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Reward-based decision-making in mesial temporal lobe epilepsy patients with unilateral hippocampal sclerosis pre- and post-surgery

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ABSTRACT

Background: Correct functioning of the reward processing system is critical for optimizing decision-making as well as preventing the development of addictions and/or neuropsychiatric symptoms such as depression, apathy, and anhedonia. Consequently, patients with mesial temporal lobe epilepsy due to unilateral hippocampal sclerosis (mTLE-UHS) represent an excellent opportunity to study the brain networks involved in this system.
Objective: The aim of the current study was to evaluate decision-making and the electrophysiological correlates of feedback processing in a sample of mTLE-UHS patients, compared to healthy controls. In addition, we assessed the impact of mesial temporal lobe surgical resection on these processes, as well as general, neuropsychological functioning.
Method: 17 mTLE-UHS patients and 17 matched healthy controls completed: [1] a computerized version of the Game of Dice Task, [2] a Standard Iowa Gambling Task, and [3] a modified ERP version of a probabilistic gambling task coupled with multichannel electroencephalography. Neuropsychological scores were also obtained both pre- and post-surgery.
Results: Behavioral analyses showed a pattern of increased risk for the mTLE-UHS group in decision-making under ambiguity compared to the control group. A decrease in the amplitude of the Feedback Related Negativity (FRN), a weaker effect of valence on delta power, and a general reduction of delta and theta power in the mTLE-UHS group, as compared to the control group, were also found. The beta-gamma activity associated with the delivery of positive reward was similar in both groups. Behavioral performance and electrophysiological measures did not worsen post-surgery.
Conclusions: Patients with mTLE-UHS showed impairments in decision-making under ambiguity, particularly when they had to make decisions based on the outcomes of their choices, but not in decision-making under risk. No group differences were observed in decision-making when feedbacks were random. These results might be explained by the abnormal feedback processing seen in the EEG activity of patients with mTLE-UHS, and by concomitant impairments in working memory, and memory. These impairments may be linked to the disruption

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of mesial temporal lobe networks. Finally, feedback processing and decision-making under ambiguity were already affected in mTLE-UHS patients pre-surgery and did not show evidence of clear worsening post-surgery.

1. Introduction

On a daily basis, the average person makes over 35,000 decisions, based on the costs and benefits associated to their actions. Both positive and negative outcomes serve to guide and reinforce future behavior according to internal monitoring processes, mediated primarily by individual sensitivity to reward (e.g., Padrão et al., 2013), but also by cognitive functions such as learning (Schultz, 2006; Marco-Pallares et al., 2008) and/or working memory (José et al., 2020).

Over the last couple of decades, feedback and reward-based decision-making have been associated with a sizeable brain network involving: the orbitofrontal cortex, ventromedial prefrontal cortex, ventral medial and dorsal lateral striatum/nucleus accumbens, anterior and posterior cingulate cortex, amygdala (McClure et al., 2004; Marco-Pallares et al., 2008; Wang, 2012; Hiser and Koenigs, 2018; Cox and Witten, 2019) and hippocampus (Johnson et al., 2007; Camara et al., 2009; Haber and Knutson, 2010; Ito and Lee, 2016; Vilà-Balló et al., 2017). In light of this, the study of patients with mesial temporal lobe epilepsy due to unilateral hippocampal sclerosis (mTLE-UHS) is crucial to determine how dysregulation of this network can affect the way in which, individuals process the positive and negative feedbacks associated with their actions, as well as motivational approach behaviors, and consequently, optimal decision-making.

Traditionally, decision-making has been studied in two situations (for review, see Liebherr et al., 2017). First, in decisions under risk, (e.g., Game of Dice Task, GDT), where the rules are explicit and the winning probabilities are known. In these tasks, the probabilities (not necessarily directly given) of gaining or losing can be calculated from the beginning. Second, in decisions under ambiguity, where no explicit information about the consequences of each decision is given, such as in behavioral gambling tasks (e.g., IOWA Gambling Task, IGT), where participants need to learn the consequences of their choices from feedback processing. Nevertheless, throughout the task, participants can learn the magnitude and the probability of the gains and losses associated with each choice, which should lead to the selection of advantageous options. Importantly, while the rules are being acquired, decision-making in tasks under ambiguity is equivalent to that of decision-making in tasks under risk. Moreover, alternative versions of the gambling tasks (Gehring and Willoughby, 2002; Marco-Pallares et al., 2008) have been developed without any underlying structure or rules, whereby rewards and punishments are delivered at random. In these tasks, behavior is guided by internal expectations rather than objective probabilities, which is more suitable for isolating electrophysiological markers of feedback processing, at a cost of evaluating behavioral and learning effects (Severo et al., 2020).

For the purpose of unraveling individual differences associated with feedback processing, gambling tasks have been combined with simultaneous electroencephalographic (EEG) recordings to obtain Event-Related Potentials (ERPs) and Event-Related Oscillations (EROs) (Chandrakumar et al., 2018). In particular, a frontocentral negative ERP component appears and peaks around 250–300 ms post-feedback onset, which has been related to frontal theta oscillatory activity (4–7 Hz, 200–450 ms). Both ERP negativity and theta activity are larger after monetary losses than gains (Gehring and Willoughby, 2002; Marco-Pallares et al., 2008; Vega et al., 2013). However, the negativity of this component overlaps with a frontocentral positivity, associated with delta activity (1–4 Hz, 200–400 ms), with a centroparietal distribution, which appears in response to monetary gains. The difference between gain- and loss-associated activity has been termed the Feedback-Related Negativity (FRN, also known as Reward Positivity, RewP, or Medial Frontal Negativity, MFN) (Bernat et al., 2011, 2015; Foti et al., 2015; Williams et al., 2021). Finally, frontal beta-gamma oscillatory activity (20–35 Hz), considered a measure of consummatory reactions to positive outcomes (monetary gains) (Marco-Pallares et al., 2008; Hajihosseini et al., 2012), is associated with later latencies than the FRN.

Concerning patients with mTLE-UHS (for a review, see Zhang et al., 2018), no impairments have been reported in decision-making under risk when patients can estimate risks using rational strategies, such as in GDTs (Labudda et al., 2009) or Probabilistic-Associated Gambling Tasks (Delazer et al., 2010). Nevertheless, it has been observed that patients with mTLE-UHS fail at decision-making under ambiguity (e.g., on the IGT), by selecting less advantageous choices, especially towards the end of the task, therefore evidencing problems in learning the rules or task contingencies (Labudda et al., 2009; Delazer et al., 2010; Yamano et al., 2011; Xie et al., 2013). Similarly, in a probabilistic, reversal learning task, patients with mTLE-UHS were unable to correctly reverse their disadvantageous choices to more advantageous ones, despite receiving probabilistic feedback after each choice (Vilà-Balló et al., 2017). Similar results have been previously reported in post-surgical patients with mTLE-UHSs (surgically treated with an anterior temporal lobectomy that included amygdalohippocampectomy) (Bonatti et al., 2009; Von Siebenthal et al., 2017). However, the impairments in feedback processing associated with these deficits remain unclear.

The main goal of the current study was to evaluate decision-making and the electrophysiological correlates of feedback processing in patients with mTLE-UHS before and after anterior mesial temporal lobe resection surgery. To this aim, we used an integrative longitudinal design combining behavioral data, ERPs, EROs, neuropsychological assessments, and a healthy, control group. To the best of our knowledge, no previous studies have addressed this issue with a similar design. Our study consisted of: (i) replicating previous behavioral studies on patients with mTLE-UHS, employing the IGT and the GDT, two tasks showing high behavioral sensitivity; and (ii) evaluating ERPs and EROs during a probabilistic gambling task with no underlying structure (Marco-Pallares et al., 2008). Despite minor behavioral sensitivity, this paradigm was selected because it is optimal for obtaining very reliable feedback-related ERP components (e.g. the FRN component) as well as oscillatory modulations (delta, theta, and beta-gamma oscillatory activities) (Gehring and Willoughby, 2002; Marco-Pallares et al., 2008; Marco-Pallarés et al., 2009; Foti et al., 2015; Vilà-Balló et al., 2015; Watts et al., 2017); (iii) obtaining neuropsychological scores in different cognitive domains to obtain a cognitive profile of our sample; finally (iv) performing an initial assessment and follow-up, to understand the impact of surgery on all of the evaluated processes in patients with mTLE-UHS.

Based on previous findings, we hypothesized that compared to controls, patients with mTLE-UHS will show: (i) an increased preference for disadvantageous decks during the IGT (especially during the final blocks) but not on the GDT (Labudda et al., 2009; Delazer et al., 2010; Yamano et al., 2011; Xie et al., 2013; Zhang et al., 2018) (ii) an abnormal feedback-related electrophysiological activity on the gambling task (Johnson et al., 2007; Camara et al., 2009; Haber and Knutson, 2010; Ito and Lee, 2016; Vilà-Balló et al., 2017); (iii) lower neuropsychological scores in memory and verbal domains (Lee et al., 2002; Roger et al., 2020); and (iv) despite not being previously addressed, we expect a general worsening of patient deficits post-surgery (Zhang et al., 2018).

2. Method

2.1. Participants

The mTLE-UHS group consisted of seventeen patients with either left

(ten patients; seven females) or right (seven patients; three females) hemisphere damage. All patients had refractory mTLE and were recruited after a presurgical evaluation at the Bellvitge University Hospital as candidates for anterior mesial temporal resection surgery. Patient diagnosis was established using clinical EEG and magnetic resonance imaging. All patients underwent a neurological and neuropsychological examination, as well as continuous video-EEG monitoring. Patients were evaluated before and at least three months after an anterior mesial temporal lobe resection for the relief of medically intractable mTLE. The surgery, performed by the same neurosurgeon each time, consisted of *en bloc* resection of the mesial temporal structures. Hippocampal sclerosis was confirmed in all patients with a histopathological study by the same pathologists. None of the patients suffered a seizure 24 h prior or during the experimental task, and all of them were on regular antiseizure medication. In the current study, the mTLE-UHS group was matched for age (Patients: 40.8 ± 12.8; Controls: 40.7 ± 15.5; t (32) = 0.012, p = 0.990), sex (Patients: 10F, 7 M; Controls: 9F,8M; X^2 (1, N = 34) = 0.119, p =.730) and years of education (Patients: 11.7 ± 4.2; Controls: 11.1 ± 4.5; t (32) = 0.394, p = 0.696) with a healthy control group. The Ethical Committee of the Bellvitge University Hospital approved the study (PR064/10). Informed consent was obtained from all of the participants. Descriptive data are reported in Table 1.

