Epilepsy & Behavior 168 (2025) 110358

Contents lists available at ScienceDirect

Epilepsy & Behavior

journal homepage: www.elsevier.com/locate/yebeh

Research Paper

Explicit and implicit timing in mesial temporal lobe epilepsy patients

Annika Hellweg [a], Michael Schwarz [b], Katrin Walther [b], Hajo Hamer [b], Antonino Visalli [a,*], Giovanna Mioni [a,*]

[a] Department of General Psychology, University of Padova, Italy
[b] Department of Neurology, Epilepsy Center Erlangen, University Hospital Erlangen, Germany

ARTICLE INFO

Keywords:
Explicit timing
Time bisection task
Implicit timing
Foreperiod task
Epilepsy

ABSTRACT

Objectives: The present study investigates the explicit and implicit timing abilities of patients with mesial temporal lobe epilepsy (MTLE). Based on previous studies, it was hypothesized that timing abilities were decreased in MTLE patients.

Methods: The performance of 21 MTLE patients and 21 neurologically healthy probands was tested on two separate tasks. The time bisection task was used to investigate explicit timing and the foreperiod task to test implicit timing.

Results: For the time bisection task, less precise temporal judgements were found in the patient group compared to the control group. This was indicated by a flatter psychophysical curve in the patients compared to controls. Moreover, participants did not differ in term of precision, but patients were more variable than controls. There was no statistical difference between the performance of the control and the patient group in the implicit timing task. Both groups demonstrated the foreperiod effect, meaning that the RTs of the participants became shorter with longer durations.

Conclusions: MTLE patients showed less precise temporal judgments in explicit timing, while their implicit timing was largely preserved. This finding suggests that explicit time perception should be routinely investigated in MTLE patients.

1. Introduction

The internal perception of how quickly time is progressing or how much time has passed since an event occurred is known as subjective or psychological time[35]. It has been demonstrated that the capacity to gauge objective time is largely stable, only changing in the presence of severe mental problems, brain disease, or pharmacological side effects [34,44]. Given that timing ability is a sensitive measure of information processing and that temporal perception can impact various cognitive processes, it is postulated that interval timing is a reliable construct to examine cognitive dysfunctions after brain damage[38,47].

A critical distinction is made between mechanisms involved in tasks during which the aim is to consciously provide an approximation of time passed (*explicit timing*) and tasks for which the aim is non-temporal but can be aided by a presumably incidental temporal context (*implicit timing*; [17]. One example of an explicit temporal task is the *time bisection task*,[1] in which a long standard interval and a short standard interval are shown to the subjects, who then are instructed to judge whether a presented interval was more similar to the long or the short standard interval[29]. The *foreperiod paradigm* provides a classic illustration of an implicit timing task[41]. In such a task, participants must react to a stimulus presented after a warning signal. Depending on the duration of the foreperiod between the warning and the target signal, the participants' response times (RTs) might change. When the short and long foreperiods are not presented in blocks but are randomly intermixed, the RTs are shorter for the long foreperiod trials, which is called *variable foreperiod effect* [41]. This effect is related to the hazard function: as the foreperiod increases, the probability that the target will appear, given that it has not occurred yet, also increases[26,27,59], Visalli et al. [60], Visalli et al. [61]. This temporal expectancy allows participants to prepare their responses more effectively for longer foreperiods, resulting in faster RTs.

These two systems have been investigated separately for a long time but recently researchers have become interested in looking for

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* Corresponding authors at: Department of General Psychology, University of Padova, Via Venezia, 8, 35121 Padova, Italy (G. Mioni and A. Visalli).

[1] We have selected time bisection task to tap explicit timing and the foreperiod task to tap implicit timing, the reader interested in other tasks used to investigate explicit and implicit timing can refer to Vatakis et al. [57].

https://doi.org/10.1016/j.yebeh.2025.110358
Received 20 August 2024; Received in revised form 26 February 2025; Accepted 26 February 2025

similarities and differences between these processes. Overall previous studies (for Parkinson's disease patients: [39]; for healthy adults: [21,62]; adults with cognitive decline: [14] seem to demonstrated that explicit and implicit timing follow distinct trajectories (Coul & Nobre, 2008) with implicit timing being independent of age and/or pathology while temporal variability in explicit timing tasks increase as a function of age and/or pathology. An explanation for these trajectories might be that implicit timing abilities are derived from automatic processes which do not depend on age and the maturation of cognitive abilities[50]. In contrast, explicit timing abilities improve with age because they partially depend on executive functions, which mature with the development of cognitive capacity[20].

