a certain length defined in physical time like seconds.
4) Temporal reproduction. The experimenter provides a specified time duration (physical time), and the subject has to reproduce this duration without any counting strategy.

The four different paradigms have different meanings: temporal estimation and temporal production need the conventional time unit (physical time) as a reference. In contrast, the reproduction and comparison paradigms do not require traditional time units, but only use the stimulus as a reference. Since the methods of reproduction and comparison are free from the external clock, they are more useful when the research interest is about the internal human clock.

1.3 Studies about the low-frequency time window

1.3.1 The low-frequency time window and the subjective present

Researchers have long questioned whether time durations lasting a few seconds are processed with separate mechanisms or not. Some researchers state that durations of a few seconds are processed according to the scalar-timing model, in which the timing mechanism is linearly uniform (Ulbrich et al., 2007). Others have proposed that different durations are processed by different mechanisms, and the demarcation is referred to as 1/3s, 1/2s, 1s, 2-3s, or 3-5 seconds (Fraisse, 1984; Lewis & Miall, 2003; Michon, 1985; Musterberg, 1889; Pöppel, 1997). Concerning the demarcation of some seconds of duration, many researchers focus on the mechanism difference for under 1s and over 1s intervals (Cellini et al., 2014; Cordes & Meck, 2014; Grondin, 2010; Hayashi et al., 2014). Some scientists believe that intervals shorter than 1s are processed automatically with no need to modulate attention. In comparison, intervals longer than 1s are presumably regulated by higher cognitive functions such as attention and working memory. However, few studies have investigated the mechanisms for longer temporal durations. In this thesis I mostly focus on the boundary of temporal intervals lasting several seconds and several tens of seconds, and I want to understand the mechanisms behind the potential boundary. The aim is to disclose brain mechanisms behind long temporal durations and provide some theoretical concept.

The theory of duration boundaries beyond 1s has primarily been described by Fraisse (1984) and Pöppel (1997). Fraisse stated that people's perceptions of periods beyond the limit of 5s are not copies of reality, but reconstructions of long-term memory or 'temporal memory'. Pöppel indicated that the 'subjective present', which is 'the state of being conscious', is restricted by the capacity of time perception. A sequence of events can only be grasped and unified to a 'gestalt' within this limitation. Many observations have demonstrated that this 'subjective present' lasts around 3s, but individuals differ from 2s to 4s; thus, it is conceived of as an operating range.

This low-frequency time window of up to a few seconds has interested psychologists for more than 100 years. Experiments concerning this window of presence have been performed in different domains, such as short-term memory, temporal reproduction, spontaneous speech, and so on. These studies have shown that information from the

external environment to the human brain needs to be segregated into many short intervals of a few seconds, and it is necessary to assume some automatic temporal-integration processes to construct a more extended platform for cognitive processing. Being an abstract notion, it is essential to indicate the experimental evidence of the subjective present.

1.3.2   The temporal-reproduction paradigm

Temporal reproduction is the most commonly used method during low-frequency, time-window studies because this paradigm avoids the influence of verbal language, and indicates how subjective durations are affected by various factors from the differences in reproduced durations.
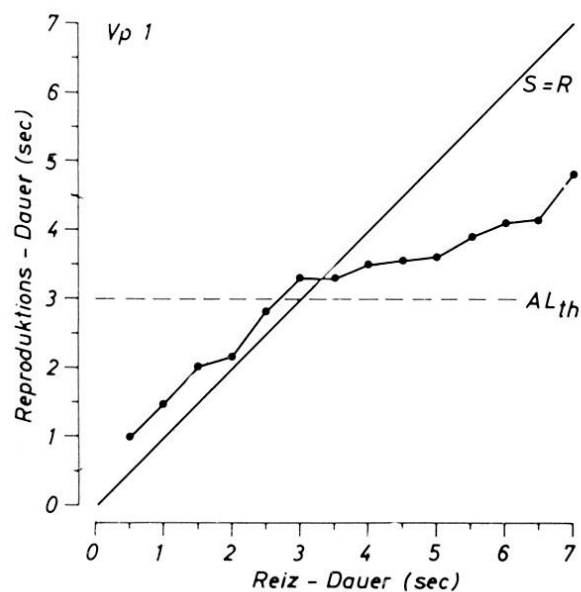
Fig.1 Reproduction of standard stimuli ranging from 0.5 and 7s, and the 'indifference point' was around 3-3.5s (Pöppel 1972)

When subjects were asked to reproduce auditory durations lasting from 0.5s to 7s (Pöppel 1972), the results showed that when stimuli were shorter than 3s, the reproduced durations were overestimated and closer to the actual duration (see Fig.1). In contrast, if stimuli were longer than 3s, reproductions were underestimated with higher variance. Presumably, short intervals are quickly stored in or extracted from working memory, while longer intervals were delimited. Pöppel's experiment more directly described the relationship between standard intervals and reproduced intervals and the

9

range of the indifference point. This well-known phenomenon has been observed in many studies.

Szelag and colleagues (2002) employed the reproduction paradigm and tried to understand the low-frequency time window from the perspective of cognitive development. Sixty children were divided into three age groups (6-7, 9-10, and 13-14 years old) and participated in both audition and vision experiments. Results revealed that all children underestimated the standard interval in the reproduced interval when standard intervals were longer than 2.5s. Younger children reproduced longer than older ones for standard durations shorter than 2s; for standard durations longer than 2.5s, the result was inverse. This may indicate that cognitive abilities develop with age. This progress presented different features within/beyond the low-frequency time window, which supports the hypothesis that there are different processing mechanisms at separate time windows.

Some studies attempted to identify temporal-integration mechanisms by looking deeply into the capability of working memory (Ulbrich et al., 2007; Yin et al., 2016). They demonstrated that the capability of subjects' working memory could affect the reproduction durations of longer standard intervals, but not those of shorter ones. Similar results were found in the pharmacologic domain. A previous study disclosed that hallucinogenic psilocybin influences subjective time perception (Fischer et al., 1966), and one double-blind study investigated how a dose of 4-phosphoryloxy-N, N-dimethyltryptamine affected subjects' performances with temporal reproduction tasks (Wittmann et al., 2007). Twelve subjects were equally allotted to placebo, medium-(115 μg/kg), and high-dose (250 μg/kg) groups. Results showed that this dose difference only influenced the reproduction of standard durations longer than 2.5s, but not that of shorter intervals.
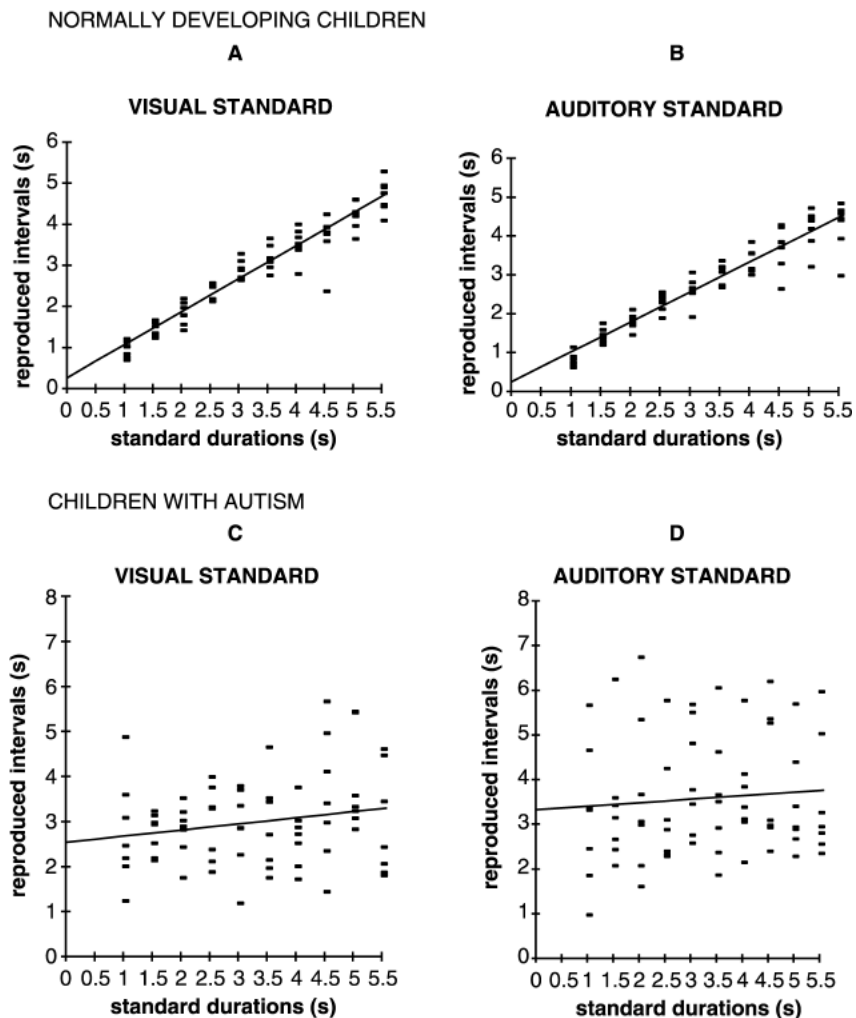
Fig.2 Mean reproduced durations in each autistic and control child when using group (normal children vs. children with autism) as between-subject factor (Szelag et al., 2004).

Aside from studies with healthy people, studies with autistic children also indicated a low-frequency time window (Szelag et al., 2004). Children with autism often show a variety of cognitive-function deficits in perception, attention, memory, emotion, social interaction, language, etc. Seven non-retarded autistic children and seven healthy children performed the temporal-reproduction task with both auditory and visual stimuli. It appeared that, regardless of the stimulus modality and duration, reproduction durations of autistic children were 3s on average (see Fig.2). Healthy children showed a similar pattern to that in the above-mentioned literature, which reported a relatively accurate response up to 3s and shorter reproductions than the stimulus itself over 3s. Another study with patients who had brain injuries in different hemispheres revealed that all patients could almost correctly reproduce intervals shorter than 2-3s. For longer

intervals, the ability to reproduce the given duration was affected more in patients with right hemispheric injuries. These results coincide with the hypothesis that the healthy human brain can retain sensory information for up to a few seconds, which suggests a temporal-integration mechanism of around 2-3s in both the audition and vision modalities. Since the patients with brain injuries did not have attentional problems, this supports the existence of different mechanisms for short and long durations, and the right hemisphere may play a critical role in the cerebral processing of longer durations.
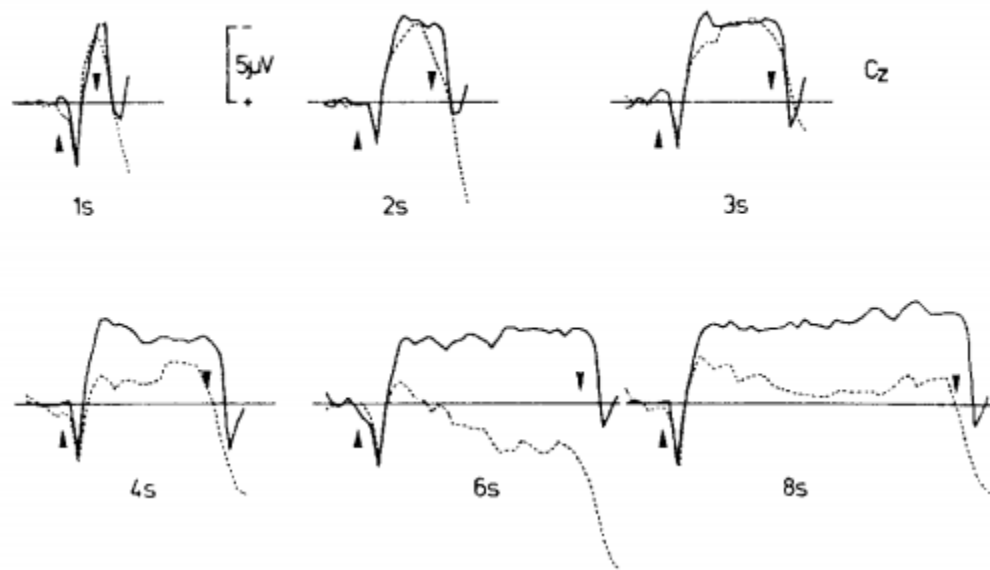

Fig.3 EEG signals from Cz with different standard durations (solid) and reproduction intervals (dotted) (Elbert et al., 1991)

The EEG technology has also been applied in the experiments on the low-frequency time window. Elbert and colleagues (1991) used 1s, 2s, 3s, 4s, 6s, and 8s as standard stimuli in temporal reproduction tasks. The behavioral results remained the same; subjects underestimated durations longer than 3s. They also discovered a negative component in the response which appeared both on standard and reproduction durations, but disappeared when standard stimuli were longer than 4s. Elbert and colleagues considered this negative wave to be a component of the "contingent negative variation", which is generally related to cognitive processing, such as expectancy and movement preparation. When standard intervals we are longer than a specific range, more cognitive processes, like memory, comparison, and decision, come into play, which may explain the appearance of a positive component resulting in a disappearance of the negative component.

1.3.3   *Other experimental paradigms linked to the low-frequency time window*

Many other studies have discovered evidence for the low-frequency time window in addition to temporal-reproduction tasks.

1) Sensorimotor synchronization

Sensorimotor synchronization is also an essential topic in temporal-perception studies (MacDorman, 1962; Najenson et al., 1989; Woodrow, 1932). This paradigm asks subjects to perform finger taps following a constant, evenly-spaced tempo, and most studies found that subjects unintentionally tapped the button before stimulus onset, which is referred to as systematic error. It is generally agree that subjects try to make finger taps to synchronize with the auditory stimulus in their mental representation; the systematic error may be due to different transfer times of the somatosensory and auditory modality. The difficulty of this task becomes more transparent when the inter-stimulus interval (ISI) of successive stimuli is longer. Wundt (1911) pointed out that the successive stimuli could be linked only when inter-stimulus intervals are shorter than 2.4s. Woodrow (1932) discovered that the synchronization between finger taps and auditory stimuli disappeared when ISIs were longer than 3.34 s. MacDorman (1962) found that if the ISIs were longer than 2.4s, the preceding response to the stimulus was inverse.

If subjects were asked to synchronize their finger taps with auditory stimuli, and the (ISI were between 300 and 4800ms (Mates et al., 1994), results showed that when the ISIs were around 600-800ms, the response onset preceded stimulus onset. When the ISIs were longer than 2400ms, subjects unintentionally began to change their behavioral patterns to react to stimuli instead of responding in advance. If a word-memory task was applied as a secondary task and a synchronization tapping task was the primary task, results showed that when ISIs are shorter than 1.5s, the automatic anticipation was not affected by attention. In contrast, during ISIs lasting 1.8s to 3.6s, anticipatory tapping was significantly influenced by the attention task. These studies demonstrated that up to approximately 2-3s, subjects can initiate an anticipatory response to the stimulus; if, however, stimuli are too far apart, it is too hard for them to programme anticipation. They prefer to react to the stimulus. This anticipatory strategy is also vital in our daily lives, like when driving. It can be used to better understand goal-directed behavior (Tanida & Pöppel, 2006).

2) Ambiguous materials

In perceptual studies, there is a class of stimuli that allows multiple perspectives by producing different subjective perceptual experiences and in which the visual figures are called ambiguous or reversible figures. For example, the rabbit-duck image (Fig.4) can be perceived as either a rabbit or a duck, depending on which background and target are chosen.
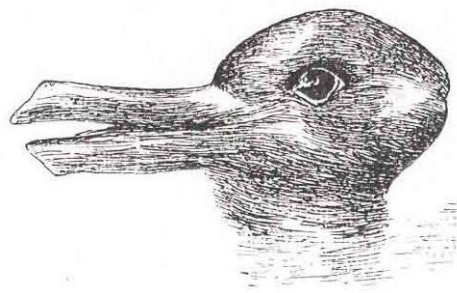

Fig.4 The rabbit-duck image, either a rabbit or a duck

Subjects were requested to look at a figure, for example (Fig. 5) the Necker cube, which has two possible perspectives, and press a button when they felt the perspective had changed (Gomez et al., 1995). It appeared that the most common value for the alternation was around 3-4s. When subjects were asked to maintain the same perspective as long as possible, the mean duration was 2.93s. This study supports the theory that there is an automatic shift in sensory perception, and the alternative content takes possession of the conscious mode at around 3s. Studies with an ambiguous-apparent-motion paradigm (Ilg et al., 2008) also discovered that an increase in stimulus frequency decreases the duration of the perceptual content, while the median stable perceptual duration is 2.69s. Such perceptual switching not only happens with visual stimuli, but also with ambiguous auditory material (Radilova et al., 1990), such as KU-BA-KU, which could be heard either as KUBA or BAKU. This study was performed with 10 subjects, and the average alternation duration was 3.1s(Pöppel, 2009).
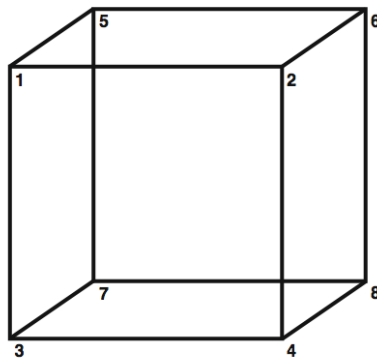
Fig.5 Necker cube

3) Binocular rivalry

Binocular rivalry is an interesting phenomenon that presents a different figure to each eye. The visual perception alternates between the two eyes so that one sometimes sees the left figure and sometimes the right one. The most classical paradigm in binocular rivalry is vertical strips for the left eye and horizontal strips for the right eye. The shift between two figures generally took approximately 2-3s. A patient with a bilateral injury to his occipital lobe still demonstrated binocular rivalry(Pöppel et al., 1978). This patient did not, however, experience a fast alternation of figures, but saw, for instance, the vertical stripes gradually being replaced by by the horizontal stripes, a process which lasted for several seconds.