2.2. Neuropsychological assessment

All of the participants (patients and controls) completed the: Logical memory I (immediate verbal memory) and II (delayed verbal memory), Visual reproduction I (immediate visual memory) and II (delayed visual memory), Digit Span and Letter Number subtests of the Wechsler Memory Scale III (Wechsler, 2004); Vocabulary subtest of the Wechsler Adult Intelligence Scale (Wechsler, 1999); Rey Auditory Verbal Learning Test (Rey, 1941; Schmidt, 1996), Trail Making Test (TMT-A and TMT-B) (Reitan, 1955; Davies, 1968), Boston Naming Test (BNT) (Kaplan et al., 2001), Semantic Fluency and Phonemic Fluency subtest of the Barcelona Test-R (Peña-Casanova, 2005), and the Rey-Osterrieth Complex Figure (copy, time, and memory) (RCF, Rey, 1941; Osterrieth, 1944; Peña-Casanova, 2005). To compare the neuropsychological functioning in patients with mTLE-UHS before and after surgical resection, results from the above-mentioned tests were grouped into seven standard cognitive domains (Riley et al., 2010; Chang et al., 2012; Palta et al., 2014; Kellermann et al., 2016; Allone et al., 2017): verbal comprehension, processing speed, verbal functioning, verbal memory, constructional ability, visuospatial memory, and working memory. Neuropsychological data for all participants are summarized in Table 2.

2.3. Behavioral game of dice task

We used a simplified, modified version of the computerized GDT (Brand et al., 2005). On each round (trial), participants saw one dice, a panel indicating the balance after each choice, the accumulated capital, and the result of the current throw (Fig. 1A). In contrast to the original version of the task (Brand et al., 2005), no dice shaker was shown and the dice was blank (no numbers) at the beginning of the round, prior to the throw. Participants began the task with a starting virtual capital of 1000€ and were instructed to attempt to increase this capital by throwing one dice during 18 rounds. Before the throw, participants had to guess which number would appear on the dice. They could guess one

Table 1
Demographic data for the patients with mTLE-UHS (left and right) and controls included in this study. Age, sex, years of education (Educ.). Pre-surgery clinical information (at the initial evaluation) for patients with mTLE-UHS, including age at epilepsy onset (Onset), disease duration in years (Dis. Duration), seizure frequency (days/month), presence of focal impaired awareness seizures (FIAS), presence of focal to bilateral tonic-clonic Seizures (FBTCS), number of antiseizure drugs (Num. ASD), and benzodiazepine (BZD), barbiturates (BARB), and Phenobarbital (PB).

Code	Group	Age	Sex	Educ.	Onset	Dis. Duration	Freq	FIAS	FBTCS	Num. AEDS	BZD, BARB, & PB
ep_02	TLE-L	39	F	8	14 M	37Y	1–2/mo	Yes	Yes	3	clobazam 10 mg/d
ep_05	TLE-R	36	M	11	18Y	19Y	4–6/mo	Yes	Yes	3	PB 100 mg/d
ep_08	TLE-R	50	F	8	18Y	33Y	6–8/mo	Yes	Yes	3	PB 100 mg/d
ep_09	TLE-L	65	F	0	4Y	59Y	4–5/mo	Yes	Yes	2	PB 100 mg/d
ep_10	TLE-R	66	M	8	41Y	25Y	4/mo	Yes	No	2	No
ep_11	TLE-L	33	F	11	16Y	17Y	30–35/mo	Yes	Yes	3	Clobazam 10 mg/d
ep_12	TLE-L	34	M	16	23Y	9Y	8–10/mo	Yes	Yes	2	No
ep_13	TLE-L	38	M	16	32Y	8Y	2–4/mo	Yes	Yes	3	No
ep_14	TLE-R	21	M	16	17Y	6Y	5/mo	Yes	Yes	2	No
ep_15	TLE-L	37	F	12	13 M	48Y	7–9/mo	Yes	No	2	No
ep_18	TLE-L	41	F	14	12 M	32Y	5–6/mo	Yes	Yes	4	PB 150 mg/d
ep_21	TLE-D	61	F	12	31Y	31Y	4–5/mo	Yes	Yes	3	No
ep_22	TLE-L	29	M	14	15Y	16Y	3–4/mo	Yes	Yes	3	PB 200 mg/d
ep_25	TLE-L	25	M	9	13Y	13Y	1/mo	Yes	Yes	2	No
ep_29	TLE-R	34	F	12	21Y	13Y	2/mo	Yes	Yes	2	No
ep_34	TLE-L	43	F	14	8Y	38Y	18–20/mo	Yes	Yes	2	No
ep_35	TLE-L	35	F	17	2Y	33Y	4–6/mo	Yes	Yes	2	No
c_02	Control	42	F	10							
c_05	Control	39	M	10							
c_06	Control	28	F	11							
c_07	Control	35	F	16							
c_08	Control	53	F	8							
c_09	Control	68	F	6							
c_10	Control	71	M	0							
c_11	Control	25	F	17							
c_12	Control	30	M	14							
c_14	Control	25	M	17							
c_15	Control	43	F	10							
c_18	Control	43	F	10							
c_19	Control	29	F	18							
c_21	Control	61	M	10							
c_22	Control	28	M	12							
c_25	Control	21	M	13							
c_27	Control	51	F	12							

Table 2
Demographic information for the controls and patients with mTLE-UHS included in this study. Age, years of education (Educ.). Mean scores of neuropsychological data for first and second evaluations, for controls and patients with mTLE-UHS. The neuropsychological measures are: LMI (Logical Memory I), LMII (Logical Memory II), VRI (Visual Reproduction I), VRII (Visual Reproduction II), Dig. span (Digit Span), Letter num. (Letters and numbers), RAVLT A1 and A5 (total learning at trials 1 and 5), RAVLT A6 (immediate recall), RAVLT A7 (delayed recall), RAVLT Rcog (recognition), TMT A (Trial Making Test A), TMT B (Trial Making Test B), Voc. (Vocabulary), BNT (Boston Naming Test), Flue. (s) (Semantic Fluency), and Flue. (p) (Phonemic Fluency), RCF Copy (Rey-Osterrieth Complex Figure, RCF, copy), RCF Time (RCF copy time), and RCF recall (RCF immediate recall). Group comparisons were performed using two sample *t*-tests or rmANOVAs. Results were grouped into six domains: Verbal comprehension, verbal functioning, verbal memory, constructional ability, visuospatial memory, and attention, working memory, and executive function.

		CONTROLS M (SD)		**mTLE-UHS M (SD)**		**t**	**Sig.**				
	Age	40.71 (15.48)		40.76 (12.84)			−0.120	0.990			
	Educ	11.06 (4.48)		11.65 (4.23)			−0.394	0.696			
		First evaluation	**Second Evaluation**	**First evaluation**	**Second evaluation**	**Evaluation**		**Evaluation × Group**		**Group**	
		M (SD)	**M (SD)**	**M (SD)**	**M (SD)**	**F**	**Sig.**	**F**	**Sig.**	**F**	**Sig.**
Verbal comprehension	Voc	41.76 (11.97)	44.41 (10.99)	33.77 (8.17)	35.31 (9.39)	3.282	0.081	0.230	0.635	5.449	**0.027**
Processing speed	TMT A	50.53 (32.85)	45.06 (42.29)	49.76 (25.58)	48.53 (28.43)	1.005	0.324	0.401	0.531	0.016	0.901
	TMT B	96.88 (76.92)	74.25 (31.69)	152.56 (141.95)	130.63 (85.50)	2.651	0.114	0.001	0.980	3.539	0.070
Verbal functioning	BNT	50.65 (9.02)	52.41 (8.44)	48.59 (6.59)	43.76 (9.40)	3.638	0.065	16.877	**0.000**	3.712	0.063
	Flue. (s)	19.29 (5.80)	20.82 (7.18)	17.82 (5.93)	15.94 (4.72)	0.040	0.843	3.734	0.062	2.955	0.095
	Flue. (p)	14.35 (5.44)	14.88 (5.43)	12.88 (6.34)	12.76 (5.73)	0.054	0.818	0.134	0.717	1.037	0.316
Verbal memory	LMI	32.76 (13.93)	40.35 (14.03)	29.12 (9.59)	25.82 (11.33)	1.719	0.199	11.040	**0.002**	5.402	**0.027**
	LMII	21.53 (10.04)	26.65 (10.43)	15.88 (7.91)	13.29 (7.55)	1.366	0.251	12.679	**0.001**	10.603	**0.003**
	RAVLT A1	5.82 (2.30)	5.65 (2.67)	5.53 (1.70)	4.53 (1.66)	2.317	0.138	1.135	0.295	1.306	0.262
	RAVLT A5	13.12 (1.83)	12.94 (2.22)	11.53 (2.79)	9.82 (3.07)	7.087	**0.012**	4.678	**0.038**	8.873	**0.005**
	RAVLT A6	11.65 (3.55)	11.65 (3.22)	8.82 (3.49)	6.47 (4.08)	3.553	0.069	3.553	0.069	14.118	**0.001**
	RAVLT A7	11.59 (3.78)	11.35 (3.52)	8.71 (3.67)	7.29 (4.21)	2.418	0.130	1.234	0.275	8.482	**0.006**
	RAVLT Recog	13.76 (2.36)	14.06 (1.60)	12.76 (2.51)	12.71 (1.45)	0.079	0.780	0.178	0.676	4.446	**0.043**
Constructional ability	RCF Copy	36.00 (14.56)	32.26 (7.63)	30.96 (7.81)	32.14 (5.02)	0.239	0.628	0.884	0.355	1.232	0.276
	RCF Time	169.41 (72.47)	172.00 (90.18)	175.15 (71.11)	192.85 (101.92)	1.027	0.320	0.570	0.457	0.204	0.655
Visuospatial memory	VRI	86.47 (22.66)	88.06 (23.90)	74.59 (20.36)	72.88 (21.58)	0.001	0.976	0.746	0.394	3.380	0.075
	VRII	76.00 (27.72)	82.88 (25.72)	55.18 (26.99)	54.76 (25.02)	1.350	0.254	1.715	0.200	8.079	**0.008**
	RCF Recall	21.03 (8.57)	23.34 (9.96)	15.53 (8.12)	12.46 (5.50)	0.237	0.630	6.617	**0.016**	8.327	**0.007**
Working memory	Dig. span	15.18 (4.90)	16.00 (5.56)	11.71 (3.65)	11.65 (3.33)	0.897	0.351	1.194	0.283	7.047	**0.012**
	Letter num.	9.24 (3.70)	10.24 (3.67)	8.06 (2.38)	7.06 (3.53)	0.000	1.000	7.406	**0.011**	3.787	0.061

Note: The N for all of the analyses was 17 per group, with the following exceptions in which there was missing data. Control, second evaluation (TMT-B N = 16, RCF recall N = 16); mTLE-UHS, first evaluation (TMT-B N = 16, RCF copy N = 16, RCF time N = 16, RCF recall N = 16, letters and numbers N = 16); mTLE-UHS, second evaluation (Voc N = 13, TMT-B N = 16, RCF copy N = 14, RCF time N = 13, RCF recall N = 14). For all of the reported analyses, only participants with complete data in both evaluations were included. Significant results are highlighted in bold. P-values were not corrected for multiple comparisons.

number (e.g., one) or a combination of two (e.g., one and two), three, or four numbers. Importantly, during each round, there was only one throw of one dice, consequently, the more numbers were selected, the greater the probability to guess the number that would appear on the dice.