Considerable controversy, however, remains on how the brain measures time with some theories positing the existence of dedicated timing networks hosting an internal "clock" (Merchant, Harrington, Meck, 2013; Grondin, 2010; Buhusi & [35], and others arguing for the distribution of timing across neural circuits (Paton & Buonomano, 2018). The mesial temporal lobe (MTL) is a crucial brain area for time perception[64]. Specifically, the hippocampus plays an important role in the cortico-striatal circuitry involved in interval timing[24,25,43]. A competitive interaction was found between hippocampal and striatal areas, which led to the conclusion that if one system was damaged, the other system was facilitated[49]. This effect might be due to the direct projections from the dorsal striatum to the MTL, which have been linked to interval timing[32,35]. In an animal study using single-cell recordings, researchers found that specific cells in the hippocampus, called "time cells", have distinct firing patterns depending on the point in time an event occurred in a sequence[31]. Furthermore, a fMRI study by Sherman et al. [52] found that longer duration judgements were associated with greater temporal pattern change in the MTL, specifically the left hippocampus. The authors postulate that this pattern is associated with subjective duration judgements.

Most of the studies investigating temporal abilities in epileptic patients have investigated explicit time processing but using different temporal tasks, temporal ranges and modalities. Vidalaki et al. [58] reported that patients with right MTL resection were more variable in reproducing long durations (see [46] for no difference between groups using time reproduction task), moreover, the same authors reported temporal overestimation only in left MTL patients compared to right MTL and controls when tested with a time bisection task and short intervals (1–2 s). However, Melgire and colleagues (2005) using the time bisection task and short temporal intervals (50——200 ms) reported only higher temporal variability in right MTL patients compared to left MTL patients and controls but no variation in perceived duration between groups. Finally, Noulhiane et al. [42] used a verbal estimation and a time production tasks with intervals in the minutes range (1–8 min) and showed that patients with left MTL lesions overestimated time in the verbal estimation and production tasks, whereas patients with right MTL lesions were only impaired in the production task.

Implicit time was less investigated and as far as we know, no previous studies have been conducted using a foreperiod paradigm. Ehrlé et al. [23] tested epileptic patients with an anisochrony discrimination task to assess temporal processing of sequential auditory information according to different presentation rates or tempos (between 80 and 1000 ms). Anisochrony discrimination thresholds for the 80 ms tempo were significantly higher for the patients with left than for right MTL and controls. Suggesting the role of left-hemisphere in processing rapid sequential auditory information. Schapiro et al. [51] in a single case fMRI study (patient reporting bilateral destruction of the hippocampus, bilateral damage to other MTL regions, and left anterior temporal lobe damage) highlighted the importance of the MTL in extracting temporal regularities. Recently, Aljishi et al. [1] showed that the ability to make predictions and learn the regularity and structure of the environment (statistical learning) was impaired in patients (temporal lobe epilepsy and extratemporal lobe epilepsy patients) with poorly controlled epilepsy irrespective of where their seizures originated.

The current study aims to examine the explicit and implicit timing abilities in patients with epilepsy. Patients from the Epilepsy Center Erlangen and neurologically healthy participants were examined using a foreperiod task as an implicit measure and a time bisection task as an explicit measure of timing abilities. We predict lower temporal abilities and higher variability in epileptic patients compared to controls considering the involvement of these areas in explicit timing[36,58]. Regarding implicit timing we can expect similar abilities in patients and controls considering that implicit timing relies on more automatic processes and that implicit time seems to be preserved even in very compromised patients[14,39].

2. Materials and Methods

2.1. Participants and procedure

Twenty-one patients with epilepsy were tested but one patient was excluded because the age was $>$ 65 years old and two were excluded because their age was $<$ 20 years old.[2] The final sample was composed of 18 patients with therapy refractory temporal lobe epilepsy and 18 controls (Table 1; see Appendix A). The patient group was recruited and tested in the Epilepsy Centre Erlangen while the control group was tested at home (Table 1). Patients with clear epileptic focus in the medial temporal lobe due to hippocampal pathology were included in the study based on the medical records (e.g. EEG, MRI data). There were six patients with right temporal lobe epilepsy, eleven with left temporal lobe epilepsy and four with bilateral temporal lobe epilepsy. Two of the patients were not on antiepileptic drug (AED) therapy, 19 were tested on medication.

We tested 21 healthy volunteers, 3 were excluded because the age was $>$ 65 years old. The final sample was composed of 18 patients, demographic information is reported on Table 1. The control subjects had no history of psychiatric or neurological disorders. Subjects were individually tested and seated in front of a computer screen (14″) with an approximate distance of 60 cm. The computer was used to run and re-

Table 1
Demographic variables and descriptive statistics.

Variables	**Control Group N = 18 (13 female, 5 male)**		**Patients with epilepsy N = 18 (7 female, 11 male)**		***t*-Tests**	
	Mean	SD	Mean	SD	*t*	*p*
Age (years)	44.28	14.49	39.78	15.18	0.91	0.369
Years of education	11.44	0.922	10.12	1.65	2.95	0.006
BDI			13.33	10.38		
IQ	117.0	12.66	103.5	12.65	3.20	0.003
Handness	92.83	14.16	45.11	71.28	2.79	0.009
BAT (*Free Recall*)	16.50	2.66	11.39	3.29	5.12	<0.001
BAT (*Semantic Interference*)	28.72	1.90	26.50	2.55	2.96	0.006
BAT (*Digit Span*)	6.78	0.94	6.78	1.31	0.00	1.00
BNT (Mistake)	2.56	1.95	10.94	10.99	−3.19	0.003
RWT	46.44	14.19	30.17	9.25	4.08	<0.001
TKS	11.88	1.90	11.11	2.55	0.99	0.328

Note: BDI = Beck Depression Inventory; IQ = verbal IQ tested with the Mehrfachwahl Wortschatz Intelligenztest; Handedness = Edinburgh Handedness Inventory; BAT = Berliner Amnesie Test; BNT = Boston Naming Test; RWT = Regensburger Wortflüssigkeitstest; TKS = Test zum kognitiven Schätzen.

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[2] We excluded participants based on age; to have homogeneous groups we excluded participants older than 65 and younger than 20. Participants older than 65 were also exclude to reduce possible sign of cognitive decline.

cord the experimental events via Psychopy Software[45]. The foreperiod task was first performed and second, the time bisection task. Taken together, the examination lasted about one hour, depending on the participants' performance. The study was approved by the Ethical committee of the Friedrich-Alexander-Universität Erlangen-Nürnberg (Request number: 23–12-B).

2.2. Neuropsychological and cognitive examination

Mehrfachwahl Wortschatz Intelligenztest (MWT-B; Lehrl, 1999**)**. The MWT-B assesses level of verbal intelligence. Participants are asked to underline existing words, ignoring the pseudo-words (e.g. "Nale – Sahe – Nase – Nesa – Sehna"). The test includes 37 items and the IQ is calculated based on the number of correctly identified words. A number of 27 correctly identified words equals an average IQ of 100.

Berliner Amnesie Test (BAT; [37]: The BAT is used for people aged 13 to 65 to assess learning ability and possible anterograde amnesia. The test lasts 45 to 60 min and is divided into eight sub-tests designed to assess mild to severe mnestic deficits. Both figural-spatial and verbal memory performance are measured. For this study, three verbal memory subtests were performed: Free Recall, Semantic Interference and Digit-Span. The *Free Recall* subtest assessed the number of words recalled from a previously learned list of 20 words; score below 12 indicates a performance below average The *Semantic Interference* subtest required to identify 15 previously learned words in a semantic context; score below 26 indicates a performance below average. The *Digit-Span* subtest assessed the participants' short-term memory. Specifically, the instructor read a three-digit-span and the participant had to repeat it correctly. If the current digit-span was recalled successfully, another digit would be added to the next digit-span.

Boston Naming Test (BNT; [28]. The test consists of 60 lines drawings of graded difficulty (from "bed" to "abacus") and takes 10 to 20 min to complete. Within a time frame of 20 s, the participants were required to name the objects correctly[53]. More than 12 mistakes indicated impaired naming abilities.

Regensburger Wortflüssigkeits test (RWT; [3]. The RWT assesses verbal fluency functions. In this study, we used a semantic fluency paradigm where the participants were required to state as many animals as possible within two minutes.

Test zum kognitiven Schätzen (TKS; [9]. The TKS assesses estimation of sixteen pictures depicting physical properties, which is supported by executive functions and semantic knowledge. Specifically, the participants of this study were asked to rate the size, weight, and number of objects shown in photographs. Raw score below 11 indicates a performance below average.

2.3. Timing tasks

The explicit and implicit timing tasks comprised the same stimulus material and general procedure but differed in the specific task instructions given to participants. For both tasks, stimuli consisted of a grey circle and a grey cross presented at the centre of a lighter grey background screen. A thin circle was initially displayed for 500 ms (Inter-Trial-Interval, ITI), followed by a thicker circle that could assume one of the following interval durations: 480, 720, 960, 1200, 1440, 1680, or 1920 ms. After the duration had elapsed, a cross appeared in the centre of the circle for 500 ms. For the explicit timing task, the experimental session started with a training phase, in which participants were instructed to memorize two standard durations: 480 (short standard) and 1920 ms (long standard), each presented 10 times. During a subsequent testing phase, participants had to indicate whether the temporal interval elapsing from the onset of the thicker circle to the onset of the cross was closer in duration to the previously memorized "short standard" or "long standard". Responses were given by pressing two response keys ("S" and "L" on the computer keyboard). In the implicit timing task, participants were instructed to press the spacebar as fast as possible whenever the cross appeared inside the thicker circle. For both explicit and implicit timing tasks, no information about stimulus durations was given to participants. The experiment consisted of a total of 6 blocks (3 blocks for each timing task) of 42 trials each (6 repetitions for each temporal interval).

2.4. Analysis of the explicit timing task

A similar analytical approach was used for statistical inference in the two tasks using mixed-effects models[15]conducted in R (https://www.R-project.org/) through the lme4 library[5]. For explicit timing task, analyses were performed using generalized linear mixed-effects models (GLMM). The probability of "long" responses was modelled through GLMMs with a probit link function (probit regression). A main model of interest was defined to include interval duration (Dur) (centered and scaled using Z-score to improve the fit of the model and the interpretation of the variable), Group (two-level factor: Controls = 0, MTLE patients = 1), and their interaction as fixed effects, and by-participants random intercepts and slopes for Dur. To control for possible confounding variables (namely: Age, Education, and the scores from the Neuropsychological and Cognitive Examination), the main model was compared using likelihood ratio tests with additional models, each adding to the main model a confounding variable and its interaction with Dur. All these variables were transformed in rank values and z-scored.

In addition to the GLMM analysis, we also computed more conventional psychometric indexes[6]such as the participants' Bisection Points (BPs, also known as the point of subjective equality) and the Just Noticeable Difference (JNDs) and compared them between the two groups using Welch two sample t-tests. BPs and JNDSs were reconstructed from a GLMM including only Dur as both fixed- and random-slope effects (for details, see [62]). The BP represents the stimulus duration that is equally likely to be classified as short or long, reflecting the accuracy of temporal judgments. It corresponds to the point on the psychometric function where the probability of a "long" response is 0.5. The JND, on the other hand, is a measure of precision in temporal driscimination tasks ([29]; see also: [2,4,10,40,48]). It represents the difference between the durations corresponding to the 84th and 50th percentiles of the probit psychometric curve (i.e., one standard deviation of the normal distribution). A larger JND indicates greater variability in temporal judgments, while a smaller JND suggests more precise judgments.

2.5. Analysis of the implicit timing task

Analyses of RTs were performed by means of linear mixed-effects models (LMM). Data from trials with missing or anticipated responses ($RT < 150$ ms) were excluded from analyses. Analyses were performed on the inverse-transformed RTs (iRT), computed as $-1000/RT$ to control for the impact of positive skewness in the distribution of RTs[62]. As for the explicit timing task, we defined a main model of interest including Dur, Group, and their interaction as fixed effects, and by-participants random intercepts and slope for Dur. To assess whether there was evidence of stress in the model fit, we inspected the model residuals and, following Baayen and Milin (2010), trials with absolute standardized residuals higher than 2.5 SD were considered outliers and removed. After outlier removal, the LMM was refitted. Finally, confounding variables were assessed as described above.

3. Results

3.1. Explicit timing task

The likelihood ratio tests showed that the inclusion of none of the possible confounders was justified (see Supplementary Table 1). Results of the main GLMM are reported in Table 2. The main effect of Group was

Table 2

GLMM results of the explicit timing task.

Predictors	Risk ratio	C.I	P
(Intercept)	1.19	0.88 – 1.60	0.265
Dur	**5.45**	**4.23 – 7.02**	**<0.001**
Group [MTLE Patients]	1.02	0.67 – 1.56	0.910
Dur × Group [MTLE Patients]	**0.59**	**0.42 – 0.84**	**0.003**

Notes: Dur, interval duration; C.I., confidence intervals.

not significant (p = 0.910), indicating that the two groups did not significantly differ in the probability of “Long” responses to the intermediate duration. However, the interaction between Group and Dur was significant ($p = 0.003$). As shown in Fig. 1, the shape of the psychometric curve of epileptic patients was flatter compared to the control group. This pattern of results was confirmed by the analyses on BP and JND scores. Specifically, BP scores did not significantly differ between groups (patients’ BP mean: −0.12 (SD = 0.44), controls’ BP mean: −0.08 (SD = 0.37), t(32.99) = -0.29, p = 0.775). However the two groups significantly differ in JND scores (patients’ JND mean: 1.00 (SD = 0.48), controls’ JND mean: 0.66 (SD = 0.37), t(21.77) = 2.88, p = 0.008). Concerning the possible confounding variables, model comparison analysis (Supplementary Table 1) showed that the inclusion of none of the possible confounders was justified. This suggests that these variables did not significantly impact performance in the explicit timing task.

3.2. Implicit timing task

The results of the LMM on iRT are presented in Table 3. We found a significant effect of Dur ($p < 0.001$) indexing the classically observed FP effect. Although Fig. 2 seems to suggest that the group of MTLE patients was generally slower, this difference was not significant (Group main effect: $p = 0.097$). The interaction between Group and Dur was also not significant ($p = 0.866$), indicating that the FP effect did not significantly differ across groups. Concerning the possible confounding variables (Supplementary Table 2), the only significant likelihood ratio tests were for Age ($p = 0.003$), BAT (Free Recall) ($p = 0.047$), and BNT ($p = 0.048$). The results of these three additional models are presented in Supplementary Tables 3-5. Concerning the model including Age, we found a significant simple effect of Age (t(33.004) = 2.723, p = 0.010), in line with previous findings[15,62], as well as a significant main effect of Group (t(33.003) = 2.181, p = 0.036). The model including BAT (Free Recall), revealed a significant simple effect of BAT (Free Recall) (t(33.000) = -2.299, $p = 0.028$). Finally, the model including BNT showed a significant interaction between BNT and Dur (t(31.874) = 2.372, p = 0.024), with smaller FP effects with increased BNT score.

Table 3

LMM results of the implicit timing task.

Predictors	Estimates	S.E.	*t*	*p*	d.f.
(Intercept)	−3.163	0.091	−34.866	0<.001	34.002
Dur	**−0.23**	**0.024**	**−9.621**	**<0.001**	33.857
Group [MTLE Patients]	0.219	0.128	1.705	0.097	34.008
Dur × Group [MTLE Patients]	−0.006	0.034	−0.171	0.866	33.968

Notes: Dur, interval duration; S.E., standard errors; d.f. Satterthwaite’s approximation of degrees of freedom.

4. Discussion

Epilepsy is one of the most prevalent neurological disorders[18] and can greatly lower an individual’s quality of life due to adverse treatment effects as well as adverse cognitive, neurological, psychological and social consequences[8]. The most prevalent form of partial epilepsies is mesial temporal lobe epilepsy (MTLE), which is often caused by hippocampal sclerosis. Previous studies have highlighted the importance of MTL in time perception in particular when explicit temporal judgments were required. However, time in not always explicitly processes and various activities are possible because we are able to use time implicitly. However, as far as we know, no studies have been conducted using implicit paradigms in epileptic patients, more important the two timing processes (implicit and explicit) have never been investigated using a within subjects design in epileptic patients.

Although the two groups had a similar age and gender, patients’ IQ was lower compared to controls. The patient group had also lower scores regarding memory (Free Recall), linguistic measures (naming) and executive functions (word fluency). Indeed, mesial temporal lobe epilepsy is known to significantly affect cognitive abilities, particularly memory, attention, and executive functions[30]. Memory impairments are commonly observed, with both short-term and long-term memory often compromised[16,43]. Attention deficits are also prevalent as epileptic networks are thought to interfere with attentional pathways, which might lead to difficulties sustaining focus or processing information efficiently[12]. Additionally, executive functions, which include problem-solving, planning, and organizing, are frequently affected, leading to challenges in daily functioning[11]. One study examining patients with childhood absence epilepsy (CAE) found that poor executive functioning was associated with decreased temporal sensitivity, reflected by temporal underestimation and high temporal variability in the time bisection task[13]. The authors reason that there is an overlap of neural substrates (i.e. the frontostriatal system) involved in both time perception and cognitive abilities that are compromised in CAE[13].

Regarding explicit time, our results are in line with previous studies

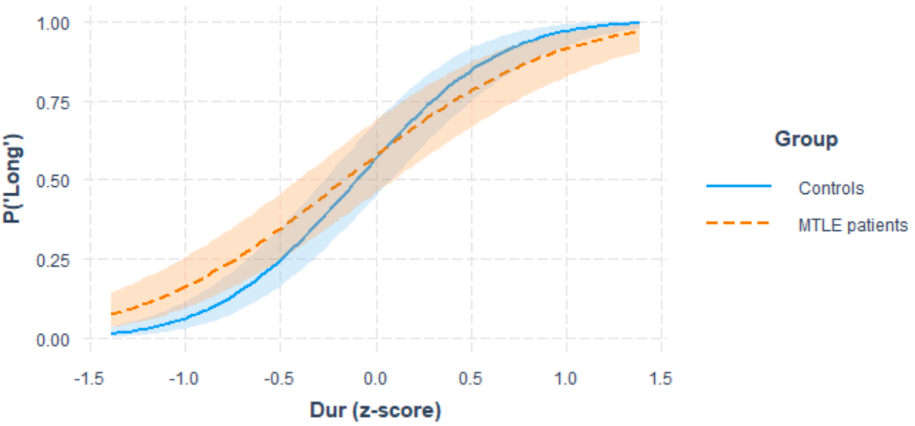

Fig. 1. Interaction plot of the effects of interval duration (Dur) and Group in the explicit timing task. The figure shows between-group differences in the psychometric curve. Shaded error bars indicate Confidence Intervals.

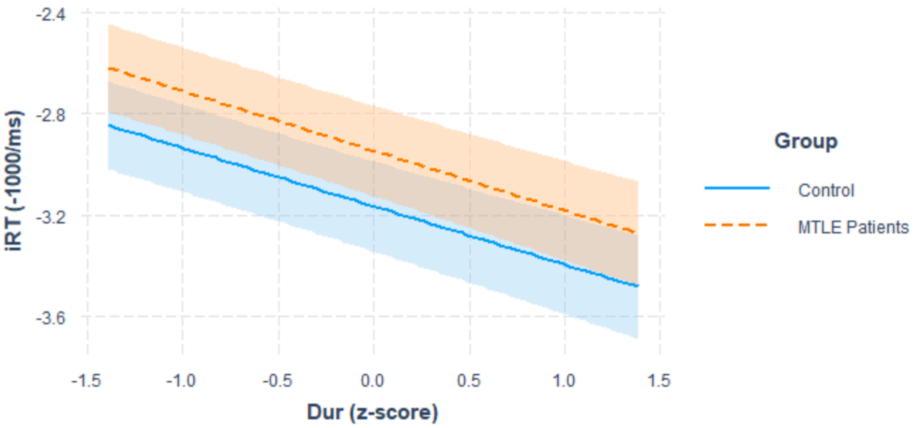

Fig. 2. Interaction plot of the effects of interval duration (Dur) and Group in the implicit timing task. The figure shows the conditional effect of Dur on iRTs across groups. Shaded error bars indicate Confidence Intervals.

reporting lower temporal abilities in epileptic patients[19,42,36,46,58]. Epileptic patients showed a flatter psychometric curve and higher temporal variability compared to controls; a sign of compromised cognitive function recruited to perform the time bisection task rather than a specific temporal impairment. The absence of evidence for a systematic over- or under-estimation bias in the time bisection task, aligns with previous studies on time bisection in both healthy [63]and pathological samples[14,62]. One possible interpretation of the flatter psychometric curve in epileptic patients is that patients had a noisier memory representation of standard durations, leading them to respond “short” to long durations and “long” to short durations. This interpretation is supported by evidence showing that similar anatomical structures underlie memory and timing functions (Lusting et al., 2005; [33]. Furthermore, memory’s role in the performance of the time bisection task is acknowledged within pacemaker-based models of time perceptionÜstün et al. [56]. Within such models, a poor memory representation of the standards would result in a flatter psychometric curve. Moreover, the WR of the patient group was higher than that of the control group, reflecting lower temporal sensitivity in epileptic patients. As explicit timing abilities pose higher cognitive demands, it was expected that epilepsy patients with MTL alterations would demonstrate a worse performance than healthy controls. In line with those results, previous studies found that TLE patients with a right-hemisphere focus displayed lower temporal sensitivity in the time bisection task than the controls[36,58]. Overall, findings from the explicit time bisection task suggest that the deficit in epileptic participants is at the level of cognitive functions rather than temporal processing, as evidenced by the flattening of the psychometric curve lack of significant under- or overestimation of interval durations (no effect of group on BP). Recently, DuBrow et al., [22] strength this conclusion showing that performance on the temporal perception task significantly predicted performance on the temporal distance task; specifically, the authors showed that damage to MTL may not directly impact timing mechanisms per se, rather, it appears to affect the interplay between timing and memory systems that are crucial for making temporal judgments over extended periods.

Regarding implicit timing, we observed no difference between groups, all participants exhibited the classical foreperiod effect, i.e., faster reaction time as the duration between the cue and target increases. In contrast to the explicit timing task, the goal of the implicit timing task was non-temporal in the sense, that participants only needed to respond to the onset of the target without memorizing or explicitly judging the interval duration between the cue and the target. Due to the nature of the instructions and the task goal, implicit timing is thought to place fewer demands on cognitive processes compared to explicit timing [17,41]. To our knowledge, no study has investigated the foreperiod effect in epileptic patients yet. Another paradigm designed to measure incidental encoding of temporal regularities has shown that controls could discriminate novel recombination from the temporal regularities while the MTL patient was not[51]. Instead, the present study could not confirm the involvement of the MTL in subconsciously extracting temporal regularities, as the foreperiod effect was preserved in the MTLE patients. In line with that, it has been reported that patients with Parkinson’s disease showed spared implicit timing in the presence of impaired explicit timing[39]. Likewise, Bégel et al. [7] found that subjects with “beat deafness” had difficulties with explicit rhythm but not implicit rhythm tasks. Also, patients with right frontal damage were impaired in deliberate attentional orientation to durations but performed normally when implicit rhythmic patterns were involved [55], Triviño et al. [54]. Recently, Visalli et al. [62] also showed that as age increased participants had larger RTs but implicit timing was not significantly affected by age, as indicated by a consistent foreperiod effect across ages. Taken together with the results of this paper, it is suggested that explicit and implicit timing abilities are distinct processes, and that implicit timing is a more stable function not heavily influenced by brain damage or neurological diseases.

5. Limitations and Strengths

Firstly, the IQ, education and neuropsychological test scores were significantly higher in the control group than in the patient group. As cognitive control processes were hypothesized to impact explicit temporal judgement[14], the patient group possibly displayed a lower temporal sensitivity because they had a lower IQ, education level and cognitive abilities.

Second, the patient group was heterogeneous concerning the etiology of epilepsy, the scope of brain damage, years of illness and age. Some patients had structural alterations of the hippocampus, while others had alterations outside the MTL as well. Also, the number of years suffering from the disease and the age differ between patients. Considering the small sample size, those differences between the patients created a highly heterogeneous sample. Moreover, no distinction was made between patients with left-, right- or bilateral alterations in the statistical analysis. Previous studies have pointed out the lateralization of time perception and future studies should increase the sample size to analyze the patients according to the lateralization of structural alterations and epileptic focus. Nevertheless, this study adds to the literature because it was the first to examine implicit time perception utilizing the foreperiod paradigm in epileptic patients, as well as it is the first to investigate explicit and implicit timing within the same participant. In doing so, this study contributes to the discussion about the differentiation of explicit and implicit time perception. Future work could also better isolate the exact role of the MTL by including an additional group of epilepsy patients with epileptic focus localized in other temporal or extratemporal brain regions.

6. Conclusion

Explicit and implicit timing abilities influence behavior and underly daily decision-making and planning. Explicit timing is the deliberate estimation of a time period, while implicit timing describes the unconscious processing of temporal information. This study revealed explicit time alteration and preserved implicit timing in patients. Overall, there was a larger difference between patients and controls in explicit timing abilities than in implicit timing abilities. Patients showed lower temporal sensitivity in explicit timing, while their foreperiod effect in the implicit timing task was largely preserved. This study was the first to explore implicit timing in epileptic patients.

Authors' contributions

AH, GM and MS conceptualized the study; AH, MS, KW, HH, and GM cured the Data; AV, and GM analyzed the Data; MS and GM were responsible for the Investigation; AH, MS, KW, HH, AV, and GM cured the methodology; AH, AV, and GM was responsible for the Resource and Software; MS KW, HH, and GM supervised the work; AH, MS, and GM wrote the original manuscript; all the authors reviewed and edited the manuscript.

Ethics approval and consent to participate: Written informed consent was collected from all participants, and the study was conducted in accordance with the Helsinki Declaration. The study was approved by the Ethical committee of the Friedrich-Alexander-Universität Erlangen-Nürnberg (Request number: 23–12-B).

CRediT authorship contribution statement

Annika Hellweg: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Michael Schwarz:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Data curation. **Katrin Walther:** Writing – review & editing, Writing – original draft, Supervision. **Hajo Hamer:** Writing – review & editing, Writing – original draft, Supervision. **Antonino Visalli:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Giovanna Mioni:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

Acknowledgements

We are deeply grateful to all participants.

Appendix

Appendix A

Demographic Characteristics of MTLE Patients.

Patients	Age (year)	Education (year)	Handness	Aetiology	Length of Illness (years)	Antiepileptic Drugs	Side
P01	34	10	100	HS	11	Brivaracetam, Lacosamid	Bilateral
P03	66	12	82	Cavernom	1	Lamotrigin	Left
P04	55	12	60	HS	55	Levetiracetam, Perampanel	Bilateral
P05	28	12	89	Meningocele, EA	6	Valproat	Bilateral
P06	27	10	100	HS	1	No AED therapy	Left
P07	20	12	−73	Ischemia	9	Lamotrigin, Oxcarbazepin	Left
P08	30	8	60	EA	1	Lamotrigin, Levetiracetam	Left
P09	54	8	100	HS, MTL resection	17	No AED therapy	Left
P10	27	10	50	HS	2	Lamotrigin, Perampanel	Right
P11	24	12	−89	Lesion	7	Lamotrigin	Right
P12	60	10	20	TBI	8	Lamotrigin, Brivaracetam	Left
P13	61	8	80	HS	50	Brivaracetam, Valproat, Pregabalin, Clobazam	Left
P14	48	10	100	HS	31	Lamotrigin, Lacosamid	Left
P15	30	8	−100	HS	12	Levetiracetam, Oxcarbazepin	Right
P16	43	10	−47	Heterotopia	3	Lamotrigin; Levetiracetam	Bilateral
P17	24		100	HSV-Encephalitis	1	Levetiracetam, Lacosamid	Left
P20	31	8	80	HS, MTL resection	31	Lacosamid	Left
P21	54	12	100	HS, aTL resection	52	Brivaracetam, Cenobamat, Quetiapine, Bisoprolol	Right

Note. HS: hippocampal Sclerosis; EA: enlarged amygdala; MTL resection: mesial temporal lobe resection; TBI: traumatic brain injury; HSV: Herpes simplex virus; aTL: anterior temporal lobe; Handness scores of 100 indicate right-handedness and scores of −100 indicate left-handedness.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yebeh.2025.110358.

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