4) Mismatch negativity

Around 40 years ago, Näätänen and colleagues (1978) found a new Event-related Potential (ERP) component, which is the brain's automatic response to sudden odd stimuli and was called 'mismatch negativity' (MMN). Studies about MMN are commonly based on the oddball paradigm, in which two kinds of stimuli are presented to subjects, one more frequently and the other, rarely. The discrepancy between them is reflected in the MMN. As a kind of component that could reflect human pre-attention, which represents the brain's capability of automatic processing, it has been applied in various research topics, like mental disease (Näätänen & Kähkönen, 2009; Takei et al., 2009). Most MMN studies used as ISI hundreds of milliseconds; only a few employed longer time durations. In one study using Magnetoencephalogram (MEG), the

researchers employed 1-12s as ISIs and found that when the ISI was 3s, the magnetic component corresponding to MMN was greatest (Sams et al., 1993). However, this result was not initially widely discussed. It has recently been confirmed by studies based on the oddball paradigm in both single-case and group studies (Wang et al., 2015).

5) The IOR effect

Inhibition of return (IOR) is a lagging response to some object or location previously perceived. In visual attention studies, there can be two stimuli; the first cue is presented to get attention, then the target appears, and the cue can point to either the right (target) side or the false side. If the cue indicates the correct side, the subject's response to the target will be promoting since the cue drew the subject's attention to the right place. However, when the interval between cue and target is longer than 300ms, the subject's response to the cued followed by the target is longer than to the incorrect target (Posner & Cohen, 1984). This phenomenon is referred to as IOR. To observe the IOR effect, the cue and target should not be separated by more than a few seconds (Pöppel, 2009). A study (Bao & Pöppel, 2007) found that the IOR effect was more potent in the peripheral visual field than in the central visual field. When the intervals between cue and target were increased, the IOR effect in both the peripheral and primary visual fields faded away. It vanished completely when the interval was 3s(Bao et al., 2013).

6) Short-term memory

In a classic study about short-term retention (Peterson & Peterson, 1959), the experimenter presented a consonant syllable and a three-digit number in each trial. Subjects were asked to count backward by 3s or 4s from the number with various durations (3s, 6s, 9s, 12, 15s, and 18s) and then recall the consonant syllable. The mean latency of correct recall was 2.83s, which indicated that a verbal syllable could only be stored in memory for a few seconds.

Weber's Law, one of the most basic psychophysical laws, has also been applied to study temporal perception. It demonstrates the difference threshold of sensory perception when the original stimulus is changed. This means the ratio of stimulus increment (ΔI) to the original stimulus (I) is a constant (K), and this constant is called the Weber Fraction. Studies applying duration-discrimination tasks initially employed standard durations in a range from 50ms to 3.2s (Getty, 1975). Results revealed that Weber's

Law did not predict the rapid increase in standard deviation for intervals longer than 2s. Kristofferson (1976) disclosed that the Weber Fraction for standard intervals lasting 500ms to 2s was constant. For human beings, the Weber Fraction is 10 percent of the standard duration for intervals from 200ms to 2s (Hirsh et al., 1990). Researchers also found that when standard durations were longer than 2-3s, the Weber Fraction increased significantly as a result of a change in the sensitivity of duration estimations beyond 2s.

7) Segmentation of spontaneous speech

It is interesting to hear the pauses when people spontaneously speak. A study in 1994 (Kien & Kemp, 1994) investigated the temporal-segmentation mechanism in speech. When 14 Germans and five Koreans were asked to read prose in their native languages, results showed the median length of phrases separated by pauses was 3.58s. However, compared to Germans, the Korean norm was 0.6s shorter. Another task when the same German subjects read Grimm's' fairy tale "Sleeping Beauty" and immediately afterwards were requested to retell the story, and the median of their speech without a break was 2.12s. If these German subjects were asked to describe something interesting, such as exciting experience, book, or film, their median phrase length was 2.31s.

8) Duration of verses in poetry

Turner and Pöppel (1983) suggested a line of poetry to be a form of semantic unit, and they discovered that the average duration of a read line of poetry was around 3s in Japanese, Chinese, English, Ancient Greek, Latin, French, and German. However, this test was not strictly controlled. Kien and Kemp (1994) asked five German speakers and five Korean speakers to read poems in their native languages. Results showed that the median duration of each read line of German poems was 1.7s and of Korean lyrics, 2.24s, which coincided with the low-frequency time window, but was restricted by the length of the lines. A more recent study attempted to compensate for various line lengths and requested subjects to listen, but not read (Zhao et al., 2018). Fifteen traditional Chinese poetic sentences were recorded with different durations lasting for 1.5, 2, 3, and 4s. Thirteen Chinese and 13 German participants were asked to listen to the sentences and make aesthetic choices on a 9-point Likert scale. The results revealed that the aesthetic ratings of both groups were highest for 2-3s.

9) Intentional acts

Human daily behavior can be organized into many short-term movements, and a study showed that a frame-content model could define the hierarchical levels. The lowest level, which can be called intentional behavioral acts, contained goal-directed movements, such as when a mother pats her child. Schleidt and colleagues(1987) conducted a data-collection study on these intentional acts. They collected behavioral data from four different cultures, Europeans, Trobriand Islanders, Yanomami Indians, and Kalahari Bushmen, and analyzed their everyday behavior which was not influenced by the surrounding environments and repeated at least three times in a sequence. Results for all these cultures showed the modal durations of behavioral acts were 2s and 3s, which suggested a cross-cultural, temporal-segmentation mechanism of short-term behavior.

10) Accentuation of successive stimuli

Wundt (1911) found that the integration of successive stimuli had a limit of approximately 2.5s. In this metronome study, he stated that when the inter-stimulus intervals of successive auditory stimuli were under 2.5s, subjects could easily link these clicks. However, if the intervals between stimuli were too long (over 3s), subjects could not unite these two clicks because they were in two different temporal windows.

11) Fore-period studies

If there is a warning signal before the target, the duration between the two stimuli is referred to as the 'foreperiod'. Since the foreperiod has a strong effect on a subject's response, such as improving the response speed to the target stimulus, these patterns have been included in the investigation of cognitive temporal characters. Although patterns of the foreperiod have not been directly linked to the low-frequency time window, some studies also referred to it (Elbert et al., 1991). A study found that a subject's response to a target stimulus was shorter when the foreperiod between the target stimulus and the warning stimulus was stable, corresponding to the response time under various foreperiod durations. When the foreperiod was stable, which meant the interval between the warning stimulus and the target stimulus is steady, and subject can make a prediction and allot his/her attention to it. The response to the target stimulus can be faster than the various foreperiods. Researchers have found that this conclusion only applied when the foreperiod was shorter than 3s. When it was longer, there was a

longer response time to the stable foreperiod and a quicker response time to various foreperiods, thus mading them similar (Niemi, 1979). In other words, when a waiting time is longer than 3s, the fixed foreperiod cannot facilitate the subject's response. This suggests that a subject cannot predict a time point beyond 3s; the subject cannot integrate these two stimuli and the waiting time in between into a unit.

EEG studies also obtained similar results. The ERP component Contingent Negative Variation (CNV) is one of the important EEG indicators, and this slow, single-phase wave appears around 1s after the warning stimulus. Studies found that when the foreperiod ranged from 1s to 3s, the warning-stimulus-evoked CNV had a larger amplitude; when the foreperiod was longer than 3s, the waveform of CNV had a second peak (Loveless & Sanford, 1974). Although there is no recognized explanation for this component, it is generally thought to refer to cognitive activities, such as anticipation, attention, and movement preparation (Rockstroh, 1989). The fact that the amplitude of the CNV was larger when the foreperiod was shorter than 3s suggests that the neurons related to temporal processing were more active.

2. Question

The theory of the low-frequency time window as a part of the mundane scale is essential for the understanding of temporal information processing, in which the temporal-reproduction task plays an important role. Most studies employing the temporal-reproduction task have been based on research by Pöppel (1972), and they only employed the indifference point as the definition for the low-frequency time window. However, this method hypothesized that the form of the standard duration and the reproduction duration should be the same processing construct. Previous studies using EEG or Magnetoencephalography (MEG) technology demonstrated that the processing of these two intervals occurs in different brain regions. The quantitative equality was not very accurate; i.e., one could not use the number to make a comparison. The relationship between standard and reproduced durations is not very clear.

Excecpt for the numeric comparison and the comparison of neural indicators, additional studies attempted to design the experiment based on the idea of double separation. A particular variable was manipulated to change the subject's reproductions and then compare whether the response durations (RDs) have different alternation patterns under short or long durations. Many research fields, such as developmental psychology, pathology, and pharmacology, have applied this concept.

A new perspective for temporal reproduction studies is to examine the pause between the standard stimulus and the reproduced duration. Sensorimotor- synchronization and fore period research have investigated these patterns in the inter-stimulus interval. Pause durations (PDs) could possibly reveal some features of the low-frequency time window. Previous studies with temporal-reproduction tasks commonly adopted fixed PDs, and aside from some MEG or EEG studies, used PDs longer than 5s. Most behavioral studies applied durations between 1s and 3s, which suggest the relationship between the PD and the low-frequency time window.

Researchers have recently employed time-frequency analysis and investigated the electrical brain activity during the inter-stimulus interval with the temporal-comparison task. Arresting alpha oscillation was revealed. Since the alpha oscillation is stronger

during short standard durations, researchers interpreted that it represents the standard duration in working memory. Although this oscillation index was derived from waiting duration, these researches focused primarily on the difference under various standard-duration conditions. The alpha wave from the PD was only used as an indicator to explore how standard durations regulated this oscillation index(Chen et al., 2015; Yu et al., 2017).

Another more direct approach is to investigate how various pause durations (PDs) affects reproduced durations. The study of difference under different PDs can be traced back to 1868, when Vierordt recorded the results of two temporal-reproduction experiments on himself. In the first experiment, there were three button-pressing intervals: the interval between the first two pressings was the standard duration, and the interval between the second and the third pressing was a reproduction, i.e., the reproduction was right after the standard period. In the second experiment, there were four button-pressing intervals in which the interval between the first two was still the standard duration, and the duration between the last two was the reproduced duration, while the pause between the standard and reproduced durations was the subjectively chosen comfortable duration. Lejeune and Wearden (2009) interpreted that these results demonstrated that, compared to the first experiment, which was with no PD (Fig.6), the second experiment that had a PD made the reproduction longer (Fig.7), and the indifference point (the beginning of the underestimation of the reproduced duration compared to the standard duration) occurred later.
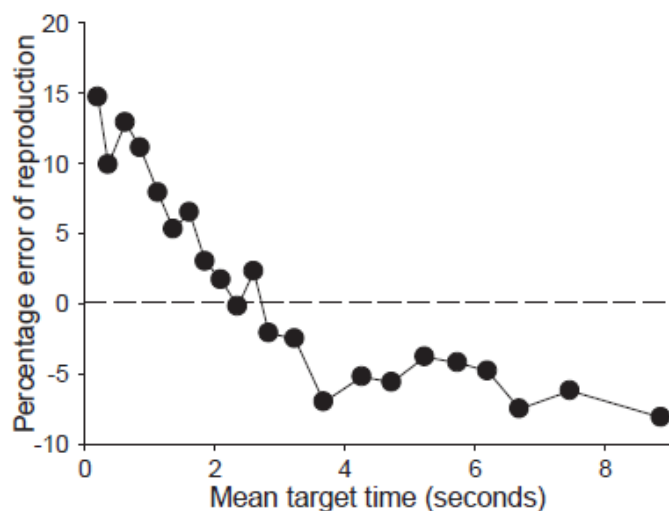

Fig. 6 the first experiment without pause duration. The y-axis is the percentage difference between reproduction and standard duration(Lejeune & Wearden, 2009).
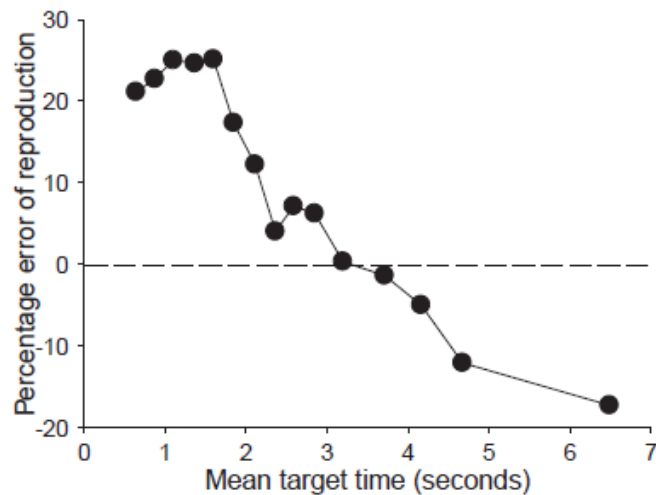
Fig. 7 the second experiment with pause duration(Lejeune & Wearden, 2009)

It is still unclear whether the PD affects reproduction or how possible the mechanism really is. One possibility is that an effect occurs only with or without a pause. Another possibility is that the length of the interruption can affect the reproduction, but only to a limited extent. Since previous studies did not employ short PDs, this question remains unsolved.

Pöppel's single study (1973) supports the second possibility. One subject was asked to reproduce the 2s duration, and the reproduction onset appeared randomly after a PD in a range from 0.5s to 50s. It revealed that the subject's reproduced length increased with the increase in the PD and gradually came to a plateau. This increase only occurred in the range of around 2s. Pöppel considered that this result was related to the low-frequency time window and involved two aspects: firstly, the effect of the PD matched the low-frequency time window; secondly, with the increase in the PD, the reproduced period gradually tended toward a stable value in the range of 2s to 3s. Pöppel referred to this value as a subjective set-point and observed that it was also close to the range of the low-frequency time window (Fig.8). He concluded that spontaneous oscillations occur during temporal- information processing.
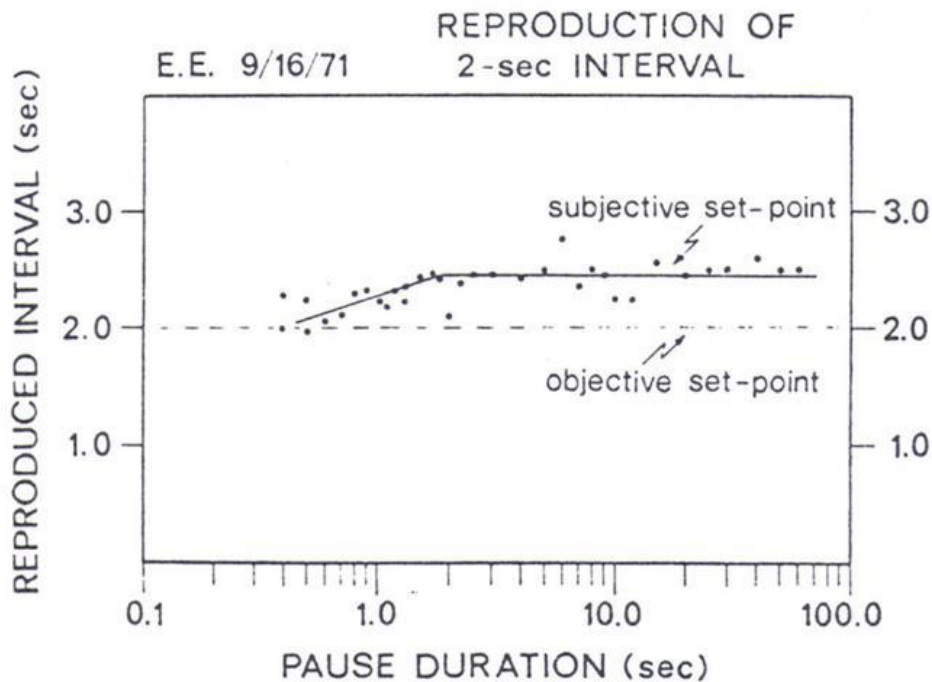
Fig. 8 Reproduced durations of a single subject with pause durations logarithmically from 0.5s to 100s (Pöppel,1973)

At that time there were few studies using the temporal- reproduction task, and explanations of the results were obscure. I interpret Pöppel's theory as follows. Most studies used the fixed PD of around 2-3s, and although they often referred to one another, this relatively uniform selection tendency suggests that this temporality has a specific particularity. It can not only prevent the two stimuli from being too close and losing their independence and identity, but also prevent them from being too far apart. When the PD varies to some extent, these two stimuli are perceived not as one unit, but as two independent stimuli, resulting in the change in reproduction.

The subjective point can refer to the previously-mentioned study on autistic children by Szelag and colleagues (2004). That study discovered that the autistic children reproduced intervals independent of the length of the standard durations, and the average reproduction duration was around 3s. Szelag and colleagues thought this might relate to the low-frequency time window. Since autistic children lack temporal cognitive functions, the expression of spontaneous oscillations is more robust, explaining their reproduced durations of approximately 3s. One can inquire whether the plateau value of an increase in the PD in healthy subjects results from the shift toward spontaneous

oscillations. However, if the PD only affects short durations of a few seconds, it is too short for that subject to lose the representation of the standard stimulus. This subjective set-point requires further investigation.

I wish to perform further experiments to explore earlier results. I would first like to confirm the effect of the PD on reproduction. Pöppel's study has some limitations: 1) There was only one subject, and the result could be too individual. 2) Although it contained 80 trials, these trials were not repeated. 3) The conclusion of the experiment was inferred, but not statistically tested. I therefore employed a group study and used 2s as a standard duration to investigate how reproduction was affected by various PDs under a strictly controlled experimental environment.

3. Behavioral Studies

3.1   Experiment 1

3.1.1   Participants

Twelve volunteer students (aged 18 to 25), including two males and ten females, participated in this experiment. They had no history of mental or neurological disease. All of them were right-handed and had normal hearing.

3.1.2   Design and Apparatus

Before the final experiment, the subjects finished a practice session that contained ten trials, including each PD twice. Standard stimuli were 2s, and PDs were 1, 2, 4, 8, and 16s. In the final experiment, each PD appeared 20 times, and a total of 100 trials were randomly distributed into four sessions. Intervals between sessions lasted 3 minutes.

The experimental program was based on Matlab and Psychtoolbox. The computer used for the experiment was a Dell T3610 with a sound adapter Blaster Audigy 5; the ASIO interface was used to improve the timing accuracy of auditory stimuli. Subjects used in-ear headphones, and the volume was in a stable, comfortable range. The space button was used for a response with the right hand.
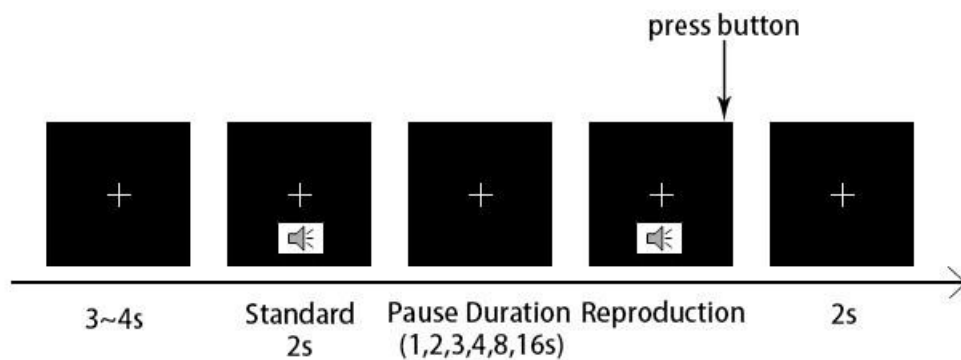

Figure 9: Procedure of Experiment 1

3.1.3   Procedure

Subjects were asked to sit in front of the screen and put their heads on the chin strap; the response button was placed at a comfortable distance on the right in front of them. At the beginning of each trial, a small cross (0.8 °) appeared on the screen for 3 to 4s. The

300Hz standard auditory stimulus lasted for 2s followed by varied PDs. Then the same auditory stimulus automatically reappeared. The subject was to press the button to stop the second stimulus and try to make it last the same amount of time as the previous standard one. The cross remained for another 2s after the subject's response and then disappeared until the onset of the next trial. The task procedure is shown in Fig.9. Subjects were informed that they should only concentrate on time, and any kind of calculation method was forbidden. Previous research showed that this is the best and easiest method to avoid counting (Rattat & Droit-Volet, 2012).

3.1.4 Result

A scatter graph of subjects' responses showed that the subjects sometimes pressed the button either immediately or never, which meant they misunderstood the task. These trials were excluded from the dataset. Responses over 2 SDs were also excluded. The whole dataset included 95.39% of the trials. The averaged reproduction durations is showed in Fig.10.

One-way ANOVA of the five PDs was performed; the main PD effect proved significant ($p < 0.001$, $F(4,68) = 10.439$). Further analysis showed that the reproduced durations (RD) of PD =1s were significantly shorter than others ($p < 0.01$).
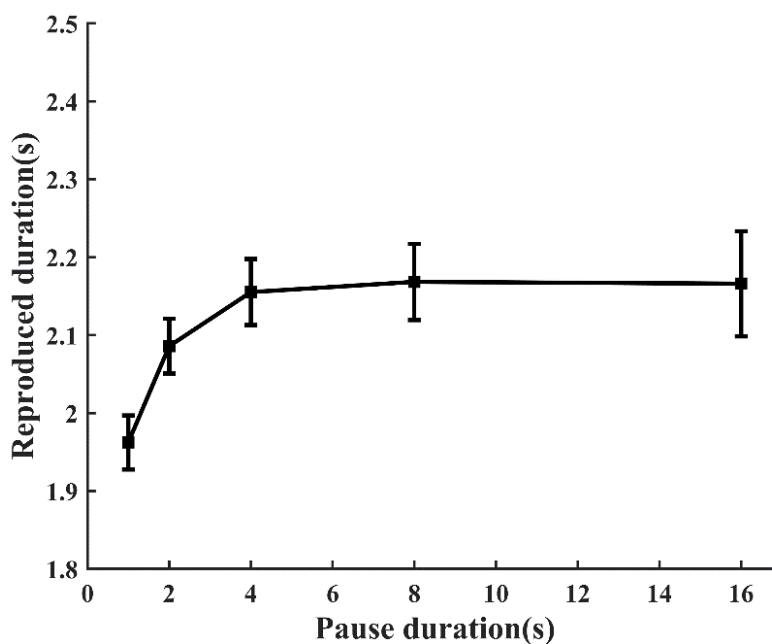

Fig. 10 Averaged reproduced durations of 2s standard durations after different PDs

3.1.5 Discussion

Experiment 1 was a repeated experiment based on Pöppel's 1973 study, but included several subjects. The two main results of the previous- single-case study are given below.

1) Reproduction durations increased with the PDs within a specific range, and the PDs had no influence on reproduction within this range.

2) Reproduction durations gradually tended toward a stable value, which was slightly longer than the standard duration (2s).

Although the results of Experiment 1 were not all the same as in the previous study, reproduction durations in Experiment 1 increased, but only significantly with PD = 1 and others, which differed from the one until PD=2 in Pöppel's 1973 experiment**.** This could be the result of the difference between a single-case study and a group study.

Results of Experiment 1 showed that when PDs were shorter than 4s, the reproduction durations increased with the PD, but when PDs were longer than 4s, the reproduction durations levelled off. Pöppel's study was limited in scope without producing an absolute value. However, combining his and my results indicates that the increase in reproduction intervals with PD may relate to the low-frequency time window. As for the plateau, Pöppel proposed a subjective point under the effect of the default timing system. We could clarify this phenomenon with the current single-standard-interval research. Further studies focusing on how and in which direction reproductions change under various standard durations should be performed.

3.2 Experiment 2

3.2.1 Participants

Twelve students from the Peking University (aged 18-25; 2 males) participated in this experiment. They had no history of mental or neurological disease and were right-handed with normal hearing.

3.2.2 Design and Apparatus

Experiment 2 employed three standard stimuli (2s, 3s, and 4.5s), and subjects were asked to come on three different days on which only one standard duration was tested. The sequence of three standard durations was randomized among all subjects.

PDs for each standard stimulus varied logarithmically from 1s to 32s, and each appeared 18 times. A total of 108 trials were randomly distributed into 6 sessions. Before each final experiment, a practice session was performed which contained each PD twice. The standard duration was the one that had been tested on that day.

3.2.3 Procedure

Subjects were asked to come on three different days to measure different standard durations and the sequence was counter balanced in subjects. On each day, the process of Experiment 2 was almost the same as in Experiment 1; the only difference was that a PD = 32s was added for each standard stimulus.
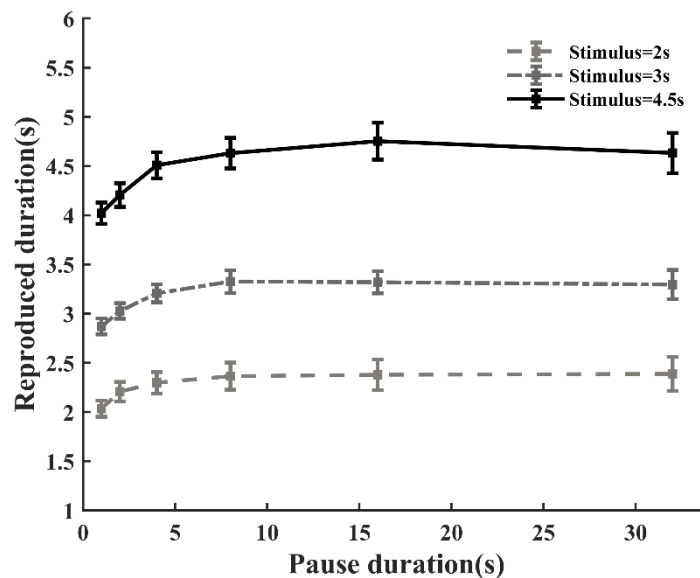

Fig.11 Mean reproduction durations for three standard durations after different PDs

3.2.4 Results

Abnormal responses (reproduction durations shorter than 0.5s and longer than 8s) were excluded. Repeated ANOVA was employed with SPSS 22.0.

A two-way ANOVA was performed with 3 standard durations $\times$ 6 PDs. The main effect of the standard duration (SD) was significant ($p < 0.001$, $F(2,26) = 280.376$), and the main effect of the PD was significant ($p < 0.001$, $F(5,65) = 15.119$). The interaction between SDs and PDs was also significant ($p < 0.01$, $F(10,130) = 4.54$).

Further analysis of the simple-effect test showed that for SD = 2s, the RD of PD = 1s was shorter than PD = 2s, 4s, 8s, and 16s. The RD of PD = 2s was marginally shorter than PD = 4s ($p = 0.073$), while the RD of PD = 4s, 8s, 16s, and 32s had no significant difference.

For SD = 3s, the RD of PD = 1s was significantly shorter than PD = 2s, 4s, 8s, and 16s and marginally longer than PD = 32s ($p = 0.058$), and the RD of PD = 2s was markedly shorter than PD = 4s, 8s, and 16s, while there was no significant difference among the RDs of PD = 4s, 8s, 16s, and 32s.

As for SD = 4.5, the RD of PD = 1s and PD = 2s were significantly shorter than PD = 4s, 8s, and 16s, while PD = 1s, and PD = 2s showed no significance, not among the RDs of PD = 4s, 8s, 16s, and 32s.
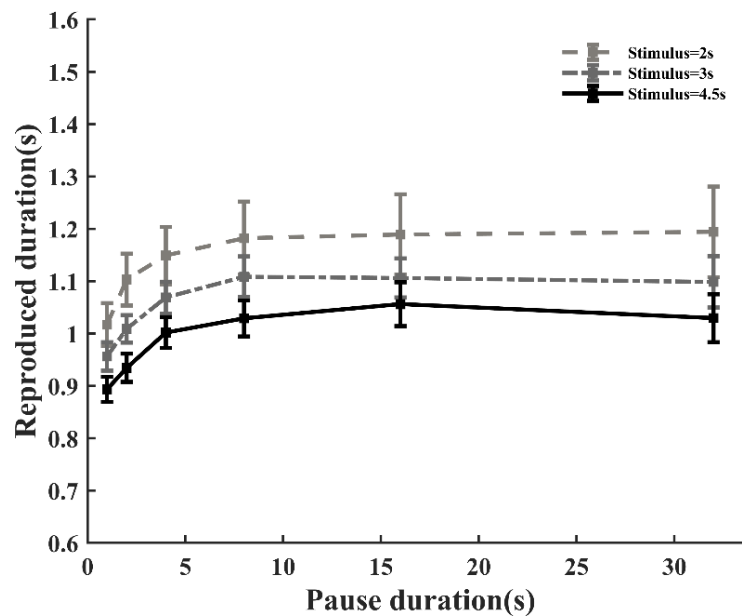

Fig. 12 the ratio of reproduction against standard durations after different PDs

I also did repeated ANOVA for the ratio of the RD and the SD with 3 SDs $\times$ 6 PDs. Results showed that the main effect of the SD was significant ($p < 0.01$, $F(2, 26) = 7.954$). The main impact of the PD was significant ($p < 0.001$, $F(5, 65) = 13.944$), whereas the interaction between the SD and the PD was not significant.

A post-hoc analysis of the SD found that SD = 2s was significantly larger than SD = 4.5s ($p < 0.01$). A post-hoc analysis of the PD found that the ratio of the PD=1s to SD was significantly smaller other than that of PD = 2s, 4s, 8s, and 16s and marginally shorter than PD = 32 ($p = 0.051$). The proportion of PD = 2s was markedly lower than PD = 4s, 8s, and 16s. The ratio of PD = 4s, 8s, 16s, and 32s to SD showed no significant differences.

3.2.5 Discussion

Experiment 2 focused on whether different standard durations influence the transition zone or the plateau. I added 3s and 4.5s as standard stimuli along with longer PDs of 32s, which were used to investigate how this affected reproduction durations.

This experiment revealed that there was an increase in reproduction durations with PDs below 4s for all three different standard intervals with a tendency to flatten off beyond 4s. This observation contradicted our expectations. On the basis of Pöppel's (1973) study, I hypothesized that, when standard intervals were longer than 3s, the reproduction durations would gradually tend toward the subjective set-point, which is decided by the low-frequency time window. I expected the reproduction durations to decrease with the increase in the PDs and tend toward some specified value for longer standards. However, the results showed that when the standard intervals were 3s and 4.5s, although there was a change in reproduction durations which tended to be stable, the PDs showed an increase instead of a decrease. This indicated that the variation in the reproduction durations with the PDs did not correspond with the low-frequency time window under the default timing system, but resulted from some other mechanisms.

Although the variety in reproduction durations was not what I had expected, their temporal features with PDs were further revealed. The previous study had employed only 2s as a standard duration; the correlation of this paradigm with the low-frequency time window was not well explored. In Experiment 2, the effect of the PD within 4s

occurred not only with the 2s standard intervals, but also with the longer standard durations of 3s and 4.5s; thus, this phenomenon was not limited to a 2s range. The analysis based on the ratio of PD to SD also showed that the change in reproduction durations following different standard durations had the same temporal character.

In these experiments, the shortest PDs were below 4s (beginning at 1s), which are located within a time window of a few seconds; if giving subjects some PDs that were longer than 4s, the reproduction durations might still increase and be followed by a plateau. An experiment with PDs beginning at 5s was performed to find out whether this effect was based on the low-frequency time window or only shorter ones.

3.3   Experiment 3

3.3.1   Participants

Twelve university students aged 19 to 25, including seven males, were recruited for this study. They had no history of mental disorder and had normal hearing.

3.3.2   Design and Apparatus

The experimental design was the same as for Experiment 2, but the PDs were changed to 5s, 6s, 8s, 16s, 20s, and 36s.

3.3.3   Procedure

The experimental procedure was the same as in Experiment 2.

3.3.4   Results

Data screening was performed first. Data outside of 2 standard deviations were excluded under each condition, and the mean data was analysed with Repeated ANOVA (3SDs $\times$ 6 PDs).
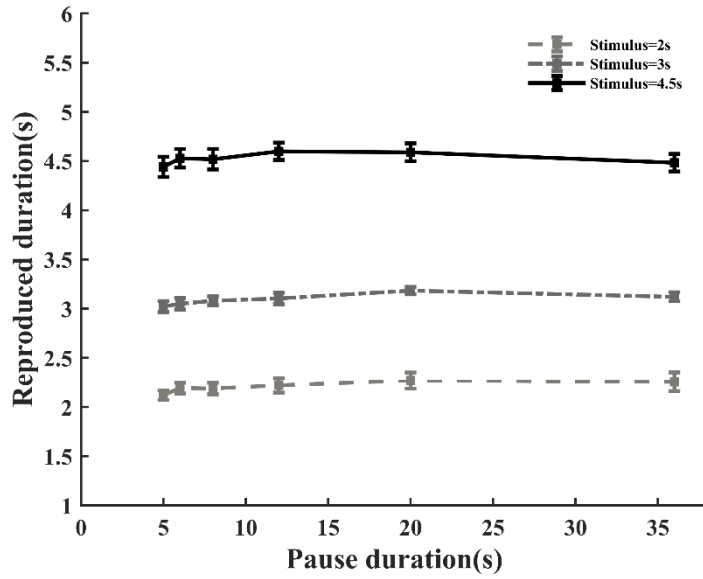
Fig.13 Mean reproduced durations of standard durations after long PDs
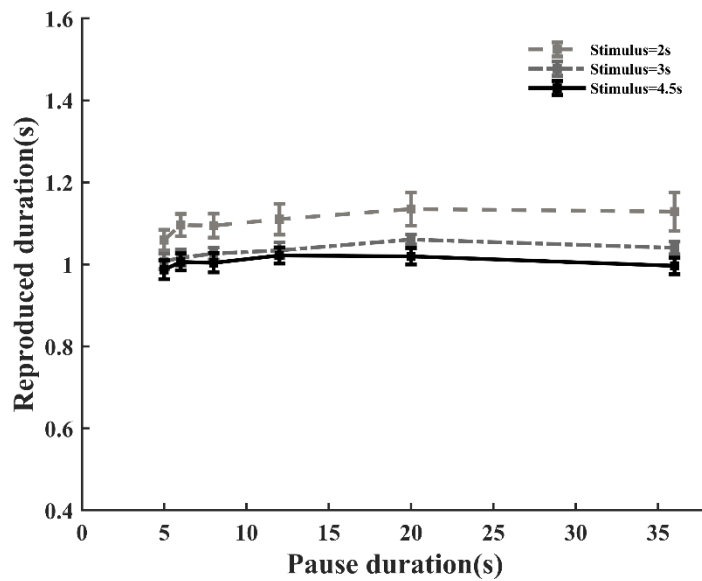
Fig.14 Ratio of reproductions against standard durations after long PDs

Both the main SD effect ($p < 0.001$, F (2,22) = 382.334) and the main PD effect were significant ($p < 0.001$, F (5,55) = 6.965), and there was no interaction.