In our version of the task, participants were free to choose one, two, three, or four numbers, but they could not select the specific numbers included in each choice as these were fixed and adjusted between rounds (for an example, see the combination of numbers in Fig. 1A). Each choice was associated with a virtual amount of money and the participants bet: 1000€ on one single number, 500€ on two numbers, 200€ on three numbers, and 100€ on four numbers. Selection of the choice was carried out by pressing the Z, X, N, or M buttons of the keyboard, with the middle or index finger of the left or right hand, depending on the choice. Then, after the virtual throw, and during 5000 ms, a number was presented on the dice and participants were informed in the balance panel if they won or lost the previously chosen amount of money. Then, after 1000 ms, the next round began and new numbers were presented. The rules, as well as the extent of gains and losses, were explicitly described and visualized during this task. The probability of winning could be deduced through the occurrence ratio (1:6, 2:6, 3:6, 4:6). Therefore, choosing either one or two numbers make up the disadvantageous conditions, whereas selecting three or four numbers constitutes the advantageous ones. For example, if a participant decided to guess one, two, three or four numbers each time, then the final balance (taking into account the starting capital and the accumulated outcomes) after 18 rounds would be −11.000€, −2000€, 1000€, or 1600€, respectively. The results of the throws were pseudo-randomized across the task, with each number appearing three times but in a balanced order. See Fig. 1A for a schematic illustration of the GDT.

2.4. Standard behavioral IOWA gambling task

We used a computerized version of the IGT (see Fig. 1B) designed by Bechara et al. (1994). Four rectangles were presented in the middle of the screen, representing decks of cards, labeled A, B, C, and D on the bottom end. On each trial, participants had to select one card from any of the four decks, by pressing the Z (deck A), X (deck B), N (deck C), or M (deck D) buttons of the keyboard, with the middle or index finger of the left or right hand. After the selection was made, a red or black "0″, representing a red or black card respectively, was displayed in the middle of the selected card. After each card had been selected, the participants received some amount of virtual money, which varied depending on the deck, and was displayed on the top of the screen (e.g., "You win 100€"). Specifically, participants received 100€ for each card selected from decks A and B and 50€ for each card selected from decks C and D. However, there were some penalty cards in each deck. The penalty was announced once the card selection had been made, and was displayed on the same deck with a "negative red number" (replacing the red 0), but also below the message indicating the win (e.g., "You lost 250€"). Importantly, when the selected card did not contain a penalty, a

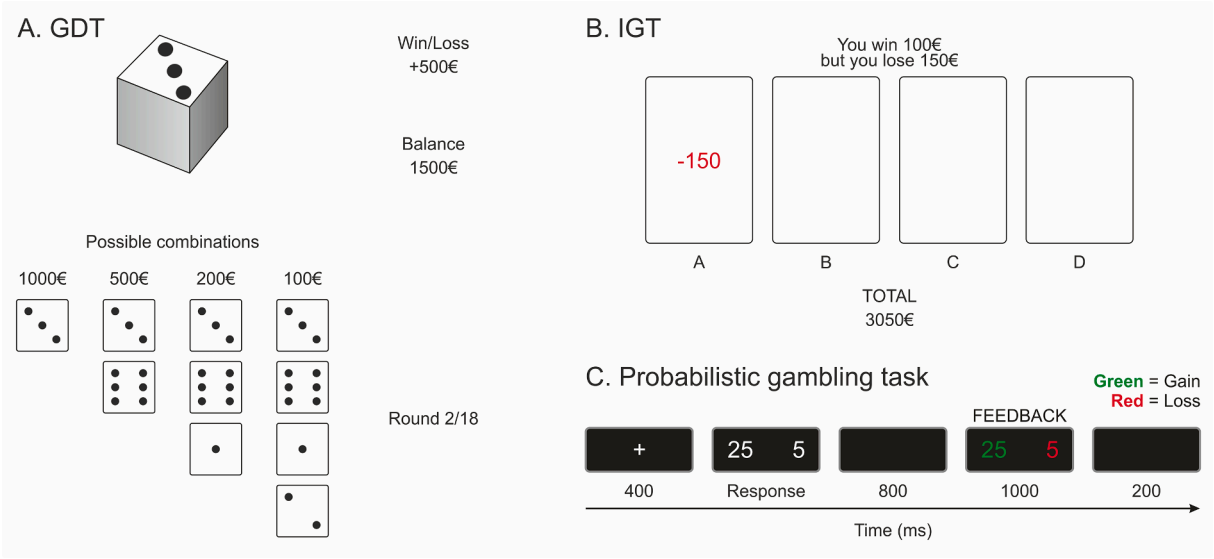

Fig. 1. A. A schematic illustration of the GDT. In this example, the participant was in the second round out of a total of 18 rounds, and pressed the X button of the keyboard with the index finger of the left hand. Consequently, the participant selected the option of two numbers (bet = 500€), which included the numbers three and six. After the throw, the number on the dice was three, and consequently the participant won 500€. The balance was updated and this amount was added to the initial capital of 1000€. **B.** An illustration of the IOWA. In this example, the participant selected deck A by pressing the Z button of the keyboard with the middle finger of their left hand. The selection of this deck involved winning 100€. However, the participant obtained a penalty of 150€. The total balance was updated taking into account both outcomes. **C.** The sequence of stimulus and response events in the probabilistic gambling task used in the present study (Marco-Pallarés et al., 2009). After a warning signal, a pair of numbers ([5 2 5] or [2 5 5]) was presented, and participants were instructed to select one of the two alternatives by pressing the corresponding button on the left- or right-hand side (response choice). One second after the response choice, one of the numbers turned red and the other green (feedback), indicating a gain (green) or loss (red) of the corresponding amount of virtual money in Euro cents.

red or black zero appeared in the middle of the screen. The penalties varied based on the decks, and their positions in the decks were fixed (same position for all participants). The duration of the task was fixed to 100 card selections. Each deck of cards was programmed to contain 40 cards, 20 with a black face and 20 with a red face. The back of the cards was represented with a white vertical rectangle inside a black frame (see Fig. 1B). For each deck, the fixed order of black and red cards, as well as penalties, was programmed according to the original version of Bechara et al. (1994), keeping in mind that we replaced American Dollar values with Euros. Specifically for deck A, on every 10 cards, participants won 1000€ but there were five unpredictable punishments from 150€ to 350€, leading to a total loss of 1250€. On the other hand, for every 10 cards from deck B the gain was 1000€, and there was only one penalty of 1250€ in the deck. Decks A and B were equivalent in that both of them produced a total net loss of 250€ every 10 trials, and were disadvantageous over the long term. For deck C, however, every 10 cards led to a gain of 500€, with five unpredictable penalties from 25€ to 75€, generating a total loss of 250€. Similarly, the gain after selecting 10 cards from deck D was 500€, but there was a single penalty of 250€. Decks C and D were equivalent in producing an overall net gain of 250€, and were advantageous over the long term. If a participant selected 40 cards from the same deck, the deck was finished (indicated by a black, dashed line displayed in the middle of the deck), and the participant had to choose cards from the other decks for the remainder of the game. Participants began with a virtual credit amount of 2000€ and were informed that some decks were better than others. They were also instructed to avoid the disadvantageous decks and choose the advantageous ones, to win as much virtual money as possible. On each trial, participants could select one card from any deck and they were also permitted to switch between decks from trial to trial. Participants were able to see their accumulated capital throughout the entire task.

2.5. Probabilistic gambling task

A modified ERP version of the probabilistic gambling task (Marco-Pallares et al., 2008) was employed, similar to the one described by Gehring and Willoughby (2002). In this task, two numbers (25 and 5) were presented in the middle of a computer screen (Marco-Pallarés et al., 2009; Camara et al., 2010). Only two possible displays were given, either [2 5 5] or [5 2 5] (see Fig. 1C).

Participants were required to choose the number they wanted to bet on, and press either the left or right mouse button with their right index finger, depending on their choice. For example, in a [2 5 5] display, pressing the left button indicated the selection of the number 25, and pressing the right button indicated the selection of the number 5. After this step (with a fixed interval of 800 ms), one of the numbers turned red while the other turned green. If the selected number changed to red, the participant lost the corresponding amount in virtual Euro cents, whereas if the subject's chosen number turned green, they won this amount in virtual Euro cents. The duration of the feedback stimulus was 800 ms. The subsequent trial began after 200 ms with the presentation of a warning signal ("+", lasting 400 ms), followed by a new pair of numbers.

The experiment consisted of 17 blocks of 40 trials. In each block, four different feedback types were presented in random order: [**2 5 5**], [2 5 **5**], [**5** 2 5], and [5 **2 5**] (note: nonbold font stands for red [a loss], while bold font indicates green [a win]). Participants were encouraged to gain as much as possible. Combined with the two response options, this yielded eight different types of stimuli–response combinations. For example, if the participant chose the left number in a [2 5 5] event, this was scored as a "maximum gain" trial. However, if the participant opted for the right number, the trial was scored as a minimum loss.

Importantly, the mean expected value of the monetary outcome was zero on each block, to avoid potential confounding influences of a differential probability of gains or losses. The participants were informed about their accumulated amount of money (10 s duration) after each mini-block of ten trials.

3. EEG acquisition

EEG was recorded continuously (digitized, with a sampling rate of

250 Hz, bandpass from 0.01 to 70 Hz) using a BrainAmp amplifier, from 29 tin electrodes that were mounted on an elastic cap and located at standard positions (FP1/2, F3/4, C3/4, *P*3/4, O1/2, F7/8, T3/4, T5/6, Fz, Cz, Pz, FC1/2, FC5/6, CP1/2, CP5/6, PO1/2). The EEG was referenced on-line to the right ocular canthus. Biosignals were re-referenced offline to the two mastoid electrodes' mean activity. Electrode impedances were maintained below 5kΩ. Vertical eye movements were monitored by an electrode placed below the right eye.

3.1. Procedure

This study followed a longitudinal design and was comprised of three initial sessions and three follow-up sessions performed after surgery and always at least six months after the first initial sessions for all participants to reduce learning effects.

A trained clinician performed the neuropsychological assessment for each participant during the first session. A second session was conducted between one to seven days after the first session and included the GDT and the IGT. Then, participants completed the EEG session between one to seven days later. The procedure was identical in the follow-up sessions.

Throughout the manuscript, we will refer to these initial sessions as "the first evaluation", and the follow-up sessions as "the second evaluation". It is important to note that between both evaluations, the patients with mTLE-UHS underwent surgery, which was performed at least three months prior to the second evaluation (Bonelli et al., 2010, 2013).

3.2. Data processing

Feedback-locked ERPs were separately averaged for gain (combining maximum gain [+25] and minimum gain [+5]) and loss trials (combining maximum loss [−25] and minimum loss [−5]), from 100 ms before the feedback (baseline) to 924 ms after it. Epochs that exceeded ± 100 μV, on the electrooculogram (EOG) or EEG, were removed offline for further analysis using the extreme value function of the EEGLAB toolbox. For behavioral and electrophysiological analyses, only reaction times (RT) occurring between 120 and 750 ms post-stimulus presentation were considered for the analyses (Krämer et al., 2007). All artifact-free error trials were included regardless of subsequent correct responses.

To study the EROs elicited by the feedbacks, 4000 ms epochs were generated (epochs that comprised ± 2000 ms before and after the feedbacks). Epochs that exceeded ± 100 μV in the EOG or EEG were removed offline from further analyses using the EEGLAB toolbox. A 100 ms time range before the feedback was defined as the baseline. Single-trial data was convoluted using a 6-cycles complex Morlet wavelet (Tallon-Baudry et al., 1997). Changes in time-varying energy (square of the convolution between wavelet and signal), in the studied frequencies (from 1 to 40 Hz; linear increase), concerning baseline, were computed for each trial and averaged for each subject before performing a grand average.

The EEG artefact rejection rate was similar between groups and evaluations (first evaluation: controls 16.7 ± 21.0 %, TLE-UHS 28.7 ± 24.8 %; second evaluation: controls 17.9 ± 22.3 %, TLE-UHS 26.2 ± 24.9); main effect of group: $F(1,32) = 1.857$, $p = 0.182$; main effect of evaluation: $F(1,32) = 0.031$, $p = 0.861$).

3.3. Statistical analysis

For each neuropsychological measure, we performed a repeated-measures analysis of variance (rmANOVA), including Evaluation (Level 1: First, Level 2: Second) as within-subjects factor and Group (Level 1: mTLE-UHS, Level 2: Controls) as between-subjects factor.

Statistical analysis of the GDT was performed on the proportion of disadvantageous choices and using a rmANOVA. We included Evaluation (Level 1: First, Level 2: Second) as within-subjects factor, and Group (Level 1: mTLE-UHS, Level 2: Controls) as between-subjects factor.

Similarly, for the IGT we used a rmANOVA with Block (Level 1 to 5, including blocks 1 to 5, respectively) and Evaluation (Level 1: First, Level 2: Second) as within-subjects factors, and Group (Level 1: mTLE-UHS, Level 2: Controls) as a between-subjects factor, on the frequency of advantageous choices (C + D) minus the frequency of disadvantageous choices (A + B).

For the probabilistic gambling task, we assessed the tendency to bet 25 (risky choice) during the task. On this data, we performed a rmANOVA with Evaluation (Level 1: First, Level 2: Second) as within-subjects factors, and Group (Level 1: mTLE-UHS, Level 2: Controls) as between-subjects factor.

All of the electrophysiological analyses, electrode selection, time-windows, and frequency ranges (for the time–frequency analyses), were based on current data (peak amplitude or maximum power value of each range), but also on previous literature.

For the feedback-locked ERP analysis, separately for gains and losses, and for the first and second evaluations, we computed the mean amplitude at 260–310 ms time-window after feedback presentation, centered on the peak of the component at FC2 electrode, based on previous literature using the same Gambling Task (Marco-Pallares et al., 2008; Padrão et al., 2013; Vega et al., 2013). Then, we carried out a rmANOVA on the mean amplitude, with Valence (Level 1: Gain, Level 2: Loss) and Evaluation (Level 1: First, Level 2: Second) as within-subjects factors, and Group (Level 1: mTLE-UHS, Level 2: Controls) as a between-subjects factor. Please, note that the amplitude difference between both levels of Valence constitutes the FRN.

A similar procedure was used for feedback-locked ERO analyses to obtain delta, theta, and beta-gamma frequency ranges, for which we computed the mean power for each specific range, separately for gains and losses, and for the first and second evaluations. For the delta activity, we selected a region of interest (ROI) of electrodes (*P*3, PZ *P*4, PO1, PO2). This selection was done by considering the maximum power value and the widespread parietal distribution of the delta activity obtained in the current study, but also on previous literature indicating that this activity could have a widespread distribution from centroparietal electrodes (Cavanagh, 2015; Pornpattananangkul and Nusslock, 2016). Taking into account these studies and the current distribution, the term parietal delta activity will be used throughout the manuscript. We obtained the mean power at 3–4 Hz between 250 and 350 ms based on the activity peak (Williams et al., 2021). Then, we performed a rmANOVA on the mean power, with Valence (Level 1: Gain, Level 2: Loss) and Evaluation (Level 1: First, Level 2: Second) as within-subjects factors, and Group (Level 1: mTLE-UHS, Level 2: Controls) as a between-subjects factor. For both theta and beta-gamma activities, there is clear evidence of their main frontal distribution. However, since the frontal theta activity has a focal distribution and the frontal beta-gamma activity has a widespread distribution, we decided to use a single electrode for the former and a ROI analysis for the later (Marco-Pallares et al., 2008; Padrão et al., 2013; Vega et al., 2013; Williams et al., 2021). With regard to the frontal theta activity, we calculated the mean power between 4 and 5 Hz and 300–400 ms (Williams et al., 2021) at FC2 electrode (Marco-Pallares et al., 2008; Padrão et al., 2013; Vega et al., 2013), and we performed a rmANOVA on the mean power with the same factors. For the frontal beta-gamma band range, we performed an analysis between 27 and 32 Hz and 330–430 ms. As previously mentioned, following previous studies indicating its frontal distribution, we selected a ROI (F3, FZ, F4, FC1, FC2) of electrodes (Marco-Pallares et al., 2008; Padrão et al., 2013; Vega et al., 2013). Then we performed a rmANOVA on the mean power with the same factors as the ones explained above. For the decomposition of the significant interactions, we used pairwise two-tailed *t*-tests for independent sample comparisons, or two-tailed paired t-tests to delineate specific effects in each group. For all statistical effects involving two or more degrees of freedom in the numerator, the Greenhouse-Geisser epsilon was used to correct possible violations of the sphericity assumption (Jennings and Wood, 1976). P-

values after correction are reported.

Finally, as an additional exploratory analysis, Pearson correlations were carried out to evaluate the relationship between clinical variables in mTLE-UHS (i.e., age at epilepsy onset, disease duration, and seizure frequency (days/month)) and the electrophysiological measures (i.e., amplitude of the FRN (loss minus gain), delta power difference (gain minus loss)), mean delta power (mean between gain and loss), and mean theta power (mean between gain and loss), at the first evaluation.

4. Results

4.1. Neuropsychological results

Mean neuropsychological test scores in patients with mTLE-UHS and healthy controls for the first and second evaluations, along with statistical analyses are reported in Table 2.

A significant main effect of group in the rmANOVAs revealed that patients with mTLE-UHS performed worse than controls on tests related to: verbal comprehension (Vocabulary), verbal memory (LMI, LMII, RAVLT A5, RAVLT A6, RAVLT A7, RAVLT Recog), visuospatial memory (VRII, RCF Recall) and working memory (Digit span) domains. A statistically significant Group × Evaluation interaction and posterior t-tests indicated that: (i) the patients with mTLE-UHS showed a worsening in verbal functioning (BNT) and verbal memory (RAVLT A5) on the second evaluation (see Table 2); and (ii) healthy controls showed a learning effect (better performance on the second, as compared to the first evaluation) on verbal functioning (BNT), verbal memory (LMI, LMII, RAVLT A5), visuospatial memory (RCF recall) and working memory (Letter num). It is important to note that patients with mTLE-UHS did not exhibit the same learning effect as controls, across sessions.

4.2. Behavioral performance in decision-making

Decision-making performance was assessed using the behavioral GDT and IGT tasks (see Fig. 2), as well as the ERP monetary gambling task.

GDT. For this analysis, we obtained the proportion of disadvantageous choices as compared to the total number of choices (see Fig. 2A). The rmANOVA revealed no difference between evaluations [main effect of Evaluation: $F(1,29) = 1.02$, $p = .319$]. Consistent with previous literature (Labudda et al., 2009), no differences were encountered between patients with mTLE-UHS [First evaluation: $M = 0.29$, $SD = 0.19$; Second evaluation: $M = 0.27$, $SD = 0.21$] and controls [First evaluation: $M = 0.28$, $SD = 0.20$; Second evaluation: $M = 0.35$, $SD = 0.22$], as indicated by the absence of a significant main effect of Group [$F(1,29) = 0.21$, $p = .65$] and Group × Evaluation interaction [$F(1,29) = 1.56$, $p = .222$] (Fig. 2A).

IGT. The rmANOVA on the frequency of advantageous choices (C + D) minus the frequency of disadvantageous choices (A + B), in the IGT (see Fig. 2B), revealed a significant main effect of Block [$F(4,120) = 8.5$, $p < .001$], in that participants selected more disadvantageous choices in the first blocks, and more advantageous choices in the final blocks. The main effect of Evaluation [$F(1,30) = 0.04$, $p = .847$] together with the Block × Evaluation interaction [$F(4,120) = 0.74$, $p = .562$] were not significant and showed no differences in performance across evaluations. Importantly, the mTLE-UHS group selected more disadvantageous choices than the control group [main effect of Group: $F(1,30) = 4.25$, $p = .048$] (see Fig. 2B). No significant interactions involving Group were observed [Block × Group: $F(4,30) = 1.04$, $p = .381$; Evaluation × Group: $F(4,30) = 0.03$, $p = .867$; Block × Evaluation × Group: $F(4,120) = 0.72$, $p = .562$].

Probabilistic gambling task. For the analysis of the probabilistic gambling task, we computed the probability of choosing 25 (risky choice) during the task. The rmANOVA revealed no differences between evaluations [main effect of Evaluation: $F(1,32) = 0.20$, $p = .66$]. We did not observe any significant difference between controls (First evaluation: 0.54 ± 0.09; Second evaluation: 0.56 ± 0.07) and patients with mTLE-UHS (First evaluation: 0.56 ± 0.10; Second evaluation: 0.52 ± 0.12), in the main effect of Group [$F(1,32) = 0.32$, $p = .575$] or the Evaluation × Group interaction [$F(1,32) = 2.25$, $p = .144$].

4.3. ERP analysis

Fig. 3 shows feedback-locked ERPs for loss and gain trials and for both groups and evaluations. A typical FRN component, described as the amplitude difference between loss and gain trials, and peaking at about 285 ms (Gehring and Willoughby, 2002; Marco-Pallares et al., 2008), was observed for both groups. Visual inspection would suggest that it was reduced for patients with mTLE-UHS as compared to controls. We selected the activity at FC2 electrode, the location with the largest FRN peak amplitude (Gehring and Willoughby, 2002; Marco-Pallares et al., 2008) and performed a rmANOVA at FC2 electrode, with two within-subjects factors, Valence (Gain, Loss) and Evaluation (First, Second) (included Group as between-subjects factor). Please note that, the Valence factor captured the amplitude difference (difference waveform) between loss and gain trials and represents the FRN component. The significant main effect of Valence [$F(1,32) = 13.89$, $p = .001$] corroborated the increased frontal negativity for losses as compared to gains, and consequently, the presence of the FRN. Interestingly, the significant main effect of Evaluation [$F(1,32) = 4.48$, $p = .042$] indicated that overall, there was more negativity at the second compared to the first evaluation [no significant interaction was observed for Valence and

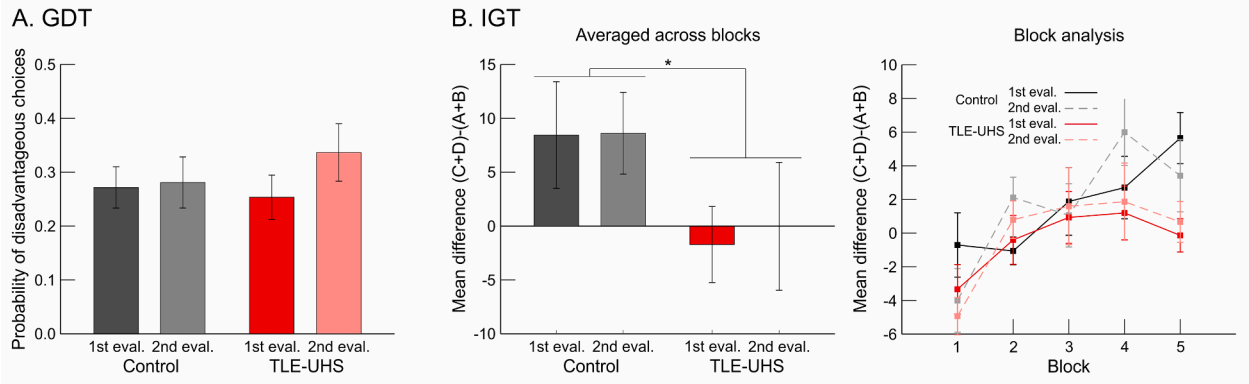

Fig. 2. A. Proportion of disadvantageous choices with reference to the total number of choices on the GDT for the mTLE-UHS group and control group at each evaluation. **B.** Frequency of advantageous (C + D) and disadvantageous selections (A + B) averaged across blocks during the IGT for the control and mTLE-UHS groups, at each evaluation. Error bars represent SEMs. **C.** Mean difference between the frequency of advantageous (C + D) and disadvantageous selections (A + B) at each block of the IGT for the control and mTLE-UHS groups, at each evaluation. Error bars represent SEMs.

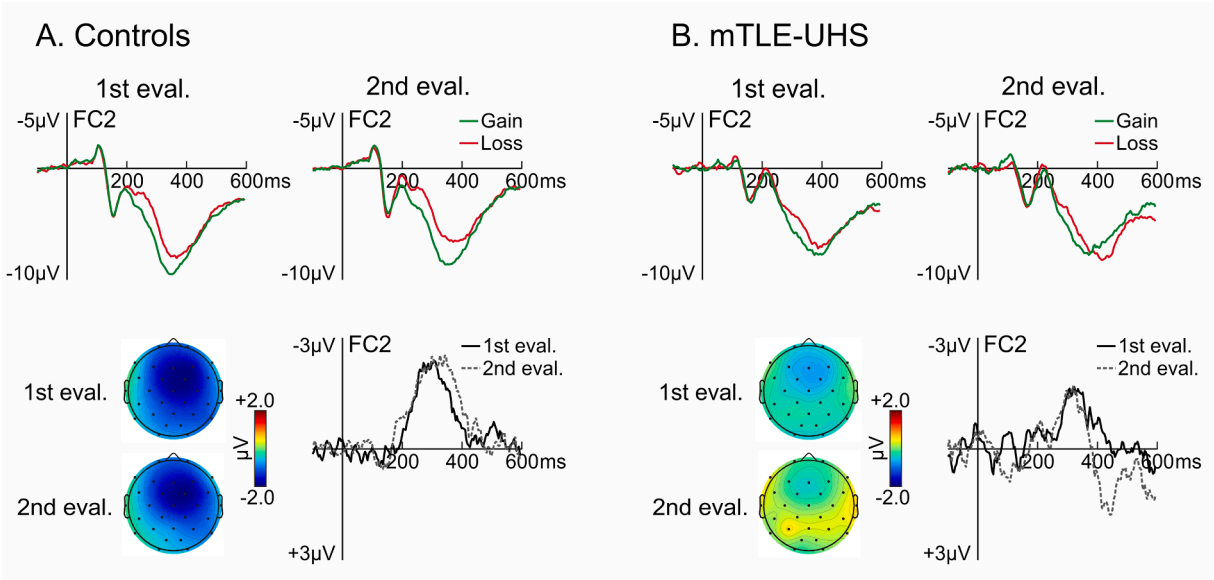

Fig. 3. Event-Related Potentials (ERPs) associated with feedbacks indicating monetary gains (solid black line) and losses (solid red line), and the differences between them (loss - gain; black pointed line) for each group (mTLE-UHS, controls) and evaluation (first, second), at FC2 electrode. Loss minus gain difference waveform at FC2 electrode for each group and evaluation (first, solid line; second, pointed line). **A.** For the control group, ERPs (top), difference waveform (bottom) and scalp topographical maps for the difference waveform (loss minus gain) between 250 and 350 ms. **B.** For the mTLE-UHS group, ERPs (top), difference waveform (bottom), and scalp topographical maps for the difference waveform (loss minus gain) between 250 and 350 ms.

Evaluation, $F(1,32) = 0.51$, $p = .481$].

No significant main effect of Group was encountered [$F(1,32) = 0.39$, $p = .536$]. Importantly, the significant interaction between Valence and Group suggest that there might be differences in the amplitude of the FRN (amplitude difference between gains and losses) between the mTLE-UHS and the control group [Valence × Group: $F(1,32) = 5.02$, $p = .032$]. In order to understand whether the group differences in the FRN amplitude were due to differences in the processing of gains or losses, pairwise *t*-test post-hoc comparisons were performed between groups. But, no significant group differences were observed in the mean amplitude of gains [$t(32) = 1.21$, $p = .235$] or losses [$t(32) = -0.047$, $p = .963$], and consequently it was not possible to disentangle whether this effect was specifically due to a stronger response to gains or to losses in either group. However, separately for each group, we performed paired *t*-test post-hoc comparisons between the mean amplitude of gains compared to the mean amplitude of losses, to test if the valence effect associated to the FRN was present in both groups. Interestingly, this contrast was significant in the control group [$t(16) = 3.22$, $p = .005$], but not in the TLE-UHS group [$t(16) = 1.98$, $p = .065$], suggesting that the valence effect, in other words the FRN, was present only in the control group (see Fig. 3 to visualize the FRN reduction in mTLE-UHS). Interestingly, FRN amplitude was not affected by surgery, as indicated by the non-significant Evaluation × Group [$F(1,32) = 0.19$, $p = .667$] and Valence × Evaluation × Group interactions [$F(1,32) = 0.31$, $p = .582$].

4.4. EROs analyses

Figs. 4–6 show the results of the oscillatory analysis for frequencies between 1 and 40 Hz, associated with gains and losses for the control and mTLE-UHS groups, respectively. A rmANOVA with two within-subjects factors: Valence (Gain, Loss) and Evaluation (First, Second), and one between-subjects factor (Group) was carried out for each frequency band.

Delta band. As expected based on previous literature, delta activity (3–4 Hz between 250 and 350 ms; Fig. 4) was higher for gain trials as compared to losses [main effect of Valence: $F(1,32) = 24.05$, $p < .001$]. No significant effects were observed between evaluations [main effect of Evaluation: $F(1,32) = 3.84$, $p = .059$; Valence × Evaluation: $F(1,32) = 0.02$, $p = .886$].

An overall reduction in delta power was observed in the TLE-UHS group as compared to the control group [Group: $F(1,32) = 7.73$, $p = .009$]. A significant Valence × Group interaction [$F(1,32) = 4.17$, $p = .049$] was observed. First, we performed pairwise *t*-test post-hoc comparisons between groups, which indicated that delta power was reduced in both conditions in the mTLE-UHS group in contrast to the control group [gains: $t(32) = 3.06$, $p = .004$; losses: $t(32) = 2.32$, $p = .027$]. Then, separately for each group, we carried out paired *t*-test post-hoc comparisons between the mean power of gains compared to the mean power of losses, to test whether the valence effect was present in both groups. Interestingly, and similarly to the results of the FRN, this contrast was significant in the control group [$t(16) = 5.06$, $p < .001$], but not in the TLE-UHS group [$t(16) = 1.967$, $p = .067$], which indicated that the valence effect was present only in the control group. Additionally, no significant differences were observed when comparing before and after surgery in patients with mTLE-UHS [Evaluation × Group: $F(1,32) = 2.31$, $p = .139$; Valence × Evaluation × Group: $F(1,32) = 0.16$, $p = .692$].

Theta band. For this oscillatory component (4–7 Hz, 200–400 ms; Fig. 5), a main effect of Valence was observed [$F(1,32) = 4.97$, $p = .033$], confirming the expected larger frontal theta activity after losses as compared to after gains. No significant differences were found between evaluations [main effect of Evaluation: $F(1,32) = 0.23$, $p = .635$; Valence × Evaluation: $F(1,32) = 0.19$, $p = .665$]. Importantly, the presence of a significant main effect of Group [$F(1,32) = 5.42$, $p = .026$], but the absence a of significant Group × Valence interaction [$F(1,32) = 0.52$, $p = .473$], suggested that the mean power of both gains and losses was reduced in the mTLE-UHS group compared to the control group. Moreover, these analyses corroborated that the difference in power between gains and losses (Valence effect) was similar between groups (see Fig. 5A and 5B). Interestingly, theta activity was not affected by surgery in mTLE-UHS [Evaluation × Group: $F(1,32) = 2.27$, $p = .141$; Valence × Evaluation × Group: $F(1,32) = 0.37$, $p = .546$].

Beta-gamma band. For this oscillatory component (27–32 Hz and 330–430 ms; Fig. 6), a significant main effect of Valence [$F(1,32) = 14.60$, $p < .001$] was encountered, corroborating that the frontal beta-gamma activity was increased for monetary gains as compared to monetary losses. No significant changes due to evaluation were found

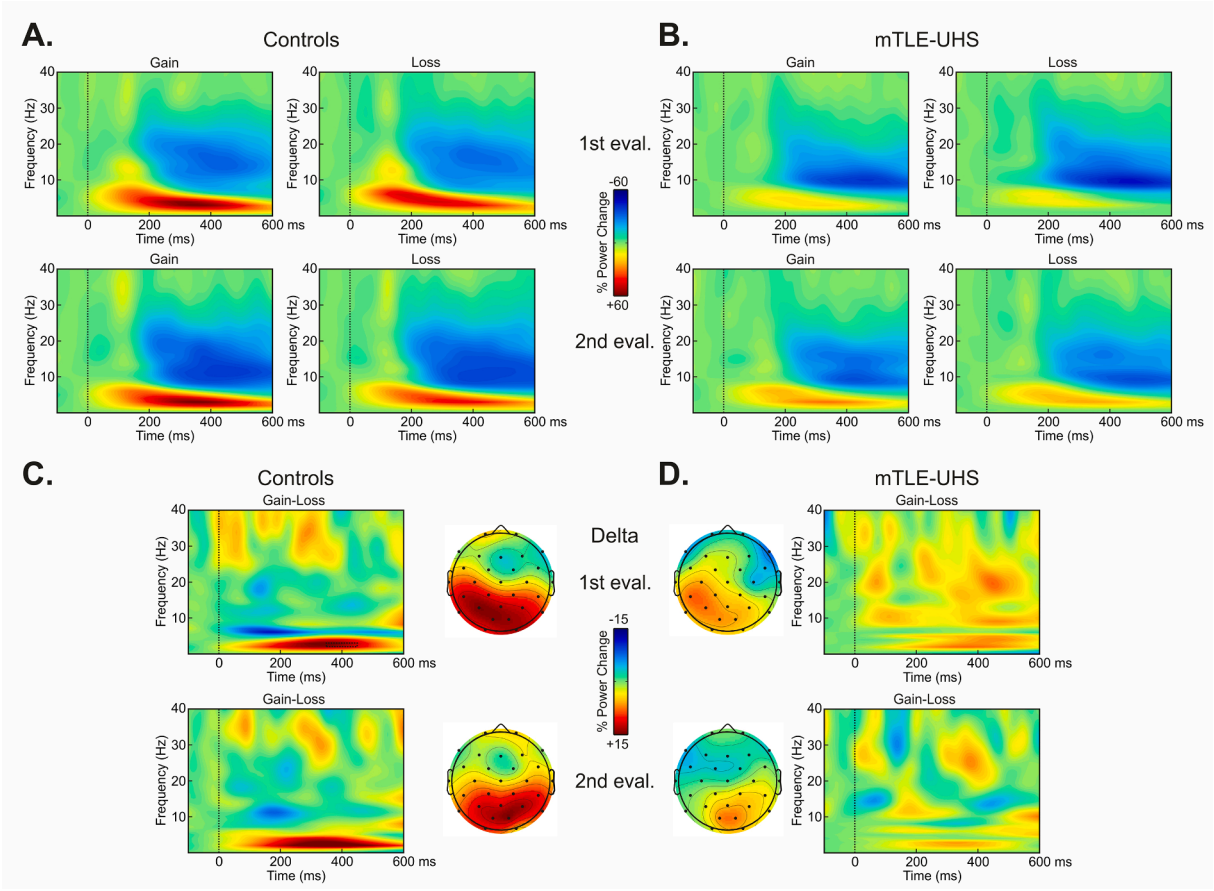

Fig. 4. Time–frequency plots representing power changes (with respect to the baseline) at frequencies between 1 and 40 Hz, at the selected ROI of electrodes (*P*3, PZ, *P*4, PO1, PO2). **A.** For the control group, time–frequency plots after gains (left) and after losses (right), for both first (top) and second (bottom) evaluations. **B.** For the mTLE-UHS group, time–frequency plots after gains (left) and after losses (right), for both first (top) and second (bottom) evaluations. **C.** For the control group, time–frequency plots with the differences between gains and losses and scalp distribution for the delta band-range (3–4 Hz, 250–350 ms), for both first (top) and second (bottom) evaluations. **D.** For the mTLE-UHS group, time–frequency plots with the differences between gains and losses and scalp distribution for the delta band-range (3–4 Hz, 250–350 ms), for both first (top) and second (bottom) evaluations.

[Evaluation: $F(1,32) = 1.09$, $p = .304$; Valence × Evaluation: $F(1,32) = 0.26$, $p = .614$]. No significant differences were observed across groups [$F(1,32) = 0.78$, $p = .385$; Valence and Group, $F(1,32) = 0.69$, $p = .412$]. Importantly, the surgery did not produce impairments in frontal beta-gamma activity in mTLE-UHS, as no significant interactions between Evaluation and Group were observed [Evaluation × Group: $F(1,32) = 0.21$, $p = .65$; Valence × Evaluation × Group: $F(1,32) = 0.06$, $p = .812$].

4.5. Correlation analyses

Correlation analyses were performed to test whether clinical variables in patients with mTLE-UHS (age at epilepsy onset, disease duration, and seizure frequency (days/month)) correlated with electrophysiological measures at the first evaluation (see Table 3). Please note that for this analysis, we only included the electrophysiological measures with significant group differences in previous analyses. Also, they were not corrected for multiple comparisons, specifically with regard to the amplitude of the FRN (loss minus gain), the mean frontal theta power (mean between gain and loss), the mean parietal delta power (mean between gain and loss), and the parietal delta power difference (gain minus loss). No statistically significant correlations were found, except for a significantly negative correlation between disease duration and parietal delta power difference.

5. Discussion

In the present study, we investigated decision-making and electrophysiological correlates of feedback processing in a group of patients with mTLE-UHS, before and after resective epilepsy surgery. We found that the mTLE-UHS group showed a riskier decision-making pattern on the IGT throughout the task, as compared to the control group. No significant group differences were found on the GDT or the probabilistic gambling task. Together with these behavioral findings, we also observed abnormal feedback processing in patients with mTLE-UHS as compared to controls, manifested by: (i) a decreased FRN, (ii) a weaker effect of emotional valence (loss vs monetary gains), together with a general reduction of the parietal delta activity, and (iii) a general reduction of frontal theta activity. Interestingly, patients also showed a normal effect of valence for the frontal theta activity and normal frontal beta-gamma activity. Importantly, in the mTLE-UHS group none of these measures significantly differed between the first and the second evaluation. These results indicate the presence of potential impairments in decision-making, specifically related to problems in feedback processing, suggesting that the malfunctioning reward system in patients with mTLE-UHS was already present, even before surgery.

5.1. Behavioral risk-related findings

In line with previous behavioral studies, we observed that under conditions of risk (evaluated with the GDT), patients with mTLE-UHS

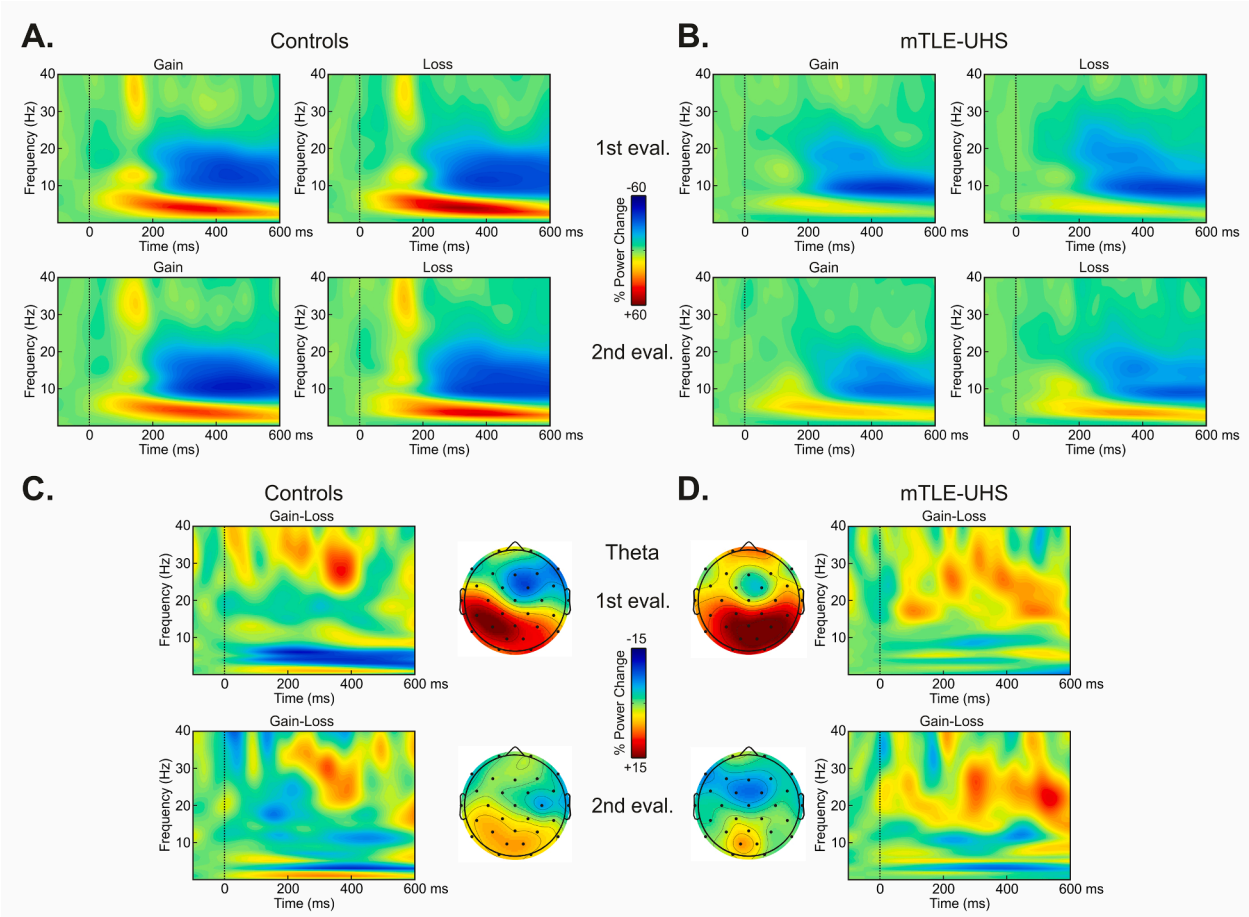

Fig. 5. Time–frequency plots representing power changes (with respect to the baseline) at frequencies between 1 and 40 Hz, at FC2 electrode. **A.** For the control group, time–frequency plots after gains (left) and after losses (right), for both first (top) and second (bottom) evaluations. **B.** For the mTLE-UHS group, time–frequency plots after gains (left) and after losses (right), for both first (top) and second (bottom) evaluations. **C.** For the control group, time–frequency plots with the differences between gains and losses and scalp distribution for the theta band-range (4–7 Hz, 200–400 ms), for both first (top) and second (bottom) evaluations. **D.** For the mTLE-UHS group, time–frequency plots with the differences between gains and losses and scalp distribution for the theta band-range (4–7 Hz, 200–400 ms), for both first (top) and second (bottom) evaluations.

performed just as well as the matched controls (Bonatti et al., 2009; Labudda et al., 2009; Delazer et al., 2010). However, under ambiguity or uncertain conditions (measured with IGT), patients showed substantial impairments in decision-making manifested through a greater number of disadvantageous/riskier card choices throughout the entire task. Interestingly, the statistical analysis corroborated the presence of impairments throughout the whole task. These findings partially align with previous research showing that patients with mTLE-UHS selected more disadvantageous cards than healthy controls (Labudda et al., 2009; Delazer et al., 2010; Yamano et al., 2011; Xie et al., 2013). This evidence may indicate difficulties in optimizing behavioral patterns based on feedback when there are only implicit rules and risky decisions should be avoided (for a review see Zhang et al., 2018), and might be linked to current electrophysiological findings. Moreover, we expected that the differences between groups would most likely occur towards the end of the IGT, when rules should be acquired, but patients might present learning difficulties. However, we were clearly unable to replicate the effect observed in past literature, as all the interactions involving group were not significant (suggesting similar learning between groups), which could probably be explained by our study's small sample size (see Limitations section for more information). It is also important to mention that no significant behavioral differences were observed between patients with mTLE-UHS and healthy controls on the ERP probabilistic gambling task. These results are in line with previous studies observing significant differences between diverse clinical groups and healthy controls at the electrophysiological level but not at the behavioral level (e.g., Miedl et al., 2014; Gomez-Andres et al., 2019; Stewart et al., 2019), which would suggest the task's lack of sensitivity in capturing behaviorally subtle clinical differences (Lin et al., 2013). Another possible explanation for these results is the reduced sensitivity to detect subtle behavioral effects due to the small sample size of each group (see Limitations section as well). Therefore, it remains necessary for future studies to carry out behavioral validation of this task and other related ones.

5.2. *Electrophysiological findings*

The typical electrophysiological pattern of feedback processing was observed on our probabilistic gambling task, consisting of a clear frontocentral FRN, greater parietal delta and frontal beta-gamma activities after gains, as compared to losses, and increased frontal theta activity after losses, as compared to after gains (Gehring and Willoughby, 2002; Cohen et al., 2007; Trujillo and Allen, 2007; Marco-Pallares et al., 2008; Cavanagh et al., 2010; Bernat et al., 2011; Foti et al., 2015; Williams et al., 2021).

Concerning group effects, we found a reduced FRN (difference waveform) in patients with mTLE-UHS as compared to controls, corroborated by the significant interaction between valence and group. To better delineate the cognitive processes involved in this effect, we decomposed the FRN component into the time–frequency domain, and

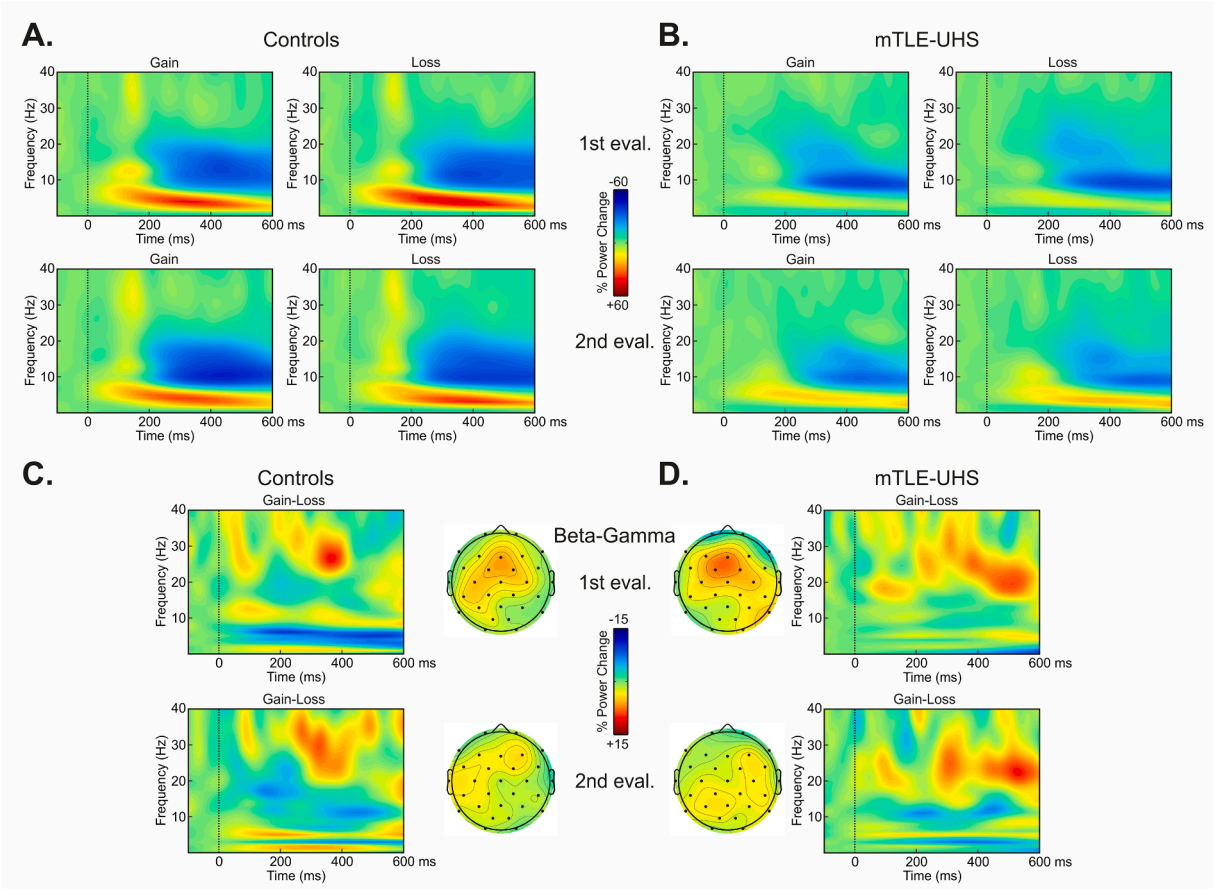

Fig. 6. Time–frequency plots representing power changes at frequencies (with respect to the baseline) between 1 and 40 Hz, at the selected ROI of electrodes (F3, FZ, F4, FC1, FC2). **A.** For the control group, time–frequency plots after gains (left) and after losses (right), for both first (top) and second (bottom) evaluations. **B.** For the mTLE-UHS group, time–frequency plots after gains (left) and after losses (right), for both first (top) and second (bottom) evaluations. **C.** For the control group, time–frequency plots with the differences between gains and losses and scalp distribution for the beta-gamma band-range (27–32 Hz and 330–430 ms), for first (top) and second (bottom) evaluations. **D.** For the mTLE-UHS group, time–frequency plots with the differences between gains and losses and scalp distribution for the beta-gamma band-range (27–32 Hz and 330–430 ms), for both first (top) and second (bottom) evaluations.

Table 3
For patients with mTLE-UHS, Pearson correlations between age at epilepsy onset (Onset), disease duration (Dis. Duration), seizure frequency in days/month (Frequency), and electrophysiological measures at the first evaluation, including the amplitude of the FRN (loss minus gain), delta power difference (gain minus loss), mean theta power (mean between gain and loss), and mean delta power (mean between gain and loss) were executed.

	FRN	Delta Difference	Mean Delta	Mean Theta
Onset	−0.021 (0.935)	0.034 (0.896)	0.037 (0.889)	0.092 (0.727)
Dis. Duration	0.184 (0.480)	**−0.506 (0.038)**	−0.269 (0.296)	−0.345 (0.175)
Frequency	0.156 (0.550)	−0.155 (0.552)	−0.194 (0.456)	−0.252 (0.329)

P-values were not corrected for multiple comparisons.

focused on its main oscillatory generators, the parietal delta and frontal theta activities (Cohen et al., 2007; Trujillo and Allen, 2007; Marco-Pallares et al., 2008; Cavanagh et al., 2010; Williams et al., 2021).

The contribution of the parietal delta activity to the FRN, mostly related with the processing of positive feedbacks, has been suggested to represent a neural index of expectancy-sensitivity (Watts et al., 2017), critical to feedback learning and choice or action selection (Cavanagh et al., 2012; Walsh and Anderson, 2012). The weaker effect of valence on parietal delta power, together with a general reduction of power in this frequency range, in the mTLE-UHS group as compared to the control group, might explain the reduced FRN and associated impairments in feedback processing. Furthermore, these results might suggest that patients with mTLE-UHS have difficulty correctly evaluating external outcomes. Moreover, this could affect the patients' capacity to make accurate predictions about future outcomes, which might explain the problems associated to riskier or impulsive behaviors in this population, on ambiguous or uncertain decision-making tasks (Labudda et al., 2009; Yamano et al., 2011; Xie et al., 2013; Zhang et al., 2018).

Frontal theta activity also contributes to the FRN, specifically by processing negative feedbacks, and has been related to cognitive monitoring and reinforcement learning, as well as indexing the need to readjust behavior and deviations from the predicted value of the actions (Cavanagh et al., 2012; Janssen et al., 2016). However, given that we did not observe a weaker effect of valence on theta power, these processes might be preserved in patients with mTLE-UHS, and the reduced FRN in this group, might not be related to theta activity. Interestingly, the total theta power is also related to other processes different from the ones related to the FRN (Rawls et al., 2020). In light of this, the general reduction of theta power observed in patients with mTLE-UHS in contrast to healthy controls, might be related to problems with encoding task-relevant information (Siegle and Wilson, 2014; Kerrén et al., 2018; Sugar and Moser, 2019).

Additionally, and despite a visual inspection of Fig. 6 potentially suggesting the contrary, we did not observe statistically significant differences between groups in frontal beta-gamma activity. This frequency

range has been suggested to be a neural marker of reward processing associated with monetary gains (Marco-Pallares et al., 2008; Marco-Pallarés et al., 2009), positive feedback, and prediction errors (Cohen et al., 2007; Cunillera et al., 2012; HajiHosseini et al., 2012). Importantly, it has also been related to expectancy mechanisms (HajiHosseini et al., 2012), and associated to information processing integration of remote structures (Buzsáki and Draguhn, 2004). Taking into account results of frontal beta-gamma activity, these processes may be preserved in patients with mTLE-UHS.

5.3. Network disorganization in mTLE-UHS

Although the focus of damage in patients with mTLE-UHS is the hippocampus, neuroimaging studies have observed that this disorder causes progressive damage and neural reorganization in regions and networks connected with the mesial temporal lobe (Spencer et al., 2002; Maller et al., 2019; Roger et al., 2020; Morgan et al., 2021). Importantly, some of these networks may have a clear role in feedback processing and decision-making (Martínez-Selva et al., 2006), but also in working memory, episodic memory, language, verbal comprehension, processing speed, and constructional abilities (Zhang et al., 2018; Reyes et al., 2019; Ives-Deliperi and Butler, 2021). For this reason, the current findings provide important insights about which brain networks might be affected in mTLE-UHS.

Along these lines, it has been suggested that the processes related to the generation of the delta activity associated to the FRN were supported by connections between the ventral striatum and other subcortical regions linked to the mesial temporal cortex (Foti et al., 2015). Importantly, the disorganization of this network in mTLE-UHS, may have a clear impact on impairing the proper processing of feedbacks, diminishing the delta power and FRN amplitude, and affecting the selection of choices (Cavanagh et al., 2012; Walsh and Anderson, 2012) during decision-making, at least, under ambiguity (IGT). Additionally, the negative correlation found between disease duration and delta power difference, may add additional support in understanding how progress in network disorganization might generate progressive impairment of these processes.

In contrast, the frontal theta activity linked to the FRN relies more on networks connected with the anterior cingulate cortex. This activity has been suggested to reflect the influence of a decrease in ventral tegmental area dopaminergic signals in the midbrain after unexpected punishments, which is transmitted to the medial prefrontal cortex (mPFC), especially the anterior cingulate cortex (Holroyd and Coles, 2002; Nieuwenhuis et al., 2004; Müller et al., 2005). This signal is related with mediating subsequent behavioral adjustments (Cohen et al., 2007; Marco-Pallares et al., 2008; Foti et al., 2015). Interestingly, these processes were not significantly affected in our sample of patients with mTLE-UHS, suggesting a functional preservation of the anterior cingulate cortex network (Morgan et al., 2021).

However, we observed a clear reduction in total frontal theta power in the mTLE-UHS group as compared to the control group. The amount of theta power has been strongly associated with the hippocampus, but also with the mesial temporal regions in general, and has been linked to cognitive control, computational processes (Buzsáki, 2002), and importantly working-memory and memory encoding (verbal and visuospatial) (Brzezicka et al., 2019). Thus, the reduction in theta activity observed in patients with mTLE-UHS, might also reflect a dysfunction of active information maintenance, but also encoding abilities, as well as difficulties in learning from feedbacks in uncertain and ambiguous situations due to the inability to create expectations across the task (Vilà-Balló et al., 2017). Importantly, the mesial temporal network supporting these processes is one of the first being affected in patients with mTLE-UHS (Li et al., 2015).

Taking together behavioral, electrophysiological, and neuropsychological findings, it is possible to suggest that a relative preservation of the cognitive route, despite a disruption in the emotional route (Bonatti et al., 2009; Delazer et al., 2010) might also explain why patients with mTLE-UHS did not present significant impairments in decision-making under risk. However, the disruption of feedback processing (emotional route), together with the difficulties in working memory and memory, might explain the poor performance shown by patients with mTLE-UHS when performing decision-making under ambiguity (Martínez-Selva et al., 2006; Toplak et al., 2010; Yamano et al., 2011; Von Siebenthal et al., 2017). Interestingly, the disruption of mesial temporal lobe networks, with a special emphasis on the hippocampus, may partially explain these impairments (Stretton and Thompson, 2012). However, it is also important to mention that the abnormalities in other brain networks, such as fronto-parietal networks, mostly related with working memory and memory, might participate in the observed impairments in mTLE-UHS (Stretton and Thompson, 2012; Campo et al., 2013; Enatsu et al., 2015). In this vein, reduced activations of the superior parietal lobe have been observed in mTLE-UHS patients compared to healthy controls during working-memory tasks (Stretton and Thompson, 2012; Caciagli and Bassett, 2022). In this line, other studies detected stronger functional connectivity between this region (Stretton et al., 2013) and the hippocampus ipsilateral to the lesion (Stretton et al., 2014) in mTLE-UHS as compared to controls.

When focusing on the other neuropsychological results, deficits in verbal comprehension in patients with mTLE-UHS were in line with previous results (Yang et al., 2016; Zhang et al., 2018; Reyes et al., 2019; Ives-Deliperi and Butler, 2021) on left hemisphere lesions. In this line, although we expected to find alterations in verbal functioning due to the presence of patients with left temporal lobe lesions, in this study the impact on verbal functioning (measured through the BNT and verbal and semantic fluency tasks) did not reach significance. Furthermore, no significant impairments were detected for constructional abilities, fitting with previous studies indicating that the visuospatial domain is rarely impaired in patients with mTLE-UHS (Lee et al., 2002; Tallarita et al., 2019). Interestingly, speed processing deficits have been encountered in some patients with mTLE-UHS. Here, we did not observe significant impairments to this function. This would simply suggest that our sample mostly fits with the memory profile described by Reyes et al. (2019, 2020), despite certain deficits in verbal functioning.

5.4. Post-surgical effects

The resection of the anterior mesial temporal lobe for the relief of medically intractable mTLE-UHS constitutes the disconnection of this pathological network. But, surgery usually generates additional impairments (Zhang et al., 2018) such as in naming (Hermann et al., 1994; Sherman et al., 2011; Ives-Deliperi and Butler, 2012; Busch et al., 2016, 2018), and verbal memory (Hamberger and Drake, 2006). Taking into account these studies, but also the link between mesial temporal lobe networks and reward processing (Vilà-Balló et al., 2017) and decision-making (Bonatti et al., 2009; Labudda et al., 2009; Delazer et al., 2010; Yamano et al., 2011; Xie et al., 2013; Von Siebenthal et al., 2017), we initially expected additional impairments in these processes in patients with mTLE-UHS after surgery (Zhang et al., 2018). However, contrary to our initial hypothesis, we did not find differences between the first and second evaluations in patients with mTLE-UHS at both behavioral and electrophysiological levels, which might indicate that: (i) the emotional route (related with the IGT, Delazer et al., 2010), more dependent on ventral striatum and mesial temporal cortex connections (Foti et al., 2015), was already disrupted prior to surgery; whereas (ii) the cognitive route (related with the GDT, Delazer et al., 2010), which might rely on large-scale networks, may not have been directly affected by the resection of mesial-anterior temporal areas. Moreover, the surgery affected cognitive functioning in patients with mTLE-UHS, as seen by a decrease in verbal functioning and verbal memory scores from the first to the second evaluation. These results fit with previous literature, indicating that it is common to have a reduction of verbal function particularly related to naming (Hermann et al., 1994; Sherman et al.,

2011; Ives-Deliperi and Butler, 2012; Busch et al., 2016, 2018), and verbal memory function, after the surgery (Hamberger and Drake, 2006), due to the resection of mesial temporal structures of the critical left brain networks involved in these processes.

6. Limitations

This study is not free of limitations. The first limitation is related to the small sample size of the mTLE-UHS group, which may explain the lack of a significant Block × Group interaction on the IGT and also the lack of group differences in the ERP probabilistic gambling task. Consequently, only a partial replication of previous results (Labudda et al., 2009; Delazer et al., 2010; Yamano et al., 2011; Xie et al., 2013) occurred, and generalization of these results should be done with caution. Similarly, the small sample size did not permit us to separate patients into the four profiles defined by (Reyes et al., 2019). For this reason, generalization of these results to other mTLE-UHS profiles (Reyes et al., 2019), less affected by memory impairments, should be done with prudence. The second limitation is related to the fact that the same neuropsychological tests were used for both evaluations and this may result in increased performance due to practice. In fact, the time elapsed between the two evaluations (6 months) may not be sufficient to prevent certain practice effects on neuropsychological evaluations, which have been found, in some studies, to persist for years (Grunwald et al., 1998; Basso et al., 1999; Salthouse and Tucker-Drob, 2008; Helmstaedter et al., 2020). However, in the present study, controls exhibited a practice effect (performance improvements on some measures), whereas patients did not improve on any of the measures and even showed a decline in performance, in some cases. This pattern suggests that the deterioration of verbal functioning and verbal memory, observed in patients after surgery, may have been even more pronounced if different versions of the same tests were used between evaluations. Third, despite some findings indicating that altered reward processing may be associated with the depressive symptomology, frequently observed in patients with mTLE-UHS (Kondziella et al., 2007; Keren et al., 2018; Mikulecká et al., 2019), we did not perform an adequate evaluation of psychiatric symptoms. For this reason, we were unable to infer how the presence of negative emotional states in our population could affect the present results. Further studies are needed to confirm the impairments in feedback processing observed in the current study, but also to disentangle the relationship between cognitive impairments and mTLE-UHS profiles, negative emotional states, decision-making, and the network involved in mTLE-UHS (Camara et al., 2009; Haber and Knutson, 2010; Vilà-Balló et al., 2017).

7. Conclusion

The present investigation is the first study that assesses decision-making and electrophysiological correlates of feedback processing in patients with mTLE-UHS and monitors these processes before and after the epilepsy surgery. Our results suggest that patients with mTLE-UHS have impairments in decision-making under ambiguity, when they need to make decisions using the information provided by the outcomes, but not in decision-making under risk. Additionally, no differences were found between patients and controls when the task does not have any structure and feedbacks are random. These findings may be explained by an abnormal feedback processing detected with the altered EEG activity patterns, and likely boosted by the concomitant alterations in working memory, and in visuospatial and verbal memory. Taken together, these dysfunctions may make it more difficult to generate correct expectations of the outcomes, and therefore to adaptively make decisions. Importantly, these impairments might be the consequence of the disruption of brain networks connected to the mesial temporal lobe. Furthermore, the observed impairments in feedback processing and decision-making under ambiguity were already affected in patients with mTLE-UHS before surgery, and did not significantly worsen after surgery.

CRediT authorship contribution statement

Adrià Vilà-Balló: Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Myriam De la Cruz-Puebla:** Investigation, Validation, Writing – original draft, Writing – review & editing, Visualization. **Diana López-Barroso:** Investigation, Writing – review & editing, Supervision. **Júlia Miró:** