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Time processing in neurological and psychiatric conditions

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ABSTRACT

A central question in understanding cognition and pathology-related cognitive changes is how we process time. However, time processing difficulties across several neurological and psychiatric conditions remain seldom investigated. The aim of this review is to develop a unifying taxonomy of time processing, and a neuropsychological perspective on temporal difficulties. Four main temporal judgments are discussed: duration processing, simultaneity and synchrony, passage of time, and mental time travel. We present an integrated theoretical framework of timing difficulties across psychiatric and neurological conditions based on selected patient populations. This framework provides new mechanistic insights on both (a) the processes involved in each temporal judgement, and (b) temporal difficulties across pathologies. By identifying underlying transdiagnostic time-processing mechanisms, this framework opens fruitful avenues for future research.

1. Introduction: towards a neuropsychology of time processing

Time processing has been described as a "basic unit of ability" for other cognitive and behavioral processes (Allman and Meck, 2012). Time is indeed involved at multiple levels of information processing, from perception and attention to memory (Buhusi and Meck, 2005), and across different temporal scales ranging from a few milliseconds to several seconds, minutes, hours, days and even years (Grondin, 2010). Given this critical role in cognition, and its extended neural bases, time processing is highly sensitive to pathological changes. However, knowledge about timing difficulties across several neurological and psychiatric conditions remains limited, as there is currently a gap between fundamental research on time processing and clinical applications. Time processing difficulties have recently been documented in neurological (Liu et al., 2021a) and psychiatric (Kent et al., 2022) conditions, but when it comes to temporal judgement, each of these conditions has often been considered in relative isolation, leaving a unifying taxonomy of time-related cognitive and neural alterations still to be developed.

Here, we propose this taxonomy by considering time processing difficulties across neurological and psychiatric conditions. Results reported in studies of conditions affecting time processing are mixed, both for clinical (e.g., differences in medication, severity, age of onset, etc.) and methodological reasons. Most clinical studies have focused on a specific temporal judgement with a single temporal task, and the association across temporal processes remains poorly understood. Performance on temporal tasks may also reflect non-temporal rather than temporal task components. For example, an underestimation of time

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Box 1
Explicit versus implicit assessment of time processing.

Recent investigations of temporal cognition have revealed differences in performance as a function of whether task instructions explicitly indicate that time will need to be estimated, or whether the task does not emphasize this dimension (Coull and Droit-Volet, 2018). As an example, explicit instructions can be provided about judging the duration of an interval between two signals, whereas in an implicit task, participants are asked to respond as quickly as possible after the second signal. In that latter case, participants processing performance is less related to higher-order cognitive abilities and contextual factors. While dissociations have been reported between the developmental trajectories of explicit and implicit time processing (Capizzi et al., 2022), this dissociation has not often been considered in pathological conditions. As such, the dissociation could provide important insights on temporal difficulties across pathologies. Using an implicit task, a recent study found for example preserved time perception in patients with Parkinson's disease (PD), a condition long thought to impact time perception (Mioni et al., 2018). On the other hand, in patients with schizophrenia, the use of implicit tasks show timing impairments that are independent of working memory deficits: patients do not benefit from temporal cues, or from the passage of time, when there is an uncertainty on the occurrence of the target or cues (Martin et al., 2017). These results show that dissociating implicit from explicit timing may be crucial in further analyzing the processes involved in temporal processing and identifying the different sources of impairment in neurologic and psychiatric disorders. Future research should aim at further specifying this distinction in pathologies, especially in patients with limited consciousness of their cognitive impairments. This strategy would enable further specification of the presence of double dissociations of duration processing performance when no explicit information is provided. This could reveal intact, or less impaired, processing in activities showing difficulties in explicit conditions.

may be related to an attention deficit linked to an insufficient attentional focus on temporal information (Zakay and Block, 1996), and noisy representation of durations may be related to limited working memory capacities (Zélanti and Droit-Volet, 2012). Therefore, important work remains in order to identify the different abilities - both temporal and non-temporal - required to complete a given time processing task. Furthermore, the most commonly used procedures in human adults are tasks of explicit timing, in which participants are instructed to pay attention to the passage of time (see Box 1). Explicit time judgment is more demanding in terms of cognitive control than implicit time processing, which does not require conscious processing of temporal information. Patients also differ in their ability to verbally describe their temporal difficulties. The lack of a clear taxonomy of the different timing mechanisms thus complicates the investigation of these conditions.

Our goal is not to extensively review the theoretical and experimental findings related to timing (Grondin, 2010; Teghil et al., 2019; van Wassenhove et al., 2019; Droit-Volet and Wearden, 2003; Kononowicz et al., 2018; Matthews and Meck, 2014; Merchant et al., 2013; van Wassenhove, 2009; see Box 2), but instead to focus specifically on time processing difficulties across selected, well-documented neurological and psychiatric conditions. Bringing together the different lines of research can yield mechanistic insights that are less apparent when considering the literature in a more fragmented way. Our approach has three advantages: a) it may lead to a better understanding of patients' subjective difficulties and cognitive deficits, which are not always expressed in temporal terms, b) it may deepen our knowledge by specifying common difficulties across pathologies for a given temporal judgement, and joint temporal difficulties for a given condition, c) it would allow the identification of the most relevant temporal measurements for a given pathology. Our taxonomy therefore represents a first and promising way for improving diagnostic and therapeutic approaches to time processing difficulties, as well as identifying pathways for future fundamental research.