A post-hoc analysis of the SD showed that the RD of the 2s SD was significantly shorter than the 3s SD and the 4.5s SD. The RD of the 3s SD was markedly shorter than that of the 4.5s SD. A post-hoc analysis of the RD showed that the RD of the 5sPD was significantly shorter than that of the 6s, 8s, 12s, and 20s PDs.

The RDs from each condition subdivided by SDs were converted to a ratio and entered into repeated ANOVA. The ratio of the RD to the SD was also calculated in a two-way ANOVA, and both the SD ($p < 0.05$, $F (2,22) = 5.606$) and the PD ($p < 0.01$, $F (5,55) = 7.339$) were significant. A post-hoc analysis of the SD showed that the ratio of the 2s SD was significantly larger than that of 4.5s SD. A post-hoc analysis of the PD showed that the ratio of the 5s PD was significantly shorter than that of the 6s, 8s, 12s, and 20s PDs.

3.3.5   Discussion

In this experiment, although the reproductions of the 5s PD were shorter than those of others, there was no other difference among various PDs, which ruled out diverse PDs affecting reproductions. These results indicated that the PD influenced the reproduction durations of different standard intervals, but this effect appeared only within 4s, which could relate to the low-frequency time window. Since previous studies mostly paid attention to the different cognitive-processing mechanisms with various standard durations, this result provides a new aspect to the low-frequency time window.

The mechanism behind this phenomenon is still unclear. I initially hypothesized that subjects would not be able to maintain the time duration due to an uncertain PD, and the representation of the time interval in the working memory would gradually decline, resulting in the tendency of reproduction to be 2-3s. The autistic children with information processing problems maintained reproduced intervals that averaged 3s. The results of long standard durations showed that this hypothesis was not sufficient to explain this phenomenon.

The mean reproduced interval of a 5s PD differed from that of 6s, 8s, 12s, and 20s PDs, but not for the average intervals and ratio of the 36s PD to SD indicating that there could be a slow increase beyond 3s. The results of other studies on temporal durations may derive from different mechanisms in the low-frequency time window, and long durations attained more attention and memory processing.

To link the effect of PDs within 4s to the low-frequency time window, the relationship between this effect and sensory effects should be clarified since the low-frequency mechanism is based on the 'pre-semantic' domain. In these experiments, the same

auditory stimulus for the standard and the reproduction may have confused some subjects. On the one hand, subjects may have used the sensory effect of the same auditory stimuli as a strategy. On the other hand, studies have revealed that stimuli without temporal aspects can also affect time perception, especially when the same stimulus is repeated (Matthews, 2011). Therefore, it is crucial to clarify whether our conclusions resulted from neural activities in the sensory domain due to the use of the same two stimuli. To investigate the possible influence of the same standard and reproduced stimulus, Experiment 4 employed two different stimuli. I removed PD = 32s and then added PD = 3s to further specify the temporal character of the PD effect.

3.4 Experiment 4

3.4.1 Participants

Eighteen university students participated in this experiment (aged 18 to 25), including six males and 12 females. They had no history of mental disorder and normal hearing.

3.4.2 Design and Apparatus

The design of Experiment 4 was similar to that of Experiment 2. Compared with Experiment 2, the auditory-reproduction stimulus was changed to 400Hz, and PDs were altered to 1s, 2s, 3s, 4s, 8s, and 16s. For each standard stimulus, each PD appeared twice in the practice session and 18 times in the final experiment, making a total of 12 practice trials. The final experiment contained 108 trials distributed into 6 sessions. As in the previous experiment, subjects needed to come on three different days and perform different standard stimulus durations.

3.4.3 Procedure

Experiment 4 was almost the same as Experiment 1, but in Experiment 4, subjects were asked to come on three different days for different standard durations, and the sequence was counter-balanced in subjects.

3.4.4 Results

I also employed two-way ANOVA for this experiment, and results showed that the main effect of the SD ($p < 0.001$, $F(2,34) = 272.838$) and the PD ($p < 0.001$, $F(5,85) = 39.566$) were both significant. The interaction between the SD and the PD was also significant ($p < 0.001$, $F(10,170) = 5.745$).
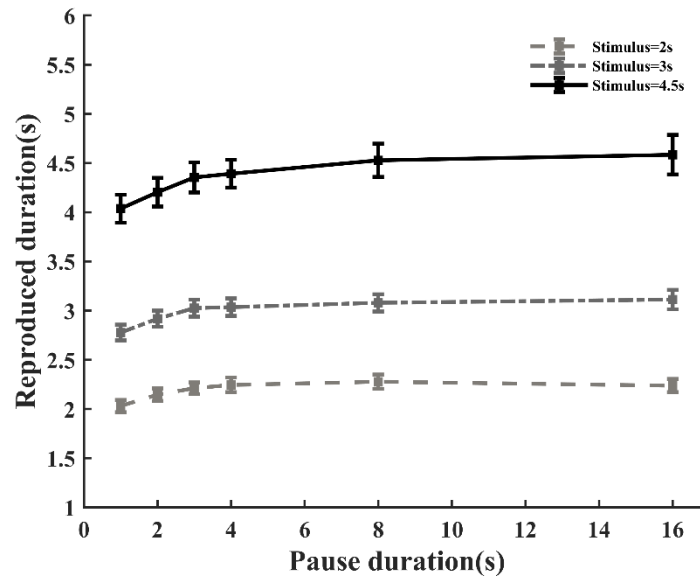
Fig. 15 Mean reproduced durations after different PDs with different auditory frequencies for standard stimulus and reproduced stimulus

Further simple-effect tests were performed to check the effect of the PDs. The results showed that for SD=2s, the RD of the PD = 1 was still significantly shorter than others, and the RD of the 2s PD was significantly shorter than the 4s and 8s PDs, while there was no marked difference among the RDs of the 3s, 4s, 8s, and 16s PDs.

When SD = 3, the RD of the PD = 1s was significantly shorter than others. The RD of the PD = 2s was significantly shorter than PD = 3s, 4s, 8s, and 16s, and RD 3s, 4s, 8s, and 16s. PD =3s, 4s, 8s and 16s showed no marked difference. As for SD = 4.5s, the RD of PD = 1 was significantly shorter than others. The RD of the 2s PD was significantly shorter than the 3s, 4s, 8s, and 16s PDs, but no significant difference among the 3s, 4s, 8s, and 16s PDs were found.

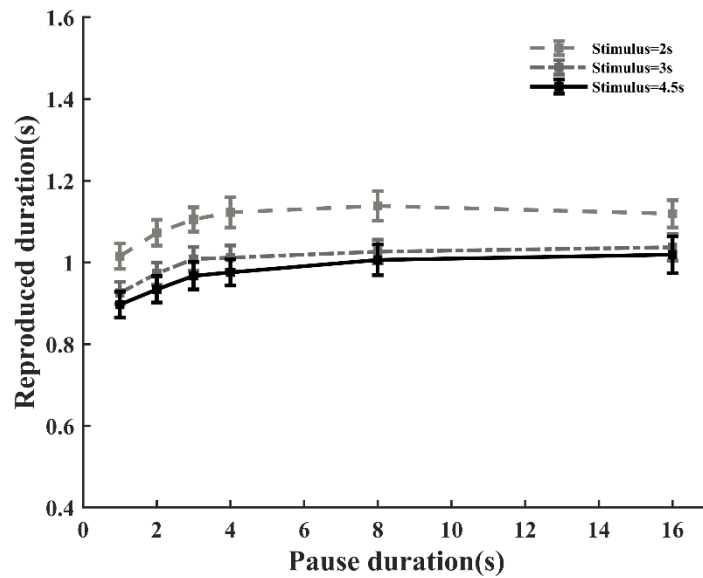Fig. 16 the ratio of reproductions against standard durations after various PDs with different auditory frequencies for standard stimulus and reproduced stimulus

The two-way ANOVA was used to calculate the RD/SD ratio. Both the SD ($p < 0.001$, $F(2,34) = 13.961$) and the RD ($p < 0.001$, $F(5,85) = 39.013$) showed a difference in the interaction between the SD and the PD, but was not significant. Therefore, we performed post-hoc analyses. The post-hoc analysis of the SD confirmed that the ratio of RD/SD = 2 was significantly larger than RD/SD = 3s and RD/SD = 4.5s. The post-hoc analysis of the PD confirmed than the ratio of RD/PD= 1 was significantly smaller than others. The ratio of RD/PD = 2 was significantly lower than that of RD/PD = 3, 4, 8, and 16. The ratio of RD/PD =3 was substantially lower than RD/PD = 8. The ratio of RD/PD =4, 8, and 16 showed no significant difference.

3.4.5   Discussion

Using different auditory frequencies for stimuli did not change the main conclusion: reproductions were regulated by various PDs for these three standard durations. The transition zone was clearly independent of the auditory features. I added PD = 3s to clarify the PD effect. Results showed that the reproductions of PD = 3s and PD = 4s had no difference under all standard durations, while a significant difference appeared below PD = 3s. This indicated that the PD effect was below 3s, which was consistent with the theory of the low-frequency time window. Moreover, when the RD/PD ratio = 3 was significantly shorter than RD/PD = 8, this indicated that different processing

36

mechanisms between short and long temporal windows can exist. When the standard and the reproduced stimuli were the same, subjects could refer to sensory information to make the correction. Therefore, experiment 2 did not have this difference in ratio.

Evidence of the relationship between the PD effect and the low- frequency time window had already been obtained in behavioral experiments. I intended to further explore this phenomenon or neural markers based on EEG technology.

There have been only few EEG studies employing the temporal-reproduction task and no reviews on the early components of the Event-Related Potential (ERP) and its parameters (latency, amplitude, etc.). The main reason may be that with this task, each trial lasts too long, and it is difficult to obtain enough trials for statistics. These studies usually employed ERP components that only contained phase-locked and time-locked information. There was no study focusing on non-phase-locked neural oscillations. Studies with the temporal estimation task found that the amplitude of alpha oscillations was regulated by the standard duration, which may relate to the representation of standard durations in working memory. Thus, an EEG study employing the temporal-reproduction task was performed to get additional information and neural markers. Only the 2s standard duration was used to obtain enough trials.

4. The EEG Study

4.1 Brain oscillations

Brain oscillations generally contain five components: delta (δ), theta (θ), alpha (α), beta (β) and gamma (γ) waves. Studies on these oscillations are based on the hypothesis that all different frequencies are correlated to specific perceptual processing.

The Delta wave (1-3 Hz) is a low-frequency wave with around 10-30uV and frequently occurs in the cerebral cortex during deep sleep (Iber et al., 2007), in babies and patients with severe organic encephalopathies, such as schizophrenia (Alfimova & Uvarova, 2007), and epilepsy (Walter, 1936).

The Theta wave (4-7 Hz) often occurs during meditation, hypnotic states, or sleep in adults (Aftanas & Golocheikine, 2001). As a behavior-specific wave, it is related to many cognitive functions, such as working memory (Jensen & Tesche, 2002), episodic memory (Nyhus & Curran, 2010), spatial coding (Welday et al., 2011), and emotions (Knyazev et al., 2009).

The Alpha wave (8-12Hz) is the relaxion state of our brain. It is most evident when eyes are closed and one is mentally relaxed. It is diminished or interrupted when attention is concentrated, especially during visual and mental tasks (Magosso et al., 2019). Alpha waves have a high preference for the right hemisphere (Moore Jr & Haynes, 1980) and are associated with many tasks, especially working memory (Jokisch & Jensen, 2007; Sauseng et al., 2005) and attention (Magosso et al., 2019). Changes in alpha waves are also related to age (Spector et al., 1971).

The Beta wave (15-30Hz) appears throughout the brain, but mainly around the frontal and temporal regions. Beta waves can be further divided into low beta (12-20Hz) and high beta (20-30Hz). Beta waves are associated with certain functions, such as motor anticipation (Joundi et al., 2012), inhibition of movement (Bartolo & Merchant, 2015), and preservation of the current status (Bartolo et al., 2014).

The Gamma wave (30-100Hz) is the highest oscillation observed in the human brain. Due to its synchronization across multiple brain regions, many studies on brain-network

activities focus on it (Buzsaki, 2006). It is also supposed to correlate with many mental diseases, like Alzheimer's disease (Van Deursen et al., 2008) and epilepsy (Hughes, 2008).

4.2   Time-frequency analysis

The EEG is the most commonly used technique to capture dynamic cognitive processes due to its high temporal resolution, as most cognitive processes occur in a tiny range of tens to hundreds of milliseconds. The event-related potential (ERP) is the fastest and easiest way to test a difference between two conditions. It depends on the lock relationship between evoked potentials and superposition. However, the EEG contains information from multidimensional space. If one only examines the ERP, which includes time and amplitude, one may miss some important information. The time-frequency analysis is one method that could provide information from time and frequency domains and is therefore increasingly being used to analyze EEG data.

4.2.1   Fourier transform

The Fourier transform was proposed by Jean Baptiste Joseph Fourier (1768-1830), who pointed out that an appropriate set of sinusoids can produce a continuous periodic signal. The continuous Fournier transform expresses the square-integrable function as an integral or series of complex exponentials. It is defined as:

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt$$

.

Here $f(t)$ is the original function, $F(w)$ is the image function of the Fourier transform, and $f(t)$ and $F(w)$ together are called a transform pair. However, a computer cannot process a continuous signal; only the discrete Fourier transform can be performed on a computer. We usually reduce continuous signals into discrete ones and treat finite-length data as infinite-length data (other data points are set as zero) and then apply the Discrete Fourier transform (DFT), which is a sequence of N complex numbers discrete in both time and frequency. The DFT domain can be described as follows:

$$x_n = \sum_{k=0}^{N-1} X_k e^{i\frac{2\pi}{N}kn} \qquad n = 0, \cdots, N-1$$

.

The Fourier transform provides an essential basis for the transformation between the time and the frequency domains. However, if given a time duration, this method can only extract the frequency information, but not how the frequency information is distributed within the time domain. The Fourier transform has a pronounced effect on stationary signals, but it is not accurate for non-stationary signals. For example, in a piece of music, the Fourier transform can tell us which frequencies are included in this music, but it cannot tell us at what time this frequency is present. Most signals in nature are non-stationary, so it is not sufficient to obtain available information only with the Fourier transform. To solve this problem, we apply the short-time Fourier transform. Signals are divided into as many sections as the signals in each section are approximately stable, and then the Fourier transform is performed. In this way, localized time and frequency information can be obtained relatively precisely.

The short-time Fourier transform increases the accuracy of time and frequency information acquisition. However, this kind of processing is also flawed since the time window in this method is fixed. The resolution of time and frequency restrict each other; high temporal resolution reduces frequency resolution, and high frequency resolution restricts temporal resolution. If one chooses a narrow time window, it produces high temporal resolution and low frequency resolution and vice versa. If it is possible to employ a relatively wide time window for low-frequency information and a relatively narrow time window for high frequency information, such an adaptive window can provide complete information for non-stationary signals. This is how Wavelet analysis is designed.

4.2.2 Wavelet analysis

To achieve self-adaptation in both the frequency and time domains, wavelet analysis replaces the infinite trigonometric basis used in the Fourier transform with the decaying orthogonal wavelet basis of finite length, thus making time positioning possible.

Wavelet analysis is defined as follows:

$$WT(a, \tau) = \frac{1}{\sqrt{a}} \int\limits_{-\infty}^{\infty} f(t) * \psi\left(\frac{t-\tau}{a}\right) dt$$

The mother wave (wavelet basis) *a* is the scale variable, and *τ* is the shift variable. The scale variable is used to control the mother wave's amplitude, and the shift parameter can control the movement of the mother wave. Due to multiple mother waves, the types of wavelet are diverse, such as continuous wavelet, discrete wavelet, and wavelet packet. Since there are these heterogeneous mother waves and when different mother waves are used, one can get different results. Therefore, it is crucial to choose an appropriate mother wave. The selection of a mother wave now poses a practical problem, and in the process of actual data analysis, the selection is made according to the characteristics, symmetry, and regularity of goal signals. Researchers always choose the most familiar mother wave to obtain a more accurate result when dealing with EEG signals, as practiced in previous studies. The complex Morlet, which is created by windowing a sine wave by a Gaussian, is a frequently used mother wave in EEG data processing. It is well suited to locate frequency information in the time domain (Cohen, 2014).

4.3   Methods

4.3.1   Participants

Eighteen healthy university students (18~25 years old, eight males) with no history of mental disease participated in this experiment.

4.3.2   Design

Six different pause durations were used: 1s, 2s, 3s, 4s, 8s, and 16s. Each pause duration appeared 40 times to obtain enough EEG signals. A total of 240 trials were divided into 10 sessions in the final experiment. There was a no feedback practice before the experiment, which included 18 trials.

4.3.3   Procedure

The experimental procedure was the same as in Experiment 1.

4.3.4 EEG acquisition and pre-analysis

The EEG signal was recorded using the extended international 10-20 system, and 64 scalp-channels (see Fig.17) were used (Brain Products GmbH, Herrsching, Germany). The electrode of FCZ was used as a reference. Horizontal electro-oculogram(HEOG) was recorded by an electrode placed beside the left eye, while the electrode under the right eye was for Vertical electro-oculogram (VEOG). The resistance of all channels was under 5 kΩ. The online filter was 0.01-100 HZ, the sample rate was 1000Hz, and the 50Hz notch filter was applied.

Data pre-analyzed was performed in Matlab with EEGLAB (MathWorks, Natick, MA, USA). Data was first re-referenced by bilateral mastoid and then filtered with a 0.05-100Hz band-pass filter. Electro-Oculogram (EOG), Electromyography (EMG) and other noise signals were excluded with independent component analysis (ICA) based on EEGLAB. Continuous EEG was afterwards segmented into intervals containing 1s before standard-stimulus onset and 4s after reproduction-stimulus onset.
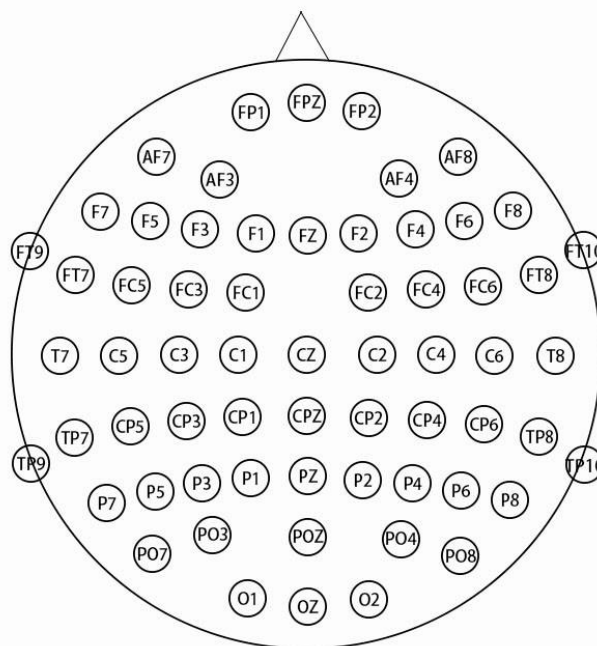

Fig. 17 the distribution of 61channels

4.3.5 Data analysis

The event-related potential (ERP), also known as the endogenous evoked potential, is commonly applied in EEG studies because it indicates the fixed time signals resulting

from intrinsic or extrinsic events. Although these forms of brain waves are relatively weak, generally 0.1-20μV, which may be buried in the spontaneous brain potential, they can be extracted by multi-trial superposition. The ERP has high temporal resolution and could reflect human physical and mental brain activity. Therefore, it is commonly used in studies targeting brain processes lasting from stimulus onset to response.

Since most ERP components appear at hundreds of milliseconds, I focused on the durations within 500ms after the reproduction stimulus onset for each pause-duration condition, and 200ms before the standard stimulus onset served as baseline. ERPs of reproduced stimuli were obtained from superpositions over trials for each pause-duration condition. The amplitude and latency of the N1 component was measured during 80ms-160ms after the reproduced-stimulus onset, and P2 was measured during 150-250ms. Channels in the central region were the most interesting in both N1 and P2 components, so I chose three areas for statistical analysis: the central area (C1/2, FC1/2, CP1/2, CPz and Cz), the central left area (C3/5, FC3/5, CP3/5), and the central right area (C4/6, FC4/6, CP4/6). Data from each area were averaged among channels. Amplitudes and latencies were analyzed with 6 (PDs) $\times 3$ (areas) repeated analysis of variance (ANOVA) based on IBM SPSS 24.0.

Complex Morlet wavelets ranging in frequency from 2 Hz to 60 Hz in 10 steps were employed to get time-frequency information for each pause duration. Each trial consisted of 1s before the standard stimulus until 3s after the reproduction onset. 500 ~200 ms before standard stimulus onset was used as the baseline. Frequencies of theta waves (4-7Hz), low alpha waves (8-10Hz), high alpha waves (11-13Hz), low beta waves (14-20Hz), high beta waves (20-30Hz), and gamma waves (30-50Hz) were studied for reproduction durations.

4.4   Results

4.4.1   Behavioral results

 The data beyond ±2SD were first excluded from the database for each subject, and repeated ANOVA was then applied to the reproduction duration after various pause durations. The analysis was performed with SPSS 22.0, the Greenhouse Geisser method was used for correction of variables that did not meet the spherical test, and posthoc

comparisons were based on the Least Significance Difference (LSD) method. Averaged reproduction durations are shown in Fig. 18.

Results showed that the main effect of PD was significant ($p < 0.001$, $F(5,85) = 26.241$), and the pairwise comparisons showed that the reproduced duration of PD = 1 was significantly shorter than that of others ($p < 0.01$) . Reproduction of PD = 2 was significantly shorter than that of PD = 3 and PD = 4 ($p < 0.05$) and marginally shorter than PD = 8 (($p = 0.056$). There was no difference among PD = 3, PD = 4, PD = 8, and PD = 16. The mean reproduced durations after different pause durations are displayed on the graph below (Fig. 19).
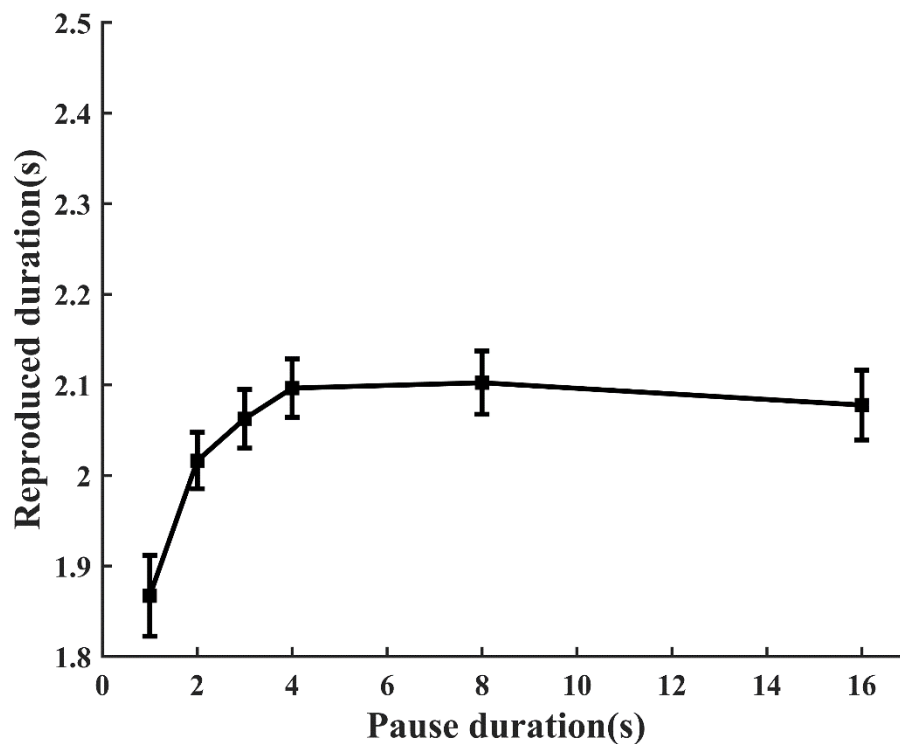

Fig.18 Averaged reproductions of a 2s standard stimulus after various pause durations
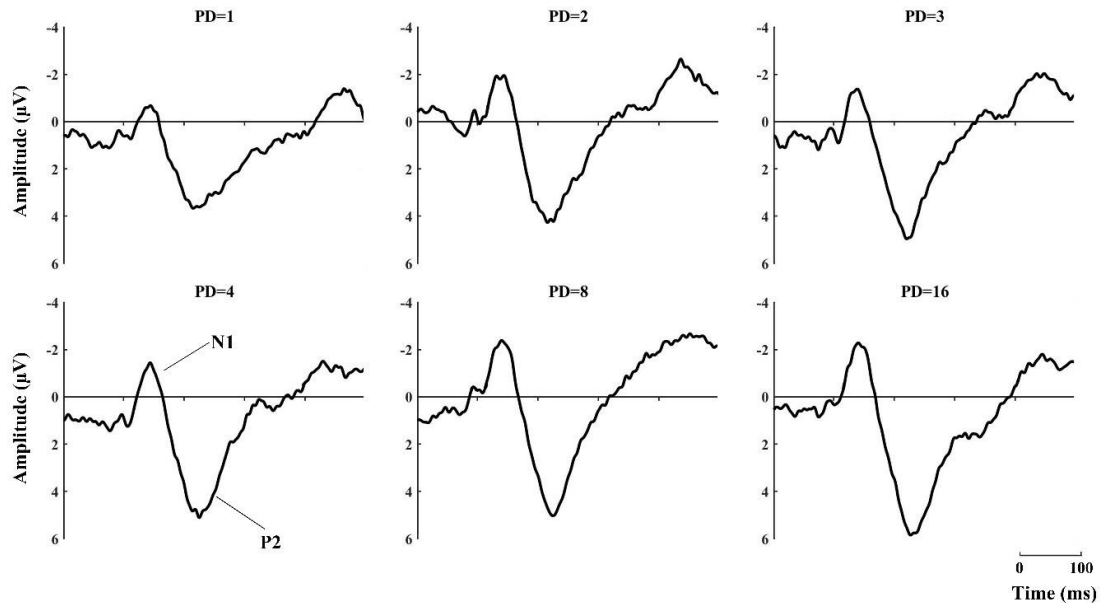
Fig.19 The ERP components during reproduction durations in the central area

N1 component

The amplitude of the N1 component after different PD conditions showed a significant difference ($p < 0.01$, $F(5,85) = 4.861$), while the area and interaction between pause duration and area did not differ. Further analysis indicated that the reproduced interval of PD = 1 was shorter than that of PD = 2, PD = 8, and PD = 16; the reproduction of PD = 2 was longer than that of PD = 3, the reproductions of PD = 3 and PD = 4 were shorter than those of PD = 8 and PD = 16, while those of PD = 8 and PD = 16 did not differ.

PD ($p < 0.01$, $F(5,85) = 5.212$) and area ($p < 0.01$, F $F(2,34) = 4.661$) were both significantly different for N1 latency, and the interaction was also significant ($p < 0.05$, $F(10,170) = 2.764$). A post-hoc analysis showed that when PD = 1, the N1 latency of the central area was significantly shorter than that of the central right ($p < 0.05$) and the central left ($p = 0.003$) areas, and when PD = 3, the N1 latency of the central area was significantly shorter than that of the central left area ($p < 0.01$).
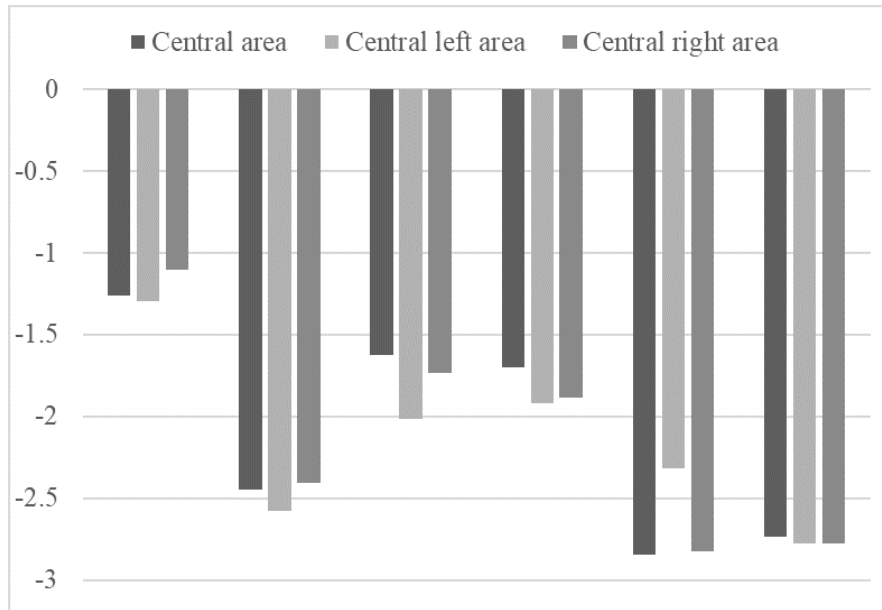
Fig. 20 N1 amplitudes after different PDs at three areas (central area, central left area, and central right area)

For the central area, the N1 latency of PD = 1 was significantly shorter than that of PD = 4, 8, and 16; the latency of PD = 2 was significantly shorter than PD = 16; the latency of PD = 3 was significantly shorter than that of PD = 2, 4, 8, and 16, while no differences among PD = 4, PD = 8, and PD = 16 were noted.
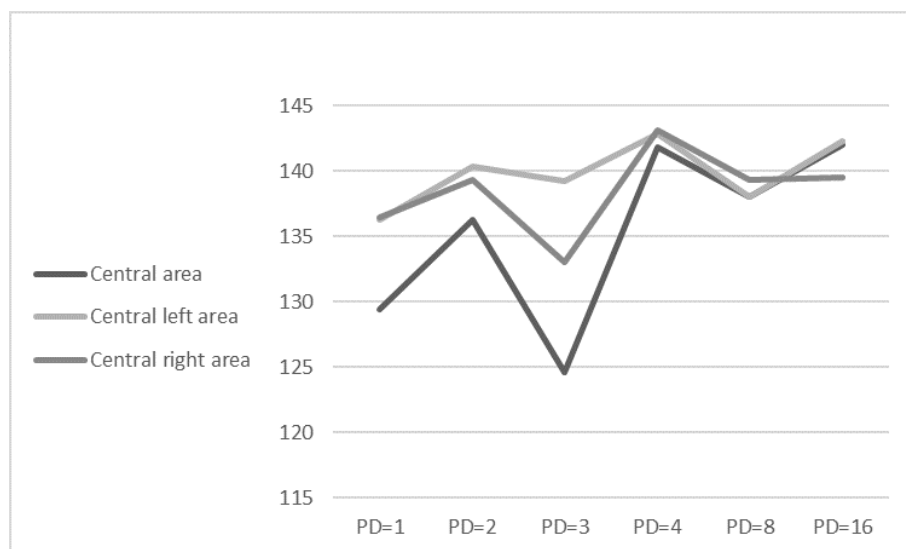
Fig. 21 N1 latencies after different PDs at three areas (central area, central left area, and central right area)

P2 Component

The main effect of area and the interaction between PD and area were shown on both P2 amplitudes, while PD alone showed no main effect. Further analysis showed that for all pause durations, the central area had higher P2 amplitudes than the central left and the central right areas ($p < 0.01$), while no difference in the PDs between the central left and central right areas was noted.
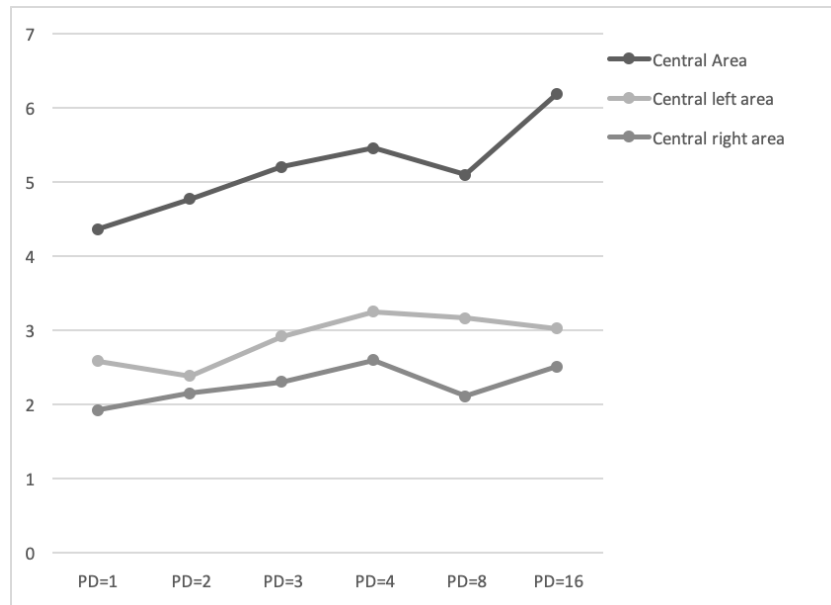
Fig. 22 P2 amplitudes during reproductions after various PDs in three areas (central, central left, and central right areas)

As for the central area, the P2 amplitude of PD = 1 was significantly lower than PD = 3 ($p < 0.05$), and PD = 16 was significantly higher than PD = 1 ($p < 0.05$), PD = 2 ($p < 0.05$) and PD = 8 ($p < 0.05$). For the central left area, PD = 4 had a higher P2 amplitude than PD = 1 ($p < 0.05$) and PD = 2 ($p < 0.05$). There was no significant difference among PDs in the central right area.

The main effect of the PD showed significant differences in latency. While no other differences. The P2 latency of PD = 1 was significantly earlier than PD = 8 ($p < 0.05$) and PD = 16 ($p < 0.01$).

4.4.3 Time-frequency analysis results

The oscillation distribution during both pause durations and reproduced durations were of particular interest.

Pause duration
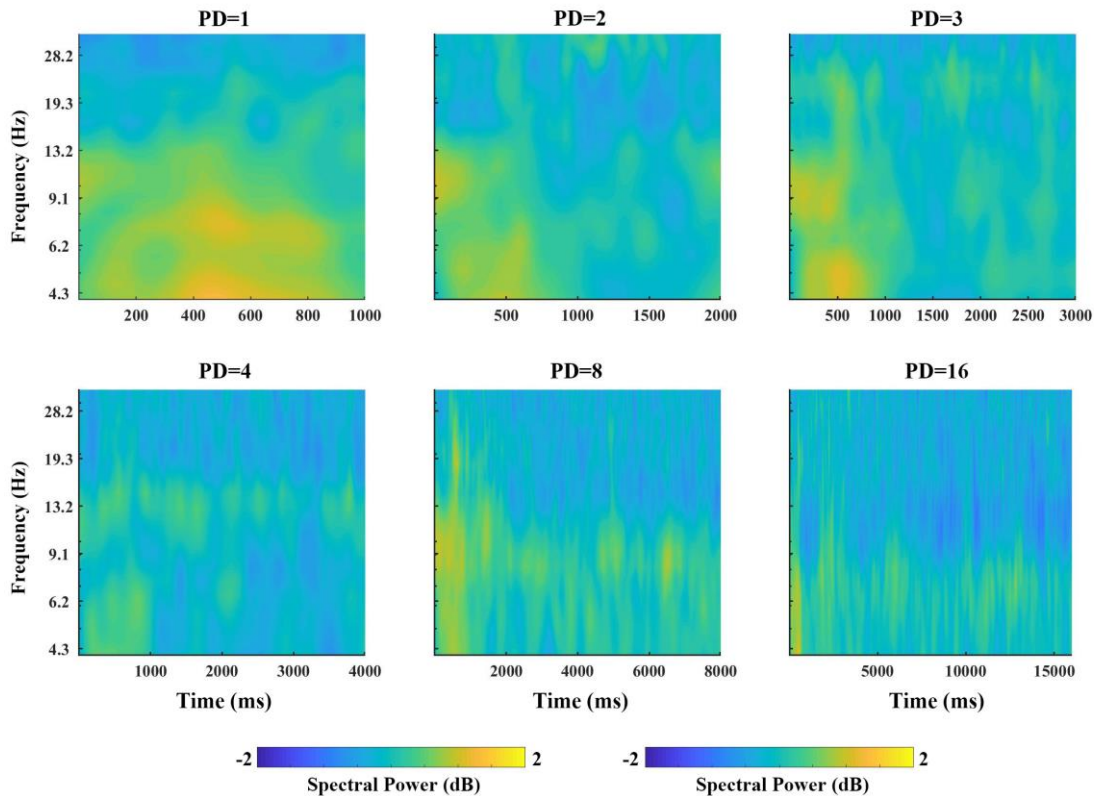
Fig.23 Spectral power of pause durations in the posterior central area

Since the time windows of different conditions differed, it was difficult to do the statistical analysis for pause durations. Therefore, I performed an exploratory statistical test. I chose the alpha and low beta oscillations as our target frequencies and 3 areas (the frontal central area, the central area, and the posterior central area) as our target regions. Since pause-duration conditions have different time lengths, I averaged the power of the alpha and low-beta oscillation for each second independently, and repeated ANOVA was performed on each second in a degressing way, which means for the first- second comparison, I employed 3 (areas) $\times 6$ (PDs) while for the second comparison I employed 3 (areas) $\times 5$ (PDs), and so on.

Statistical analysis showed that there were no significant difference among all conditions for the power of alpha oscillation for each interval of one second. However, the low beta oscillation displayed a different phenomenon.

In the first second, the main effect of the area was significant for low beta power ($p < 0.05$, $F(2,34) = 4.735$). Further analysis was employed, but I could not find any difference with the Bonferroni method. Therefore, I chose the more sensitive LSD method. Further analysis found the low beta power in the fontal central area (0.376 dB) was larger than that in the central area (0.129 dB) and posterior central area (0.112 dB), while there was no difference between the latter two areas.

For the second interval of one second, the main effect of area was also significant ($p < 0.05$, $F (2, 34) = 3.756$). The sample analysis with the LSD method showed the same pattern as that in the first second. The low beta power in the central area (-0.044 dB) and posterior central area(-0.072 dB) was lower than that in the frontal central area(-0.11 dB), and no difference between the former two areas.

Reproduction

The spectral power map of reproduction at POz is shown as an example in Figure 24. In the reproduction period, we focused on the low beta wave. We chose three areas (posterior left area, posterior central area, and posterior right area) as our regions of interest (ROIs) (Fig.25), and our interested time duration was between 900ms and 1100ms in reproduction duration. All of these choices were based on the data.
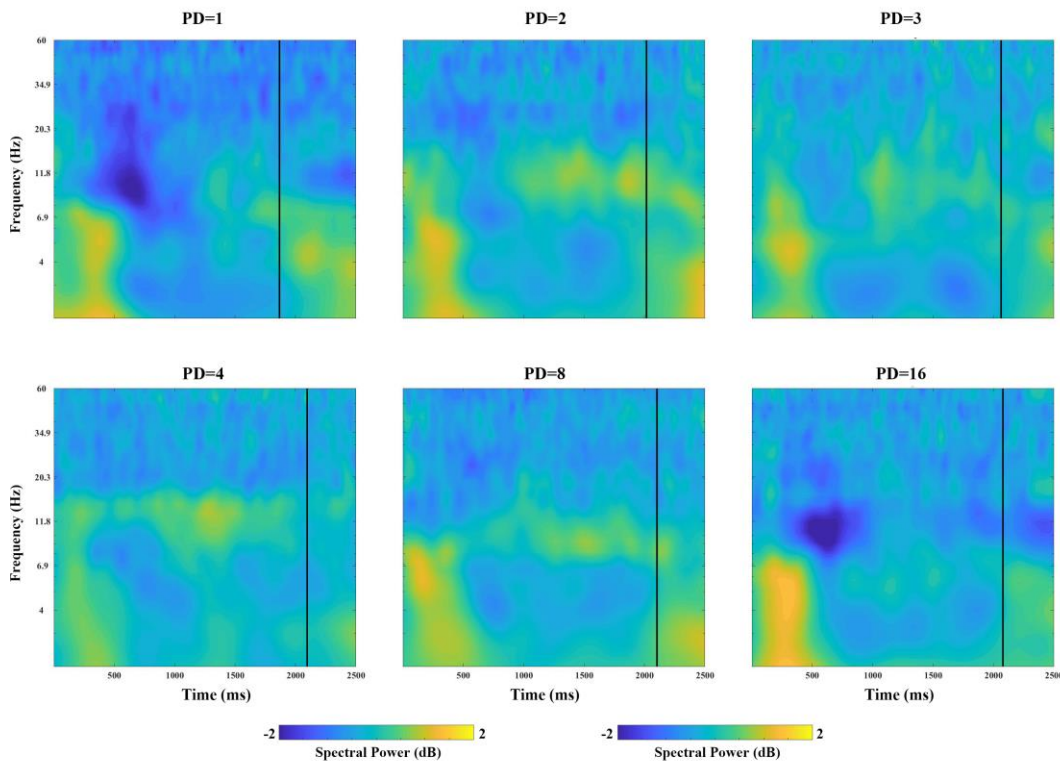
Fig. 24 Spectral power of reproduced durations after various PDs at the POZ channel

We averaged the low beta (13-20Hz) power in each area and searched the highest value during 900-1100ms in the reproduced period (Fig.26). Repeated ANOVA was done with 3 (area) ×6 (PD). It showed that the main effect of area ($p < 0.05$, F $(2,34) = 5.153$) and PD ($p < 0.01$, F$(5,85) = 4.328$) were both significant, but no interaction was observed between them. Sample analysis with the LSD method disclosed that the peak low beta power in the posterior right area was larger than that in the posterior left area and posterior central area. Furthermore, the peak value of PD=1 and PD=16 was lower than for the other PDs.
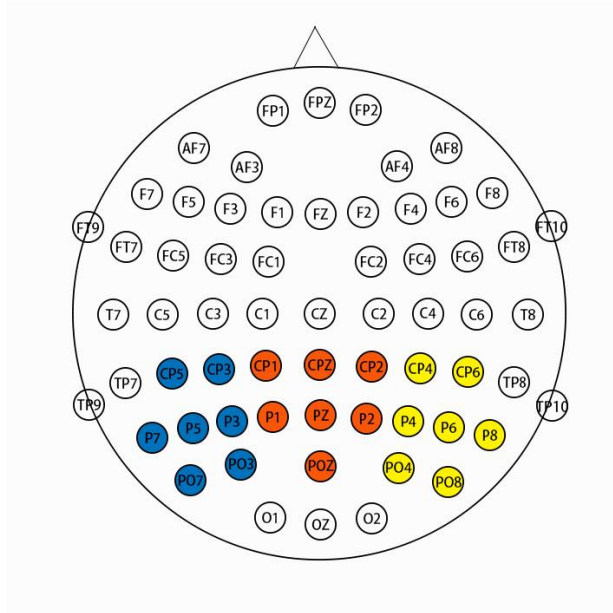
Fig. 25 The channels in ROI regions. The posterior left area contained CP3/5, P3/5/7 and PO3/5 (the blue channels), the posterior central area included CP1/2,CPz, P1/2, Pz and POz (the red channels), and posterior right area had CP4/6, P4/6/8, and PO4/6 (the yellow channels)
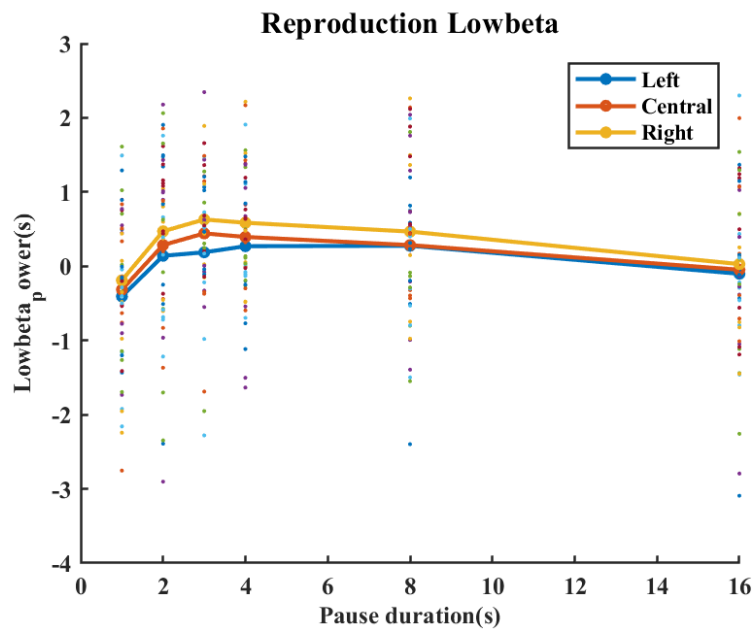
Fig. 26 The peak value of low beta power during 900-1100ms in ROIs

We also did a Person correlation between the peak low beta value in each area with the reproduction durations. It showed a positive correlation ($p < 0.05$, R = 0.232) between

peak low beta power and posterior central area (Fig.27a), and also a positive correlation ($p < 0.01$, R = 0.327) between the highest low beta power and posterior right area (Fig.27b).
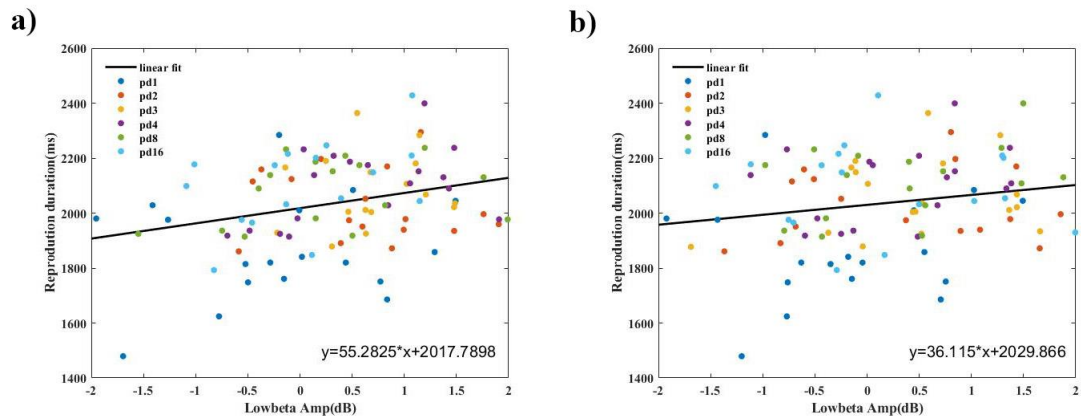
Fig.27 Correlation between the low beta peak power and reproduction durations.

a) the correlation between low beta power at posterior right area with reproduction for all PDs.

b) the correlation between low beta power at posterior central area with reproduced intervals for all PDs.

4.5   Discussion

In the EEG experiment, I used 1s, 2s, 3s, 4s, 8s, and 16s as pause durations to further investigate the relationship between the pause-duration effect and the low-frequency time window. The 32s PD was not included here because it would have taken too long. Subjects needed to perform the experiments with the leads on their scalps for the whole time, and if the experiment had taken too long, it would have been difficult for participants to pay enough attention to the task.

I first analyzed the behavioral data, whose results were similar to previous ones. As expected, the reproduced durations increased when pause durations were shorter than 3s, and then levelled off. This confirmed the results of the previous behavioral studies.

I then checked the ERP components during the first 500ms of the reproduced durations because most ERP components were within these durations. CNV components were not included later in the analysis since previous studies had found that the CNV amplitude changed only when the standard stimuli differed (Elbert et al., 1991). I only employed one standard interval in this EEG study, so it was not relevant to analyze the CNV component. Not many researchers talked about the early components during the reproduction period. One study employing a temporal-reproduction task explored the difference between children with attentional deficit hyperactivity disorder (ADHD) and the control group in early ERP components (González-Garrido et al., 2008), and results showed the ADHD group had a larger P2 amplitude than the control group. Another study in which subjects were asked to distribute attention to either temporal information or tone (Chen et al., 2007) found that the N1 component did not differ among the different conditions. At the same time, the P2 amplitude was lower when participants only paid attention to the temporal information.

Since I explored how pause durations affect the reproduction phase, I focused on the very early N1 and P2 components. For the N1 component, I found that the N1 amplitude of PD = 8 and PD = 16 was significantly greater than that of PD = 1 and PD = 3, perhaps because N1 was enhanced when more attention was being paid. Longer durations always need more memory and attention processing, while shorter durations can be mentally united. The finding that the N1 amplitude of PD = 2 was significantly greater than that of PD = 1 and PD = 3 was an interesting exception. I predicted that the EEG response to shorter durations could be correlated with the behavioral responses, but this turned out to be wrong. This could have resulted from the same length of the standard stimulus and pause duration, and repeated durations may enhance the results. Previous studies showed that the amplitude of N1 was refractory with repeated stimuli (Hsu et al., 2016), but this effect faded away when stimulus-onset asynchronies (SOA) increased. Moreover, in those studies, this effect appeared with the two consecutive stimuli, while I compared the N1 amplitudes of the second stimuli in different conditions. This may explain why I obtained enhanced N1 amplitudes on repeated durations. I found that N1 had the shortest latency when PD = 3, while for longer durations, like PD = 8 and PD = 16, N1 latencies were much longer than shorter durations of PD = 1 and PD = 3. The exceptional PD = 2 was also evident. The decrease

in the N1 latency with PD = 1 and PD = 3 may relate to a more complete integration mechanism since the low-frequency, integrated temporal window was around 3s.

P2 component amplitudes in the central area tended to increase with pause durations, but not significantly. This result coincided with previous studies. Gibbons and colleagues (Gibbons et al., 2003) asked subjects to discriminate the temporal duration or tone for the same auditory stimuli, and results found that the P2 amplitude of these two tasks differed significantly. Chen and colleagues (Chen et al., 2007) conducted a study in which subjects were requested to pay attention to either temporal duration or tone, and they found that the P2 amplitudes were significantly different when subjects concentrated only on time or only on the tone. These studies indicated that the P2 phase might be an integral part of temporal information processing. MMN evoked by duration differences can also constitute corroborative evidence. Kujala and colleagues (2007) used 120ms as a standard stimulus and 20ms as an oddball stimulus and found that the evoked MMN appeared right around 190 ms, which corresponded to the P2 component. I also found that the P2 amplitude of PD = 8 was an exception. The previous behavioral studies also found that the reproduced durations of PD = 8 can sometimes be an exception, which suggested that there can be more involvement of attention and memory processes during this long pause duration. To sum up, whether this P2 component is a neural indicator of the low-frequency time window requires further research.

Compared with EEG signals in the time domain, which indirectly reflected the pause-duration effect, time-frequency analysis results can directly examine changes in brain activity during the pause-duration and reproduction phase. I observed the changes by applying continuous wavelet analyses. I compared them second by second for pause durations, especially for the shorter durations, and statistics showed that the only low beta frequency showed a difference between the areas. However, with this kind of comparison, it was hard to tell whether the low beta oscillation played a role or not.

About the reproduced durations, I observed statistical difference of low beta power only during 900-1100ms in reproduction. Although the statistical significance was only for PD=1 and PD=16, if one looked at the change pattern, it is obvious that there were an increase of low beta power when pause durations were shorter than 3s,

which showed that low beta oscillation may play an essential role in the temporal-integration mechanism of the low-frequency time window. If beta oscillation would not be related to the temporal integration mechanism, then there would not be a correlation between low beta power and reproduced durations.

In the low-frequency time-window theory, the time-window mechanism is assumed to work in the form of oscillations, and the oscillation form of the EEG signal meets that criterion. The concept that the brain constructs time perception in the form of oscillations gradually has become mainstream. In this experiment, the low beta oscillation only showed for short durations, and this characteristic feature seems to be in the range of the low-frequency tine window. The question arises whether the beta oscillation can be used as a neural indicator for the low-frequency time window. Here I would like to cite related studies on beta oscillation for further discussion.

Previous studies have pointed out that beta oscillation (13-30Hz) is related to maintaining the current state and expectation of incoming activities. Baumgarten and colleagues (2015) explored whether human sensory perception is continuous or discrete. They performed a tactile study with MEG and asked subjects to report whether they felt one or two electrical pulses. The results showed that the alpha and low beta bands (8-20Hz) can represent the discrete perceptual model in the somatosensory domain. This study suggested that beta oscillation is strongly linked to the discrete perception theory. Ghaderi and his colleagues (2018) conducted 15-minute studies which contained one exploratory experiment and one confirmatory experiment. Their results showed that the subjects who overestimated duration evoked low beta power, and the results of graph theoretical analysis showed beta activity among subjects who over- or under estimated time were significantly different.

Studies have also proved that beta oscillation in the basal ganglia is associated with Monkeys' internal timing (Bartolo et al., 2014). Bartolo taught monkeys to do a synchronization-continuation task (SCT) and a serial reaction–time task (RTT) and found that beta power was greater for longer durations, suggesting that beta oscillation is linked to subjective time perception (Bartolo & Merchant, 2015). If beta oscillations are only linked to motor behavior, there should not be any relationship between beta power and behavioral action. Kononowicz and van Rijn (2015) conducted a time-

production task and requested participants to produce an interval of 2.5s with feedback which was either too long or too short. They found that trial-to-trial beta power positively correlated with the length of time production, and beta power at the onset of temporal production can be used to estimate the length of this produced window. The most significant difference among short, correct, and long production durations was around 0.9-1.1s, which closely resembled my results for PD = 1 and PD = 3. As for PD = 2, intense beta activity was observed 500ms earlier (0.4~0.6s after reproduction onset). This phenomenon can result from the same length of the standard stimulus and pause duration.

Combining the results of our experiment with previous studies, one can state that low beta oscillation is linked with the internal time estimation of standard intervals, and it also reflects the regulation of the low-frequency time window.

To further interpret these results in connection with the low-frequency time-window, it is necessary to consider the stability and assessability of the previous stimulus for a certain period and to ensure its assessability of the new stimulus after a certain period and the form of new mental representation. I found that an increase in the pause duration leads to a gradual decrease in possible assessability of the standard stimulus. This results in a variation of assessability of the reproduction duration, and apparently beta oscillations are evoked. When the pause duration exceeds a certain range, the earlier representation of a previous stimulus changes from 'now' to 'past', the perception of the standard stimulus fades away, and a new perceptual cycle emerges. Subjects then rely mainly on the second representation, which is in storage (a cycle). The pause-duration effect does not make a difference anymore and does not induce beta oscillation.

To explain the increase of low beta activity only within the 3s pause duration, I suspect that when pause durations are longer, the beta-rebound effect is fading away. One study (Fujioka et al., 2012) used regular intervals (390, 585, and 780ms) and random intervals (varying from 390ms to 780ms) for auditory stimuli. Results showed that the decreases in beta oscillations after stimulus onset were the same for all conditions, while the increase in beta activity remained the same in stable conditions. Fujioka and colleagues suggested the changes in beta oscillations represent the internalization of predictable intervals. They used only short intervals, while our stimulus and pause durations were

much longer. I speculate that in our experiment, the initiation of the reproduction stimulus first suppresses the beta activity, this suppression fades away, and then beta activity rebounds. When the pause duration are longer than 3s, which cannot be explained by the low frequency time integration mechanism, the rebound of beta activity disappears.

Since this experiment only used one standard stimulus, whether the above results and interpretations can be extended to other intervals needs to be further tested. This beta-rebound effect would have to be confirmed with more different standard durations. Aside from the ERP and oscillation that I chose, future studies should employ more techniques, like MEG, to explore the functional brain network for different pause durations.

5. General Discussion

Studies with various paradigms and different domains have indicated a low-frequency time window of around 2~3s, indicating its importance in cognitive processing (Pöppel, 1997). The temporal-reproduction task provided experimental evidence for the low-frequency time window. Based on Weber's law, Pöppel (1972) employed the temporal-reproduction task and found that the subjects underestimated long intervals and correctly reproduced or overestimated short intervals. The demarcation point was around 3s. Many investigations subsequently confirmed this classical behavioral study. Additional evidence resulted from following studies in fields such as EEG, cognitive development, working memory, and pharmacology (Elbert et al., 1991; Szelag et al., 2004; Ulbrich et al., 2007; Wittmann et al., 2007).

However, some questions have no specific explanation; for instance, most temporal-reproduction studies concentrated on standard durations and overlooked the waiting period. Considering other paradigms, such as sensorimotor synchronization, mismatch negativity, and fore-period, which focused on the inter-stimulus interval, it is essential to investigate whether the pause duration influences the temporal-reproduction task. I can then better understand a detailed cognitive mechanism under the temporal-reproduction task, which provides a new perspective on the low-frequency time window.

5.1   The influence of pause duration on reproduction

Few studies have been conducted on the effect of pause durations on temporal reproduction, and existing studies have reached no clear conclusions. Vierordt (1868) used himself as a subject and found that reproduced durations after a waiting period were longer than immediately reproduced durations. Some studies compared the temporal-reproduction results with different pause durations (Guay, 1982a, 1982b), but they were not identical. It may be the result of inappropriate pause lengths, since the influence of pause durations may only appear within a small range. This explanation was supported by a single-case study by Pöppel (1973), in which 2s was used as a standard stimulus and resulted in the increase in temporal reproduction with pause durations within 2s and then came to a plateau.

Since our experimental design and method were not rigorous enough, I first completed another experiment to confirm the results of experiment 1. This experiment still employed the temporal-reproduction task and used 2s as a standard stimulus. To control the experimental length and ensure that enough trials would be conducted, I chose 1s, 2s, 4s, 8s, and 16s as pause durations. The results showed that pause durations do influence the subject's reproduction of standard durations, but only within a certain range. This confirmed Pöppel's (1973) conclusion and coincided with the previous study.

Pöppel (1973) stated that the effect of pause durations was within around 2s, and our results verified this. However, in experiment 2, all three standard durations (2s, 3s, and 4.5s) showed that the reproductions of PD = 2 and PD = 4 differed significantly, which indicates that the effect of pause durations might be longer than 2s. The question remained whether this pause-duration effect appears with shorter waiting durations or only within a few seconds. Experiment 3 was performed to confirm this effect's range, and I used 5s, 6s, 8s, 12s, 20s, and 36s as pause durations. The reproductions of PD = 5 were slightly different from others, but no more, which indicated that the mechanism of the pause-duration effect was not based on shorter durations in the experiments, but was within a range of a few seconds. To further specify this effect, I added 4s as a pause duration in experiment 4 and found that the reproduced duration of PD = 2 was different from that of PD = 3, while no difference was found between that of PD = 3 and PD = 4. I therefore conclude that the effect is around 2-3s, while there remain individual differences and inconsistencies among trials.

5.2 The mechanism of the PD effect and low-frequency time window

The range of the pause-duration effect was around 2-4s. This, however, was not sufficient to prove that this effect represented the low-frequency time window, especially when various standard durations were used. To further indicate that this effect was not peculiar to a standard duration of a 2s, I employed 2s, 3s, and 4.5s as standard durations and obtained the same result. The pause-duration effect was within 4s for these different intervals. A further experiment was performed to confirm that this effect was based on the 4s window, but not shorter on durations in the task. 4s plus the conditions applied in experiment 2 were used in experiment 3. The reproduced durations of other pause durations showed no differences except for PD = 5, proving that the pause-duration effect lay within 4s. The difference of PD = 5 can be explained

that the sudden appearance of a long waiting period triggered attention. I also computed the ratio of reproduction duration to standard duration to measure the indicator of reproduction. Results revealed that the main effect of pause duration was significant, while there was no interaction effect. This suggested that the pattern of reproduction-duration changes under various standard intervals shared the same paradigm.

The auditory stimuli of the standard stimulus and the reproduced stimulus were the same in experiments 1 and 2. Although this is common in temporal-reproduction experiments (Szelag et al., 2002), researchers have employed different tones as the standard stimulus and the reproduced stimulus in recent studies (Wittmann et al., 2010; Yin et al., 2016). Two factors could influence the reproduction results (Matthews, 2011). One is that subjects may complete the experiment utilizing a consistent feeling of two stimuli; the other is non-temporal information, such as the sensory and perceptual properties of the stimuli, which may affect the subject's perception. Since it is possible that the subject's strategy or neural activities at the sensory level might have been affected when the same stimuli were used for both the standard and the reproduction durations in experiments 1 and 2, I performed experiment 4.

In experiment 4, I employed different frequencies of auditory stimuli for the standard and the reproduced intervals, and the longer PD = 32s was changed to PD = 3s to expand the effect range of pause durations. Results indicated that the reproduction durations increased with the pause duration, whose effect range was around 3s. Although frequency is only one of the auditory properties, experiment 3 indicated that this phenomenon was not only based on the same perceptual and sensory properties for standard and reproduced stimuli. I found that the reproduction durations for PD = 3 and PD = 8 for standard duration 4.5s differed, which contrasted with the previous study. This difference may derive from higher cognitive processing, such as attention. When the waiting time was too long, the subject's attention was lower, resulting in a slower response or a slower internal clock. When the reproduction stimulus differs from the standard stimulus, it is hard for a subject to correct this temporal impression through sensory information, resulting in an increase in the reproduced interval.

After completing all four experiments, I concluded that the PD effect was based on one processing window regardless of the length of the standard duration and auditory

frequency. In combination with sensorimotor synchronization, fore-period, MMN, etc. , I believe this effect can be explained by a low-frequency time window. As a pre-semantic, automatic temporal- integration mechanism, it provides a logistic platform, which can both maintain the identity of mental representation and accept a new psychologic representation (Pöppel & Bao, 2014). When the standard stimulus and reproduction stimulus were very similar, the mental representation of the first stimulus was still integrated and active. With an increase in the pause duration, the mental representation of the first stimulus gradually transforms from working memory into a new format (some kind of reference memory) separate from the second stimulus. Therefore, the subject's response schema converts from the automatic and united matching strategy to re-extract the first stimulus representation, and it becomes two independent processes. It requires more time to complete the process of extracting the memory from the reference system, which can explain why the increment of the reproduction duration was proportional to the standard intervals.

With the increase in the pause duration, the reproduced duration increased and was proportional to the standard stimulus. The subjective point itself (Pöppel, 1973) may have had no quantitative correlation with the low-frequency time window (Szelag et al., 2002), and it represented a certain stable storage in working memory, while the low-frequency time window was mainly reflected in the range of the pause-duration effect.

5.3   The comparison of my study with the conventional pause-duration task

To avoid the subject's intentional repetition, I randomized the pause-duration conditions within each standard duration, and the results were consistent with previous studies using similar paradigms (Vierordt, 1868). Considering that the previous behavioral studies employed only pause durations below 2-3 seconds, it was hardly possible for the subject to use the repetition method.

The exploration and definition of the low-frequency time window with the temporal-reproduction task were mainly based on Vierordt's law and Pöppel's study. They stated that the standard durations that could be precisely reproduced or slightly overestimated were the 'short time duration' in the low-frequency time window, and the uncertain description could possibly be explained by individual differences or, by the pause-duration effect (Vierordt, 1868). In studies with pause durations longer than 1s, subjects

frequently overestimated or tended to overestimate the short intervals (Elbert et al., 1991; Wittmann et al., 2007; Yin et al., 2016), while in studies with pause durations of 1s, subjects tended to reproduce the short intervals more accurately (Ulbrich et al., 2007; Wittmann et al., 2007). My results may also apply to the interpretation of fixed-pause-duration studies. Future studies could also consider controlling the pause duration within groups and comparing the pause-duration effects on the reproduced intervals.

Based on the previous discussion, one can compare the ratio of standard duration and reproduction to define the length of the low-frequency time window. Although this phenomenon is closely related to the low-frequency time window, the modality, pause duration, and age (Szelag et al., 2002; Vierordt, 1868) will influence the length of the reproduced interval. This indifference point with this method is appropriate for the standard of the 3s time-window.

5.4 The neural mechanism of the low-frequency time window

Many studies employed different paradigms to explore the processing window in the temporal-integration mechanism. However, except for studies related to MMN (Wang et al., 2015), which is a commonly used ERP component, most researchers focused on the behavioral indicator. There are not many studies on the neural mechanism of the temporal-reproduction task. Only Elbert revealed the continuous negative component (CNV) in the encoding and reproduction phases and found that the CNV in the temporal-reproduction phase was regulated by the standard duration (Elbert et al., 1991).

I chose 2s as a standard duration in experiment 5 to further clarify the pause-duration effect and look for the neural indicator corresponding to the low-frequency time window. I also checked the early ERP components and the low beta activity during the reproduction duration. The CNV component was not included in this analysis because the previous study had demonstrated that the CNV difference mostly results from different standard stimuli, while I only applied one standard stimulus.

N1 is a very early component after the onset of auditory stimuli, and results showed that N1 amplitudes were higher after longer pause durations and that the N1 latency was shortest after PD = 3. Since previous studies showed that the N1 amplitude was higher when the attention level was higher (Hsu et al., 2016), one may infer that longer

durations require more memory and attention processing, which leads to a higher N1. The decrease in the N1 latency after PD = 1 and PD = 3 also implicate the low-frequency time window. I presume that the N1 component can be an index of the low-frequency time window. However, both the amplitude and latency of N1 after PD = 2 were exceptions. Combined with other parameters, like P2 and oscillation, I presume that the exceptions can result from the same standard and pause intervals.

The P2 component amplitudes tended to increase with longer pause durations, but statistics did not show significance. Previous studies (Chen et al., 2007; González-Garrido et al., 2008) found that the P2 amplitude can be quite different when dealing with temporal information and others such as tones. I only examined temporal differences, resulting in the lack of difference in P2 in this experiment.

The results of the time-frequency analysis match the behavioral result; there was an increasing low-beta power (13-20 Hz) for the reproduction after pause durations up to 3s, but not for longer durations. This result was similar to that of previous studies. Many studies found that beta oscillation can play an important role in internal temporal information processing (Bartolo & Merchant, 2015; Baumgarten et al., 2015; Ghaderi et al., 2018), and it can be a bridge for temporal anticipation and motor actions. The 2.5 temporal-reproduction task (Kononowicz & van Rijn, 2015) found that beta power can be quite different for shorter, correct, and longer produced durations; the greatest difference appeared around 0.9-1.1s. Results indicated that the beta power could provide an index for time estimation. Our experiment also found vigorous low beta activities around 1s after reproduction onset for PD = 1 and PD = 3, while that of PD = 2 was around 0.5 seconds. If one neglects the difference of time, this strong low beta activity only appears for pause durations below 3s, corresponding to the low-frequency time window. In correlation with previous studies that confirmed that the beta wave was related to discrete perceptual cycles and internal timing processing, I agree that beta oscillation plays a the role as a neural marker for the low-frequency time window. As for the different appearance time of beta activity for PD = 1, 3 and PD = 2, in correspondence with the idea of beta suppression after auditory stimulus onset and then rebound, I deduced that when the standard stimulus and the pause duration are of the same length, the beta rebound after suppression will occur sooner because of the stable time length.

I also believe that the observed beta oscillation did not represent the time duration, but reflected the existence of the temporal perceptual unit. When pause durations are shorter than 3s, our brain can deal with the information in working memory by the same unit. However, when pause durations are too long, our brain does not extract the information from the working memory unit, but needs to refer to other memory systems. This interrupts the perceptual cycle, so the brain cannot refer to the previous perception, and no beta oscillation can be elicited. This new unit stabilized the reproduced durations to a plateau. However, whether the different onset of beta oscillation was from the same length of the former two durations still needs to be further confirmed with more standard stimuli.

6. Summary and Future Prospects

As a classic temporal-perception paradigm, the temporal-reproduction task is commonly used to explore the low-frequency time window. However, researchers mainly focused on the quantitative relationship between standard and reproduced durations or whether the standard interval can regulate some variables. The pause duration between the standard and reproduction stimuli was neglected. In experiment one, I used 2s as a standard stimulus and explored the effect of pause durations on reproductions, which clarified how pause durations affect reproduced intervals. Since it was difficult to interpret the significance of our preliminary results, I added 3s and 4.5s as standard stimuli. Results showed that the patterns of reproduced intervals after different standard stimuli were the same, which indicated that the pause-duration effect was independent of standard stimuli. Experiment 3 was performed to confirm that this pause-duration effect is based on the low-frequency time window, but not on the shorter waiting period in the task. To explore whether this result represents one temporal-integration mechanism or is based on sensory information, I included different auditory frequencies for standard and reproduced stimuli in experiment 4 and obtained similar results as previously. Experiment 5 I used EEG technology and the wavelet-analysis method to discover the neural indicator for this mechanism. Results indicated that beta oscillation may be an indicator of the low-frequency time window.

The new approach in these studies included an improvement of the paradigm. I used varied pause durations to investigate the pause-duration effect and its range. I also chose a specific perspective to examine the low-frequency time window. Finally, I employed an advanced EEG analysis and explored the reproduction and the neural activity during pause durations.

I must mention some shortcomings in this study. Most studies used the relatively continuous and broad scope of standard stimuli for the choice of standard stimuli. For the convenience of statistical testing, I only used some discrete standard stimuli with a relatively narrow range, and the experimental results could have been affected by the expectations and attentional status of the subjects. Due to the different study aims, the stimulus levels of experiments 1, 2, and 3 differed. Although the main study results were not influenced, the different stimuli distribution could have affected the response

states and participants' results to the same standard stimulus. In experiment 3, the standard and reproduced stimulus volume parameters were not corrected according to the equal loudness curve. In experiment 4, I did not use a permutation test or any other form of confirmation.

In future studies, one could add more interesting aspects to the experimental paradigm. For example, one could use continuous pause durations to explore the transition threshold or let the subject freely choose the pause duration and investigate his/her time-range preference. According to the physical characteristics of the stimulus, further studies could employ a visual stimulus to verify the transition zone. One could also acquire more EEG data and investigate the functional brain connectivity during the temporal-processing period.

References

L. Aftanas, & S. Golocheikine. (2001). Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: high-resolution EEG investigation of meditation. *Neuroscience Letters, 310*(1), 57-60.

M. Alfimova, & L. Uvarova. (2007). Changes in the EEG spectral power during perception of neutral and emotionally salient words in schizophrenic patients, their relatives and healthy individuals from the general population. *Zhurnal vysshei nervnoi deiatelnosti imeni IP Pavlova, 57*(4), 426-436.

Y. Bao, & E. Pöppel. (2007). Two spatially separated attention systems in the visual field: evidence from inhibition of return. *Cognitive Processing, 8*(1), 37-44.

Y. Bao, Z. Wang, W. Liang, Y. Wang, E. Pöppel, & H. Li. (2013). Inhibition of return at different eccentricities in the visual field share the same temporal window. *Neuroscience Letters, 534*, 7-11.

R. Bartolo, & H. Merchant. (2015). β oscillations are linked to the initiation of sensory-cued movement sequences and the internal guidance of regular tapping in the monkey. *Journal of Neuroscience, 35*(11), 4635-4640.

R. Bartolo, L. Prado, & H. Merchant. (2014). Information processing in the primate basal ganglia during sensory-guided and internally driven rhythmic tapping. *Journal of Neuroscience, 34*(11), 3910-3923.

T. J. Baumgarten, A. Schnitzler, & J. Lange. (2015). Beta oscillations define discrete perceptual cycles in the somatosensory domain. *Proceedings of the National Academy of Sciences, 112*(39), 12187-12192.

G. X. Buzsaki. (2006). *Rhythms of the Brain*: Oxford University Press.

N. Cellini, M. Fabbri, M. Martoni, L. Tonetti, & V. Natale. (2014). Discontinuity in the perception of sub-second intervals. *Procedia-Social and Behavioral Sciences, 126*, 222-223.

Y. Chen, X. Chen, C. Kuang, & X. Huang. (2015). Neural oscillatory correlates of duration maintenance in working memory. *Neuroscience, 290*, 389-397.

Y. Chen, Z. Zhang, X. Guang, X. Guo, H. Yuan, & T. Zhang. (2007). Attentional modulation of time perception: an ERP study. *Acta Psychologica Sinica, 39*(06), 1002-1011

M. X. Cohen. (2014). *Analyzing neural time series data: theory and practice*: MIT press.

S. Cordes, & W. H. Meck. (2014). Ordinal judgments in the rat: An understanding of longer and shorter for suprasecond, but not subsecond, durations. *Journal of Experimental Psychology: General, 143*(2), 710.

F. C. Donders. (1969). On the speed of mental processes. *Acta psychologica, 30*, 412-431.

T. Elbert, R. Ulrich, B. Rockstroh, & W. Lutzenberger. (1991). The processing of temporal intervals reflected by CNV-like brain potentials. *Psychophysiology, 28*(6), 648-655.

G. T. Fechner. (1860). *Elemente der Psychophysik.* Leipzig: Breitkopf und Härtel.

R. Fischer, S. England, R. Archer, & R. Dean. (1966). Psilocybin reactivity and time contraction as measured by psychomotor performance. *Arzneimittel-Forschung, 16*(2), 180-185.

P. Fraisse. (1984). Perception and estimation of time. *Annual review of psychology, 35*(1), 1-37.

T. Fujioka, L. J. Trainor, E. W. Large, & B. Ross. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *Journal of Neuroscience, 32*(5), 1791-1802.

D. J. Getty. (1975). Discrimination of short temporal intervals: A comparison of two models. *Perception & psychophysics, 18*(1), 1-8.

A. H. Ghaderi, S. Moradkhani, A. Haghighatfard, F. Akrami, Z. Khayyer, & F. Balcı. (2018). Time estimation and beta segregation: An EEG study and graph theoretical approach. *PLoS One, 13*(4), e0195380.

H. Gibbons, S. Brandler, & T. H. Rammsayer. (2003). Dissociating aspects of temporal and frequency processing: a functional ERP study in humans. *Cortex, 39*(4-5), 947-965.

C. Gomez, E. Argandona, R. Solier, J. Angulo, & M. Vazquez. (1995). Timing and competition in networks representing ambiguous figures. *Brain and Cognition, 29*(2), 103-114.

A. A. González-Garrido, F. R. Gómez-Velázquez, D. Zarabozo, R. López-Elizalde, A. Ontiveros, H. Madera-Carrillo, O. L. Vega, J. O. D. Alba, & J. M. D. L. S. Tuya. (2008). Time reproduction disturbances in ADHD children: An ERP study. *International Journal of Neuroscience, 118*(1), 119-135

S. Grondin. (2010). Timing and time perception: a review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception, & Psychophysics, 72*(3), 561-582.

M. Guay. (1982a). Long-term retention of temporal information. *Perceptual and Motor Skills, 54*(3), 843-849.

M. Guay. (1982b). Short-term retention of temporal auditory information. *Perceptual and Motor Skills, 55*(1), 19-26

M. J. Hayashi, M. Kantele, V. Walsh, S. Carlson, & R. Kanai. (2014). Dissociable neuroanatomical correlates of subsecond and suprasecond time perception. *Journal of Cognitive Neuroscience, 26*(8), 1685-1693.

I. J. Hirsh, C. B. Monahan, K. W. Grant, & P. G. Singh. (1990). Studies in auditory timing: 1. Simple patterns. *Perception & psychophysics, 47*(3), 215-226.

Y.-F. Hsu, J. A. Hämäläinen, & F. Waszak. (2016). The auditory N1 suppression rebounds as prediction persists over time. *Neuropsychologia, 84*, 198-204

J. R. Hughes. (2008). Gamma, fast, and ultrafast waves of the brain: their relationships with epilepsy and behavior. *Epilepsy & Behavior, 13*(1), 25-31.

C. Iber, S. Ancoli-Israel, A. L. Chesson, & S. F. Quan. (2007). *The AASM manual for the scoring of sleep and associated events: rules, terminology and technical specifications* (Vol. 1): American academy of sleep medicine Westchester, IL.

R. Ilg, S. Burazanis, A. M. Wohlschläger, A. Wöller, S. Wagenpfeil, & M. Mühlau. (2008). Stimulus frequency influences spontaneous perceptual reversals in ambiguous apparent motion. *Perception & psychophysics, 70*(3), 437-442.

O. Jensen, & C. D. Tesche. (2002). Frontal theta activity in humans increases with memory load in a working memory task. *European journal of Neuroscience, 15*(8), 1395-1399.

D. Jokisch, & O. Jensen. (2007). Modulation of gamma and alpha activity during a working memory task engaging the dorsal or ventral stream. *Journal of Neuroscience, 27*(12), 3244-3251.

R. A. Joundi, N. Jenkinson, J.-S. Brittain, T. Z. Aziz, & P. Brown. (2012). Driving oscillatory activity in the human cortex enhances motor performance. *Current Biology, 22*(5), 403-407

J. Kien, & A. Kemp. (1994). Is speech temporally segmented? Comparison with temporal segmentation in behavior. *Brain and Language, 46*(4), 662-682.

G. Knyazev, J. Y. Slobodskoj-Plusnin, & A. Bocharov. (2009). Event-related delta and theta synchronization during explicit and implicit emotion processing. *Neuroscience, 164*(4), 1588-1600.

T. W. Kononowicz, & H. van Rijn. (2015). Single trial beta oscillations index time estimation. *Neuropsychologia, 75*, 381-389.

A. B. Kristofferson. (1976). Low-variance stimulus-response latencies: Deterministic internal delays? *Perception & psychophysics, 20*(2), 89-100.

T. Kujala, M. Tervaniemi, & E. Schröger. (2007). The mismatch negativity in cognitive and clinical neuroscience: theoretical and methodological considerations. *Biological psychology, 74*(1), 1-19

H. Lejeune, & J. H. Wearden. (2009). Vierordt's The Experimental Study of the Time Sense (1868) and its legacy. *European Journal of Cognitive Psychology, 21*(6), 941-960.

P. A. Lewis, & R. C. Miall. (2003). Brain activation patterns during measurement of sub-and supra-second intervals. *Neuropsychologia, 41*(12), 1583-1592.

N. Loveless, & A. Sanford. (1974). Slow potential correlates of preparatory set. *Biological psychology, 1*(4), 303-314.

C. F. MacDorman. (1962). Synchronization with auditory models of varying complexity. *Perceptual and Motor Skills, 15*(3), 595-602.

E. Mach. (1865). Untersuchungen uber den Zeitsinn des Ohres. *Sitzungsberichte der mathem.-naturwiss. Klasse d. Kaiserl. Akademie d. Wissenschaften, 51*, 1-5.

E. Magosso, F. De Crescenzio, G. Ricci, S. Piastra, & M. Ursino. (2019). EEG Alpha Power Is Modulated by Attentional Changes during Cognitive Tasks and Virtual Reality Immersion. *Computational intelligence and neuroscience, 2019*.

J. Mates, U. Müller, T. Radil, & E. Pöppel. (1994). Temporal integration in sensorimotor synchronization. *Journal of Cognitive Neuroscience, 6*(4), 332-340.

W. J. Matthews. (2011). Stimulus repetition and the perception of time: The effects of prior exposure on temporal discrimination, judgment, and production. *PLoS One, 6*(5), e19815.

J. A. Michon. (1985). The compleat time experiencer. In *Time, mind, and behavior* (pp. 20-52): Springer.

W. Moore Jr, & W. O. Haynes. (1980). A study of alpha hemispheric asymmetries for verbal and nonverbal stimuli in males and females. *Brain and Language, 9*(2), 338-349.

H. Musterberg. (1889). Beitrage zur experimentellen Psychologie: Heft 2. In: Akademische Verlagsbuchhandlung von JCB Mohr, Freiberg, Germany.

R. Näätänen, A. W. Gaillard, & S. Mäntysalo. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta psychologica, 42*(4), 313-329.

R. Näätänen, & S. Kähkönen. (2009). Central auditory dysfunction in schizophrenia as revealed by the mismatch negativity (MMN) and its magnetic equivalent MMNm: a review. *International Journal of Neuropsychopharmacology, 12*(1), 125-135.

T. Najenson, S. Ron, & K. Behroozi. (1989). Temporal characteristics of tapping responses in healthy subjects and in patients who sustained cerebrovascular accident. *Brain, behavior and evolution, 33*(2-3), 175-178.

I. Newton. (1687). *Philosophiae Naturalis Principia Mathematica* (F. Cajori, Trans. F. Cajori Ed.): University of California Press.

P. Niemi. (1979). Stimulus intensity effects on auditory and visual reaction processes. *Acta psychologica, 43*(4), 299-312.

E. Nyhus, & T. Curran. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neuroscience & Biobehavioral Reviews, 34*(7), 1023-1035.

L. Pan, & X. Huang. (2018). Influencing factors and thought of temporal order perception. *Advances in Psychological Science, 26*(4), 614-624.

L. Peterson, & M. J. Peterson. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology, 58*(3), 193.

E. Pöppel (1972). Oscillations as possible basis for time perception. In *The study of time* (pp. 219-241): Springer.

E. Pöppel. (1973). Influence of pause duration on the reproduction of a 2-second interval. *Bulletin of the Psychonomic Society, 2*(5), 291-292.

E. Pöppel. (1997). A hierarchical model of temporal perception. *Trends in cognitive sciences, 1*(2), 56-61.

E. Pöppel. (2009). Pre-semantically defined temporal windows for cognitive processing. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1525), 1887-1896.

E. Pöppel, & Y. Bao. (2014). Temporal Windows as a Bridge from Objective to Subjective Time, The Philosophy, Psychology, and Neuroscience of Temporality. In: The MIT Press.

E. Pöppel, R. Brinkmann, D. von Cramon, & W. Singer. (1978). Association and dissociation of visual functions in a case of bilateral occipital lobe infarction. *Archiv für Psychiatrie und Nervenkrankheiten, 225*(1), 1-22.

M. I. Posner, & Y. Cohen. (1984). Components of visual orienting. *Attention and performance X: Control of language processes, 32*, 531-556.

J. Radilova, E. Pöppel, & J. Ilmberger. (1990). Auditory reversal timing. *Activitas nervosa superior*.

B. Rockstroh. (1989). *Slow cortical potentials and behaviour*: Urban & Schwarzenberg.

M. Sams, R. Hari, J. Rif, & J. Knuutila. (1993). The human auditory sensory memory trace persists about 10 sec: neuromagnetic evidence. *Journal of Cognitive Neuroscience, 5*(3), 363-370.

P. Sauseng, W. Klimesch, M. Schabus, & M. Doppelmayr. (2005). Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International journal of Psychophysiology, 57*(2), 97-103.

M. Schleidt, I. Eibl-Eibesfeldt, & E. Poppel. (1987). A universal constant in temporal segmentation of human short-term behavior. *Naturwissenschaften, 74*(6), 289-290.

A. Spector, T. Freund, L.-K. Li, & R. C. Augusteyn. (1971). Age-dependent changes in the structure of alpha crystallin. *Investigative Ophthalmology & Visual Science, 10*(9), 677-686.

E. Szelag, J. Kowalska, T. Galkowski, & E. Pöppel. (2004). Temporal processing deficits in high-functioning children with autism. *British Journal of psychology, 95*(3), 269-282.

E. Szelag, J. Kowalska, K. Rymarczyk, & E. Pöppel. (2002). Duration processing in children as determined by time reproduction: implications for a few seconds temporal window. *Acta psychologica, 110*(1), 1-19.

Y. Takei, S. Kumano, S. Hattori, T. Uehara, Y. Kawakubo, K. Kasai, M. Fukuda, & M. Mikuni. (2009). Preattentive dysfunction in major depression: a magnetoencephalography study using auditory mismatch negativity. *Psychophysiology, 46*(1), 52-61.

K. Tanida, & E. Pöppel. (2006). A hierarchical model of operational anticipation windows in driving an automobile. *Cognitive Processing, 7*(4), 275-287.

F. Turner, & E. Pöppel. (1983). The neural lyre: Poetic meter, the brain, and time. *Poetry, 142*(5), 277-309.

P. Ulbrich, J. Churan, M. Fink, & M. Wittmann. (2007). Temporal reproduction: Further evidence for two processes. *Acta psychologica, 125*(1), 51-65.

J. A. Van Deursen, E. Vuurman, F. R. J. Verhey, V. van Kranen-Mastenbroek, & W. J. Riedel. (2008). Increased EEG gamma band activity in Alzheimer's disease and mild cognitive impairment. *Journal of neural transmission, 115*(9), 1301-1311

K. Vierordt. (1868). *Der zeitsinn nach versuchen*: H. Laupp.

K. E. Von Baer. (1861). *Welche auffassung der lebenden natur ist die richtige?: und wie ist diese auffassung auf die entomologie anzuwenden? Zur eröffnung der Russischen entomologischen gesellschaft*.

W. G. Walter. (1936). The location of cerebral tumours by electro-encephalography. *The Lancet, 228*(5893), 305-308.

L. Wang, X. Lin, B. Zhou, E. Pöppel, & Y. Bao. (2015). Subjective present: a window of temporal integration indexed by mismatch negativity. *Cognitive Processing, 16*(1), 131-135.

A. C. Welday, I. G. Shlifer, M. L. Bloom, K. Zhang, & H. T. Blair. (2011). Cosine directional tuning of theta cell burst frequencies: evidence for spatial coding by oscillatory interference. *Journal of Neuroscience, 31*(45), 16157-16176.

M. Wittmann, O. Carter, F. Hasler, B. R. Cahn, U. Grimberg, P. Spring, D. Hell, H. Flohr, & F. X. Vollenweider. (2007). Effects of psilocybin on time perception and temporal control of behaviour in humans. *Journal of Psychopharmacology, 21*(1), 50-64.

M. Wittmann, A. N. Simmons, J. L. Aron, & M. P. Paulus. (2010). Accumulation of neural activity in the posterior insula encodes the passage of time. *Neuropsychologia, 48*(10), 3110-3120.

H. Woodrow. (1932). The effect of rate of sequence upon the accuracy of synchronization. *Journal of Experimental Psychology, 15*(4), 357.

W. M. Wundt. (1911). *Einführung in die Psychologie* (Vol. 1): R. Voigtländer.

H. Yin, D. Li, Y. Chen, & X. Huang. (2016). The characteristic of 1~6 s duration cognition segmentation. *Acta Psychologica Sinica, 48*(9), 1119-1129.

X. Yu, Y. Chen, J. Qiu, X. Li, & X. Huang. (2017). Neural oscillations associated with auditory duration maintenance in working memory. *Scientific reports, 7*(1), 1-9.

C. Zhao, D. Zhang, & Y. Bao. (2018). A time window of 3 s in the aesthetic appreciation of poems. *PsyCh journal, 7*(1), 51-52.

Affidavit

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Ich erkläre hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Titel:

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