Based on the human temporal processing literature, four main temporal judgements are examined: I) **Duration processing**; II) **Simultaneity and temporal order**; III) **Feeling of the passage of time**; IV) **Mental time travel**. For each judgement, varying on a continuum between perception and memory, we describe the tasks used, the brain structure involved, and reported temporal difficulties. We will illustrate difficulties with neurological and psychiatric conditions that have been well documented (Fig. 1), as the investigation of conditions affecting temporal processing remains fragmented. Difficulties across temporal judgements are then discussed. Finally, we provide concluding remarks and recommendations for future work.

1.1. Duration production, reproduction, and comparison

As noted above, the most commonly used tasks to investigate duration processing in humans are based on an explicit temporal judgement, asking for example participants to produce, to reproduce, or to compare durations and intervals ranging from about 500 ms to about 30 s. Performance in these explicit tasks has been associated with attention, processing speed, and working memory abilities, and is also affected by a whole range of factors, such as emotion or task load (Matthews and Meck, 2016), such that additional work remains necessary to further clarify difficulties across pathologies.

Neuroimaging studies in human adults have identified two neural networks for duration processing, according to their length (Buhusi and Meck, 2005; Kononowicz et al., 2018; Nani et al., 2019; Agostino et al., 2011; Box 2). A first network is engaged in the processing of intervals of less than one second, and mainly involves the cerebellum and subcortical regions (thalamus, globus pallidus; Nani et al., 2019). A second network is observed in the processing of intervals of more than one second (up to about tens of seconds), and involves cortical regions (medial frontal regions, the supplementary motor area, and inferior parietal lobe). Activation of the insula, the supplementary motor area (SMA), the superior/inferior frontal gyri, the superior temporal gyrus, and the striatum, are common across contexts and duration judgements (Nani et al., 2019; Naghibi et al., 2023; Mondok and Wiener, 2023). Regarding the M/EEG brain rhythms involved, reduced alpha (8–13 Hz) zHz peak frequency has been associated with longer temporal productions (Wiener and Kanai, 2016), suggesting an association between individual oscillatory characteristics and time processing performance (Hashimoto and Yotsumoto, 2018). Furthermore, strong associations between beta-band power (13–30 Hz) and temporal decisions have been reported, with tACS stimulation of beta oscillations being associated with increased proportion of "long" answers in a duration comparison task (Wiener et al., 2018), and overall reduced beta power in individuals who tend to overestimate long durations (Ghaderi et al., 2018).

Difficulties have been reported in pathologies including autism, depression, or dementia (Liu et al., 2021a; Kent et al., 2022), although with mixed results. Reduced temporal precision (i.e., larger variability) and distorted perception of durations have been extensively described in attention-deficit/hyperactivity disorder (ADHD), and may be related to its core symptoms (i.e., inattention, impulsivity, hyperactivity; Smith et al., 2002). Indeed, children and adolescents with ADHD tend to overestimate (i.e., durations are judged as longer than controls), and to underproduce (i.e., shorter produced intervals than controls) durations over a second (Zheng et al., 2022; Walg et al., 2017). Moreover, these difficulties are larger in a dual-task context (Hwang et al., 2010).

Box 2
Models of the neural bases of time processing.

Several neural models have been proposed to account for time processing in humans, in an attempt to describe the neural mechanisms associated with one or several temporal judgements (Issa et al., 2020). The striatal beat frequency (SBF) model (van Wassenhove et al., 2019) was among the first proposed to account for duration processing and pharmacological modulations of performance (Fig. 3). According to this model, the striatum detects phrase synchrony across cortical regions and generates pulsatory activity, projected to the thalamus, the hippocampus and the cortex, forming a cortico-striato-thalamo-cortical circuit. It has been proposed that fronto-striatal communications involve theta entrained in delta oscillations, while cortical fronto-parietal communications involve gamma entrained in theta oscillations (Teki et al., 2017). Beta oscillations are also central to timing precision (Kononowicz et al., 2018). However, evidence of coincidence detection in the striatum remains scarce, and the notion of a dedicated central mechanisms has received increasing criticisms over the years, leading to new distributed approaches (Tsao et al., 2022; Hass and Durstewitz, 2016).

Alternative models (Hass and Durstewitz, 2016) include (a) ramping activity models (i.e., slowly increasing firing rates, peaking at the end of the interval to be estimated), (b) state-dependent network models (i.e., durations are encoded through the dynamic evolution of connectivity states of the entire network), (c) and sequential activations of pools of neurons (i.e., temporal information in reflected in the intrinsic and distributed synchronized dynamics of cortical activity).

According to the SBF model, impaired temporal processing is associated with the variability of phase synchrony across cortical regions, or of striatal activity. According to the state-dependent network model, impaired temporal processing is associated with the variability of neural activity over time, and with the segregation of distinct connectivity states over time. The identification of pathological changes in temporal processing has the potential to inform existing time models, and lead to new unified understanding of cognitive and neural temporal processing.

Distorted duration processing has also been consistently observed in Parkinson's disease (PD). It is among the first identified diseases adversely affecting time processing, mainly in supra-second intervals (Jones and Jahanshahi, 2014), which led to the identification of the critical role of dopamine transmission in duration processing (see Section V) (Allman and Meck, 2012). In contrast with ADHD, PD patients generally show duration underestimations (i.e., durations are judged as shorter than in control participants), and overproductions (i.e., longer produced intervals) (Smith et al., 2007). Regarding supra-second intervals in particular, a migration effect has also been reported in PD patients, i.e., a tendency towards overproduction of shorter intervals (e.g., 8 s) and underproduction of longer intervals (e.g., 21 s), which has been associated with altered working memory (Terao et al., 2021). Importantly, preserved duration processing has been reported using an implicit timing task (Mioni et al., 2018) (Box 1), confirming that patients' temporal performance is closely associated with attention allocation and conscious processing.

In summary, duration processing is altered in pathologies that are characterized by attention and working memory deficits and altered cortico-basal ganglia dopaminergic pathways (Fig. 2). This deficit in duration judgment could be associated with difficulties in anticipating up-coming events and producing adapted behaviors in rapidly changing temporal situations. Research on deficits affecting this temporal judgement should aim at further investigating the distinction between explicit and implicit timing in pathology (Box 1), and the effects of pharmacological treatments (Marinho et al., 2018).

1.2. Simultaneity and temporal order

Perception of simultaneity and temporal order are assessed using tasks involving decisions about whether two distinct events occur at the same time or follow each other, and detection of deviations in rhythmic series of stimuli. In line with previous work (Merchant et al., 2008; Rammsayer and Brandler, 2004), we discuss both simultaneity and temporal order, given that rhythms, simultaneity and order all participate in the timing of perceptions, as opposed to the perception of time (but see Love et al., 2013). Alterations of the perception of simultaneity and temporal order have been associated with the feeling that time disappears or is disorganized. This is notably the case in schizophrenia (Di Cosmo et al., 2021; Noel et al., 2018; Giersch et al., 2015; Capa et al., 2014).

At the neural level, simultaneity processing has been associated with activations of the left parietal cortices (Coull and Giersch, 2022), whereas rhythm, and more specifically the perception of beats has been related to basal ganglia (Grahn, 2009; Fiveash et al., 2022). M/EEG studies have associated pre-stimulus alpha band activity with visual simultaneity judgements and multisensory integration (Venskus and Hughes, 2021). Sustained synchronized activity between frontal and parietal regions has also been associated with the maintenance of temporal representations and the detection of deviations (Kononowicz et al., 2020), and could constitute a fundamental principle providing the functional basis for an integration time window (Bao et al., 2015).

Recent work revealed that many asynchronies are not pertinent in daily life, and are ignored in healthy volunteers, thus producing the experience of living in a coherent and stable environment (Foerster et al., 2021). Individuals with schizophrenia self-report a fragmentation of their experience of time, increased timing variability (Allman and Meck, 2012), and are abnormally sensitive to short, sub-threshold asynchronies (Foerster et al., 2021; Lalanne et al., 2012), a sensitivity that is partly independent from an explicit judgement (Box 1). Patients with schizophrenia show lower parietal alpha synchrony before trial onsets during completion of a simultaneity discrimination task, which was associated with this abnormal sensitivity (Marques-Carneiro et al., 2021). The disruption induced by short asynchronies has been associated with a decreased feeling of control in patients during motor actions, when the sensory consequence of the action is slightly delayed (Foerster et al., 2021), which highlights the association between millisecond-level synchrony impairments and clinical disorders (i.e., altered sense of self, delusions of control). Interestingly, an opposite pattern is suggested in people with PD, who seem insensitive to implicit asynchronies (Waldmann et al., 2020), albeit these asynchronies being larger (500 ms).

Temporal synchrony in autism also differs from that seen in neurotypical development (Wimpory, 2015). Atypical rhythmic patterns of parent-child interactions have been reported in autism (Papoulidi et al., 2020), together with differences in cortical synchrony (Allman and Meck, 2012). Autism has indeed been associated with difficulties in information binding over extended asynchronies between stimuli (Foss-Feig et al., 2010). Internal timing difficulties may interact with autism's primary difficulties and may also be associated with the central coherence hypothesis of autism (Nakano et al., 2010). However, temporal asynchronies of audio-visual stimuli have not always been detected in children with autism, relative to controls (Chan et al., 2016). This atypical pattern of multisensory temporal processing has been proposed as a basis for language and communications difficulties in this population (Stevenson et al., 2014), and has also been reported in children with ADHD (Panagiotidi et al., 2017).

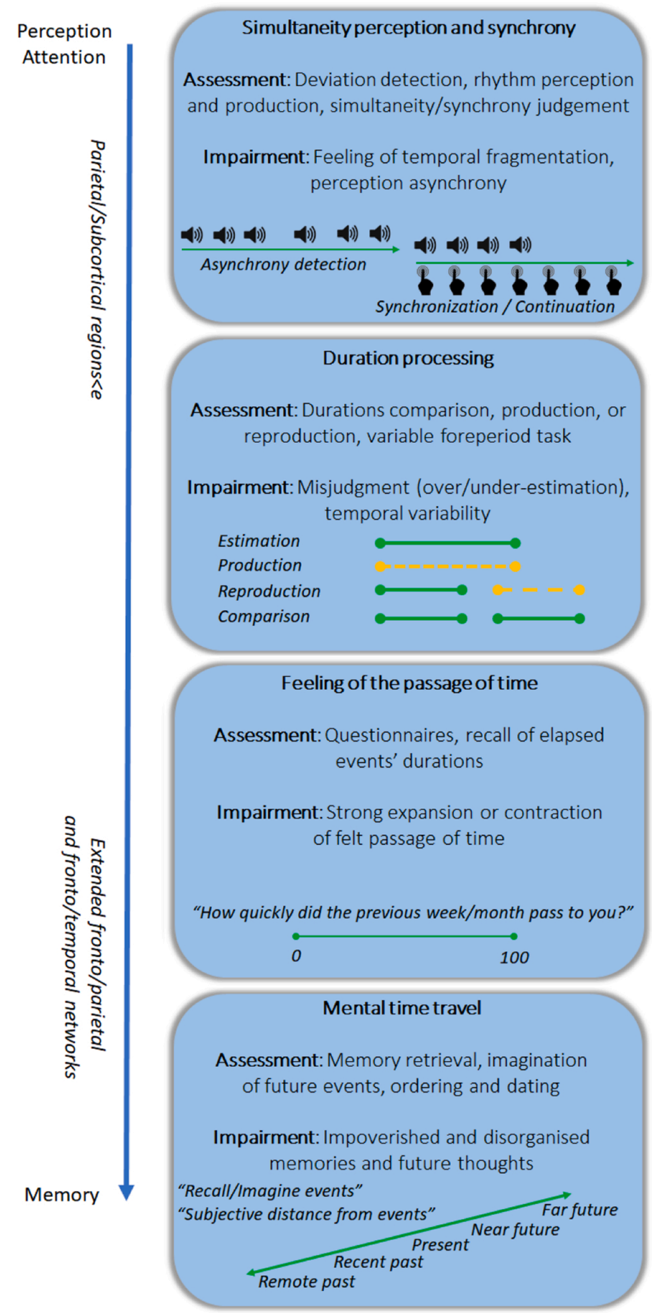

Fig. 1. Summary of the four main temporal judgements, their main assessments, and a tentative summary of possible difficulties associated with their difficulties: Impairments in temporal processing can be associated with cognitive processes, such as altered attention or memory, altered consciousness, or loss of semantic knowledge about time (Liu et al., 2021a; Tsao et al., 2022; Meck, 2005).

To summarize, temporal order and simultaneity are altered in pathologies characterized by difficulties in processing speed and working memory, together with thalamic connectivity, dopaminergic and serotoninergic pathways. Difficulties affect the integration of perceptions across modalities, both because of their inherent temporal lag (Hanson et al., 2008), and as a coherent source of information (Fenner et al., 2020). In contrast, cross-modal perceptual integration appears to be preserved in other pathologies, such as PTSD or dementia. Further work will need to specify the role of implicit mechanisms to understand how an altered timing of perceptions can lead to a temporal fragmentation of perceptions.

1.3. The feeling of the passage of time

Marcel Proust wrote in *Within A Budding Grove* (1919) that "*the time which we have at our disposal every day is elastic; the passions that we feel expand it, those that we inspire contract it; and habit fills up what remains*". The feeling that time speeds up or slows down corresponds to the phenomenological experience of time. It is typically assessed using questionnaires and self-report scales about present passage of time, together with retrospective assessments of the durations of past events for longer periods of life (e.g., weeks, years). While being a widely accepted and intuitive phenomenon, the mechanisms underlying the feeling of the passage of time have long remained elusive (Martinelli and Droit-Volet, 2022). The subjective feeling of passage of time involves understudied high-level cognitive processes related to memory and consciousness, including self-awareness in time (Martinelli and Droit-Volet, 2022), and is influenced by non-temporal characteristics such as emotional states, attentional manipulation, and task load (Wearden, 2015; Wöllner et al., 2023).

At the neural level, sustained brain oscillations and ramping brain activity over time have been interpreted as reflecting information accumulation over time and decision-related mechanisms (van Wassenhove et al., 2019; Kononowicz et al., 2018). Activity in the medial temporal lobe (Lee et al., 2020; Lositsky et al., 2016), and bursting activity in the alpha band at rest, have been associated with participants' retrospective estimation of time passing (Azizi et al., 2023; El Haj et al., 2013; El Haj and Kapogiannis, 2016; Mioni et al., 2021). The accumulation over time has been associated with activity of the supplementary motor area (see Box 2), and the posterior insula (Wittmann, 2013). However, further work on the neural mechanisms underlying the feeling of the passage of time remains necessary.

A disrupted sense of time can lead individuals to interrupt an activity they just started, thinking "enough time" has passed, or conversely to pursue an activity for an exaggerated period of time (Assal and Bindschaedler, 1990). The fact that mood and affective disorders have been shown to be associated with accelerated or slowed down passage of time (Droit-Volet, 2013; Buzi et al., 2023) supports the view that emotions play a critical role in the feeling of the passage of time (Droit-Volet and Meck, 2007). While recent work on the effect of COVID-19 lockdowns revealed mixed results of a slowed down passage of time in presence of depressive symptoms (Droit-Volet et al., 2021; Ogden, 2020; Droit-Volet et al., 2020; Abbott, 2021), meta-analyses (Kent et al., 2019; Thönes and Oberfeld, 2015) highlight a significant modulation of how time is perceived and represented in major depression. Depressed patients frequently report perceiving previous time periods as passing very slowly at the scale of days or weeks. The slowing in felt passage of time has also been associated with suicide contemplation (Cáceda et al., 2020). Changes in the passage of time could thus constitute an indicator of altered cognitive functioning or mental health issues.

A similar slowing down of time has been observed in patients with PD and dementia (Terao et al., 2021; Requena-Komuro et al., 2020). Coelho and colleagues (Coelho et al., 2016) reported a slower passage of time for extended past time periods (weeks, months) in MCI patients relative to controls, which was associated with episodic memory deficits. However, no difference relative to healthy older individuals has been observed about felt passage of time in the minute range (Heinik and Ayalon, 2010), suggesting a specific difficulty with retrospective judgments about longer durations in memory.

In summary, the subjective sense of time flow is altered in pathologies affecting attention, processing speed, and episodic memory, involving fronto-subcortical dopamine pathways. Similar difficulties have been identified in children with ADHD (Wilson et al., 2013). This ability is critical to self-assess the progression of actions, or to plan upcoming events. However, the investigation of judgment of durations of several minutes is still rare, and the underlying mechanisms remain poorly understood (Droit-Volet et al., 2018).

Pathologies	Symptoms	General cognitive difficulties	Temporal difficulties	Main neural mechanisms	Main affected temporal judgement
ADHD	Inattentiveness, impulsivity, hyperactivity	Sustained and selective attention, working memory	Duration overestimation and underproduction (>1s)	Altered fronto-striatal network. Norepinephrine and dopamine.	Duration processing
Parkinson's disease	Loss of automatic movements, tremors	Shared and selective attention, working memory decision-making	Duration underestimation and overproduction (>1s), rhythm production, altered future thinking	Nigrostriatal dopamine deficit	Duration processing
Schizophrenia	Hallucinations, disorganized thinking, altered minimal self-awareness	Working memory, selective attention, processing speed	Fragmented temporal order processing, altered future thinking	Altered frontal-parietal and fronto-striato-thalamic connectivity. Dopaminergic transmission	Order and synchrony
Autism	Difficulties with social interactions, restricted and repetitive interests	Theory of mind, processing speed, working and episodic memory	Duration underestimation (<1s), temporal rigidity, altered diachronic thinking	Atypical development of inter-hemispheric and cortico-basal ganglia-thalamic connectivity. Dopamine and serotonin	Order and synchrony
Depression	Sadness, hopelessness, loss of interest	Selective attention, processing speed, episodic memory	Duration overproduction (>1s), dilated passage of time, altered future thinking	Altered frontolimbic network. Dopaminergic transmission	Passage of time
Alzheimer	Forgotten recent events, repetitive questions, lower flexibility	Episodic memory, executive dysfunction, spatial and temporal orientation	Accelerated passage of time, altered future thinking and personal temporality	Altered hippocampal network. Acetylcholine and norepinephrine	Mental time travel
PTSD	Intrusive memories, avoidance, hyperarousal	Sustained attention, working memory, episodic memory	Duration overestimation (>1s), altered future thinking	Altered fronto-hippocampal connectivity. Norepinephrine and serotonin	Mental time travel

Fig. 2. Summary of documented pathologies showing explicit time processing difficulties in one of the four main temporal judgement types, their main symptoms, associated general cognitive difficulties, and the main neural mechanisms involved.

1.4. Mental time travel

Mental time travel refers to the ability to flexibly navigate across the personal timeline that encapsulates a person's life, including memories of the past and simulations of future events (D'Argembeau, 2020). Retrospective time judgments and recall of past events, together with the anticipation and planning of future activities, are intimately related (Block et al., 2018) and involve partly similar processes (Suddendorf and Corballis, 2007; Box 3). This temporal judgement relies on episodic and semantic memory (La Corte and Piolino, 2016). Difficulties with mental time travel can adversely affect the sense of self-continuity across the past, present, and future, as well as decision-making and goal pursuit (Liu et al., 2021a; Conway et al., 2019).

Remembering past events and simulating future events commonly engage regions of the default mode network (Benoit and Schacter, 2015). The temporal organization in memory, as well as the encoding and retrieval of event sequences, have specifically been associated with the hippocampus (Liu et al., 2021b), while ordering autobiographical events would also involve the left superior temporal gyrus and medial frontal gyrus (Bellmund et al., 2022; Rekkas et al., 2005; St. Jacques et al., 2008). Regarding M/EEG activity, mental time travel has been associated with late parietal and frontal components (Colás-Blanco et al., 2022), which were associated with hippocampal oscillatory activity using depth electrodes (Schurr et al., 2018).

Mental time travel and future thinking are altered in several psychopathological and neuropathological conditions. In dementia, an overall impairment of memory's temporal structure has been reported (Liu et al., 2021a). Parallel deficits in episodic memory and future thinking have been identified in patients with Alzheimer's disease (Irish and Piolino, 2016; Addis et al., 2009), with reports of a fragmented sense of time (Shiromaru-Sugimoto et al., 2018). However, the investigation of mental time travel deficits in dementia has also revealed dissociations between past and future thinking. Altered mental time travel in both temporal directions has been reported in Alzheimer's disease and fronto-temporal dementia. In contrast, semantic dementia is associated with impaired future thinking abilities, while episodic autobiographical memory remains relatively intact (La Corte et al., 2021). This suggests a pivotal role of semantic memory in providing schemas and meaning to

Box 3
Mental time travel and episodic memory.

Remembering past events and simulating future events commonly engage regions of the default mode network, including the medial temporal lobes, midline cortical structure, and the temporal and inferior posterior parietal cortices (Benoit and Schacter, 2015) Together, these regions support a collection of distinct but interacting processes involved in episodic remembering and future thinking, including the retrieval of episodic details, their integration into a spatial scene, the use of semantic knowledge to create coherent event representations (La Corte and Piolino, 2016) and the recruitment of self-referential and goal processing to assess the personal meaning of represented events (Stawarczyk and D'Argembeau, 2015). Some of these regions (the left posterior inferior parietal lobe and posterior dorsolateral prefrontal cortex), as well as regions of the fronto-parietal control network, show increased activity during episodic future thinking compared with episodic memory, suggesting that the imagination of novel events requires greater constructive demands (e.g., novel recombination of episodic details; Benoit and Schacter, 2015).

construct a plausible scenario of personal events in the future (Lind and Bowler, 2010).

Altered mental time travel abilities have also been found in psychiatric conditions (for review, see Brunette and Schacter, 2021); Hallford et al., 2018). Depression has been associated with a reduced ability to represent specific events in both the personal past and future (Hallford et al., 2018). Individuals with schizophrenia also show difficulties with mental time travel (Zhou et al., 2018), as they use temporal landmarks and contextual details less frequently to locate events in time, and make more errors when determining the order of past and future events (Ben Malek et al., 2019). Autism has been associated with difficulties with diachronic thinking, and mental time travel, even after the control for other non-verbal and verbal abilities (Lind and Bowler, 2010; Boucher et al., 2007; Kunda and Goel, 2011).

Temporal mechanisms in memory may prevent individuals with PTSD from distancing themselves from the traumatic event, and lead to difficulties in imagining and pre-experiencing detailed future events (Zlomuzica et al., 2018) (but see Hallford et al., 2018). Indeed, imagined future events might appear as strongly negative, or related to the initial traumatic event (Brown et al., 2014). As a result, individuals with PTSD are more likely to attribute a central role to the traumatic event in their self-image, with this experience becoming a reference point in the organization of autobiographical knowledge and in the individuals' identity (Berntsen and Rubin, 2007). Furthermore, this traumatic "*temporal disintegration*" has been associated with a larger vulnerability to subsequent negative events (Grisham et al., 2022).

In summary, mental time travel is affected in neurological and psychiatric conditions notably characterized by difficulties with episodic and semantic memory, and alteration of the hippocampal and thalamic networks, while appearing to be preserved in other pathologies such as PD or ADHD. The inability to navigate between past personal events and to imagine future events could be associated with a loss of coherence and temporal structuring in memory. However, given the various forms future thinking can take (i.e., simulation, prediction, intention, and planning (Szpunar et al., 2014), important work remains to specify the nature of altered mental time travel processes across pathologies.

1.5. *Difficulties across temporal judgements*

Although most of previous work has been conducted on specific temporal judgements, evidence of both association and independence between temporal judgements has also been suggested. Felt passage of time and mental time travel abilities appear to be relatively independent (Kosak et al., 2019). Felt passage of time and duration processing are also independent initially in young children (4–5 years), before an association is observed in children of age 8–9 years (Martinelli and Droit-Volet, 2023), when children understand the logical relationship between, speed, duration and space, i.e., use correctly the metaphor of motion to judge differences in duration. Finally, association between mental time travel and retrospective duration estimations have been reported (El Haj et al., 2013).

While associations of performance across temporal judgements remain little studied and are not always observed, investigations of the underlying neural bases for each judgment type revealed common regions and brain rhythms between the different judgments. Both SMA and bilateral insula have been observed across duration and in rhythms tasks (Naghibi et al., 2023; Mondok and Wiener, 2023), between implicit and explicit tasks (Capizzi et al., 2023), and in felt passage of time (Wittmann, 2013). The temporal regions enabling duration processing have also been associated with mental time travel abilities (Tsao et al., 2022). Regarding neurotransmission, dopamine has also been associated with duration processing abilities (Mitchell, 2018), but not temporal order (Coull and Giersch, 2022). Finally, oscillatory activity in the alpha rhythm appears to be central for temporal processing (Kononowicz et al., 2018) and has been associated with both duration processing and temporal order. Further work should aim at further specifying the association and distinctions in the proposed taxonomy of temporal judgements.

This review article reveals that multiple conditions are associated with difficulties involving more than a single temporal judgement (Fig. 2), which may reflect common cognitive processes involved and altered neural circuits. First, an increased overall variability of time processing has frequently been reported in patients relative to healthy controls (Allman and Meck, 2012; Liu et al., 2021a), and could represent a sensitive marker of altered temporal representations. More specifically, temporal processing difficulties in schizophrenia and autism not only affect, as we have seen, order processing but also mental time travel abilities (Raffard et al., 2016). This could suggest that these two temporal judgements rely on integration across either perceptions or memories to form coherent temporal patterns (see also Kent et al., 2022). This integration may rely on widespread fronto-parietal and cortico-thalamic connectivity, that are reduced relative to controls in both schizophrenia and autism (Du et al., 2021).

Depression is associated with a slowing of the felt passage of time, together with underestimations and overproductions of short durations (Kent et al., 2019) and reduced specificity of mental time travel, while difficulties in processing order and simultaneity have not been reported. Although this should be further investigated, as lower working memory

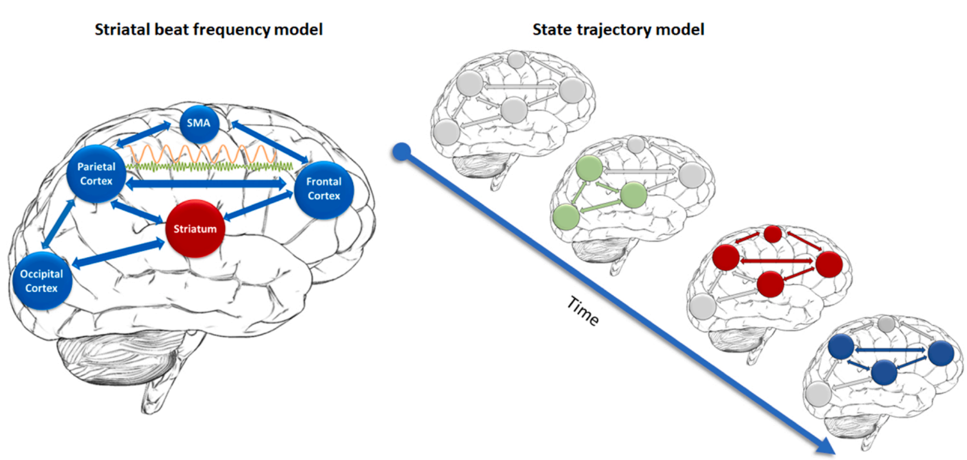

Fig. 3. : Summary of the striatal beat frequency and state-dependent models of time processing: In the striatal beat frequency model, a central timing mechanism in the striatum (red) generates temporal information based on the detection of neural synchrony across cortical regions in different frequency bands (orange and green); In the state-dependent model, durations are encoded in the dynamic evolution of network states without the need for a specific centralizing mechanism. SMA: Supplementary Motor Area. Pathological changes may result in desynchronized neural dynamics, or altered sequential neural activity.

and attention abilities may contribute to altered temporal performance (Mioni et al., 2016), changes associated with depression were interpreted as reflecting a slowing of duration processing, which could impact both temporal representations and sense of time flow. A similar association across judgements, with faster duration processing and time flow, has been reported in ADHD (Wilson et al., 2013). Representations of durations and felt passage of time abilities could involve fronto-limbic and fronto-striatal connectivity, which are altered in these conditions (Fang et al., 2012; Nikolaidis et al., 2022).

Importantly, dopaminergic deficits and altered nigro-striatal-prefrontal pathway have been reported in several pathologies associated with altered duration processing (depression, PD, ADHD, schizophrenia). Dopamine and basal ganglia activity have been associated with duration processing (Buhusi and Meck, 2005), together with attention and working memory performance (Klaus and Pennington, 2019). The effects of pathology on this neurotransmitter may therefore alter temporal judgements closely associated with these processes. The main temporal processing difficulties in each pathology could be differentiated on the basis of the involvement of cortico-thalamic connectivity (autism, schizophrenia), relative to fronto-striatal (ADHD, PD) or fronto-limbic (depression) pathways. Finally, impaired passage of time and mental time travel abilities in both PTSD and Alzheimer's disease have been interpreted as reflecting a "temporal disintegration" (Liu et al., 2021a; Grisham et al., 2022), a loss of the personal timeframe that is crucially related to longer durations and sense of self (El Haj and Kapogiannis, 2016). In contrast to the other pathologies discussed in this section, Alzheimer's disease and PTSD have been associated with cortico-hippocampal pathways, and other neurotransmitters such as norepinephrine, which could be consistent with qualitatively distinct processes involved.

Considerations of pathology-related time processing difficulties lead to questioning the neurotransmission underlying temporal aspects of cognition. In this respect, pharmacological modulations of dopamine, acetylcholine neurotransmitters have been associated with changes in time processing (Teixeira et al., 2013). While dopamine has been proposed to mediate the speed of temporal information encoding, acetylcholine appears to be involved in sequencing and temporal memory (Buhusi and Meck, 2005). For example, drugs that affect the dopaminergic system have been associated with altered timing performance and modifications of an individual's feeling of the passage of time (Mitchell, 2018), while cholinergic-related drugs have been associated with modulations of temporal order in memory (Teixeira et al., 2013; Chassignolle et al., 2021). More specifically, dopamine agonists have been associated with underestimation of durations, and antagonists with overestimation. This interplay, involving dopaminergic midbrain neurons and fronto-striatal cholinergic neurons appears to be central to the ability to encode durations and to track elapsed time (Martel and Apicella, 2021).

However, it is important to highlight that further investigations are necessary to clarify the association between temporal judgements and neurotransmission. Furthermore, while existing results suggest the presence of common temporal mechanisms across temporal judgements, pathological impairment of time processing remains seldom explored, and the reliability of the reported findings remains unclear. Further work remains necessary to investigate pathological impairments of time processing and their association with general cognition in the pathologies reviewed in this paper.

2. Discussion and future perspectives

In this article, we focused on pathological difficulties in time processing abilities to emphasize the need for a neuropsychological approach to time processing, across a growing body of neurological, and psychiatric work (Liu et al., 2021a; Kent et al., 2019). This approach remains in its infancy and has not yet been integrated into common clinical practice. This lack of integration could partly reflect the relatively recent nature of models of time perception and their behavioral validation (van Wassenhove et al., 2019), and that previous experimental research has mainly been focused on the psychophysical sense of time (i.e., time perception) in healthy individuals. Poor integration of neuropsychological and clinical practice could also stem from the elusive nature of time-related difficulties.

First and foremost, it is crucial, if we want to accurately identify the diversity of time processing difficulties, to assess the different temporal judgements in patients in order to successfully identify and understand the causes of time processing difficulties. The identification of disorders across temporal judgements, together with the distinction between explicit and implicit temporal performance, could also lead to the design of better tasks both for diagnosis and prognosis. In line with previous work on the "*unity and diversity*" of cognitive control processing (Friedman and Miyake, 2017), it could be considered that the temporal judgements reviewed here, although partly distinct, also share a common basis for specific processing steps, time scale, or context. Based on the difficulties reported in patients, it would seem to be critical to assess temporal processing in a more in-depth and detailed way than the temporo-spatial orientation included in general cognitive tests (e.g., the MOCA test; Nasreddine et al., 2005).

Our work also highlights that most temporal processing difficulties are closely intertwined with other cognitive abilities. Therefore, we emphasize that some well-documented difficulties encountered in the clinic and that were previously interpreted as planning, memory, or attention deficits could potentially be reconceptualized as reflecting time processing impairments. As an example, the reduced processing speed with depression could reflect altered temporal representations (Kent et al., 2022). Moreover, reduced temporal ordering abilities, and altered future projection capacities could underlie memory difficulties (Liu et al., 2021a). Important work remains to be conducted on the nature of the association between temporal judgements, and their neural bases, with other cognitive processes. This is especially true for the felt passage of time, on which findings are scarce.

In addition to the cross-pathology difficulties reported in each temporal judgements (see Fig. 2), time processing difficulties have also been reported in other pathologies such as traumatic brain injury (Mioni et al., 2014), alcohol abuse (Nuyens et al., 2021), and following stroke lesions (Marinho et al., 2019; Coelho et al., 2022). However, evidence on some of these conditions remains scarce, meaning that future work should be conducted to further document their temporal difficulties. Furthermore, other tasks and temporal judgements have not been addressed in our work. For example, temporal perspective, which refers to focus and valence relative to present, past, and future personal events (Zimbardo and Boyd, 1999), also shows impairments in various pathologies (Buzi et al., 2023). In addition, important differences exist between prospective and retrospective judgements, as a difficult task will for example be estimated as retrospectively longer than an easier short, but prospectively shorter, although individuals tended to overestimate the shortest intervals and to underestimate the longest intervals in both prospective and retrospective tasks (Balcı et al., 2023). At the neural level, these two forms of duration processing appear to rely on distinct neural bases (Tsao et al., 2022; Block and Zakay, 1997).

Investigations of pathological impairment of temporal processing has provided invaluable insights about the temporal structuring of cognition and its associated neural bases (Allman and Meck, 2012; Vatakis and Allman, 2015). Although the selected pathological conditions reviewed above contribute to this knowledge, we would like to emphasize here that taking into account temporal cognition in clinical contexts could benefit patients as well. Temporal judgments are carried out on a continuous basis and very often figure in daily life (e.g., temporal prediction, time management, expression of the feeling that time is passing slowly). 'Time' is an intuitive concept, directly related to daily life activities, and is not associated with stereotype threat (relative to other cognitive processes, such as memory, in which decreased competence and increased forgetfulness might be expected). In the case of poorly understood pathologies like schizophrenia or depression, measures of timing may help understanding patients' and clinicians reports of a temporally fragmented consciousness or a "never ending time", respectively. As proposed by Northoff (Northoff et al., 2023), it may help to reconcile subjective and neurobiological abnormalities in those pathologies. Moreover, investigating difficulties in temporal processing and targeting these processes through interventions could provide a new entry point to provide help, and to prevent relapses, in several conditions. Such an approach could indeed lead to new remediation to enhance adaptive behaviors, such as delaying immediate gratification and care-related planning. Altered time processing may also serve as a marker for the early identification of disorders, as these deficits can be considered as important neuropsychological manifestations of the conditions reviewed here. Measures could also help with clarifying inter-individual heterogeneity in cognitive difficulties. Important work remains to specify the prognostic and diagnostic values of these measures, together with the most effective remediation and intervention approaches. In line with recent work on rhythm processing (Dalla Bella et al., 2017), a unified assessment using a single battery could help in reaching these goals.

This review also paves the way to new neuropsychological interventions that could target temporal judgements and aim at enhancing cognitive performance. Virtual reality can causally influence the subjective feeling of time passing, and enable the assessment of time processing abilities in ecological situations (Rutrecht et al., 2021). Communication-focused therapies have also been proposed to increase parent-child synchrony (Green et al., 2010) in children with autism. Moreover, mindfulness meditation has been associated with faster felt passage of time and increased precision of temporal representations (Droit-Volet et al., 2019, 2015; Schötz et al., 2016; Thönes and Wittmann, 2016), which suggest it could be promoted in a variety of clinical situations. Finally, music could entrain and enhance brain rhythms of time processing (Lakatos et al., 2019). Musicians were found to outperform non-musicians in temporal tasks by showing higher temporal sensitivity for small temporal differences between stimuli, and showing a smaller variability in temporal estimates (Vibell et al., 2021), in line with the potential long-term effects on the encoding and retrieval of temporal representation (Rammsayer and Altenmüller, 2006).

3. Conclusion

Several questions on time processing remain open, as for example how the distinction between explicit and implicit performance could further our knowledge about pathological impairments. The proposed transdiagnostic taxonomy of time processing has the potential to further our understanding of both individual variability and differences across conditions. This taxonomy remains nevertheless limited, because there are few systematic studies of time judgment difficulties and the associated neural circuits across pathologies, although the number of studies and meta-analyses has increased these last years. Progressing towards a neuropsychology of time processing is thus critical for our understanding of temporal difficulties in clinical conditions for different types of temporal judgments and at different time scales.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

No data was used for the research described in the article.

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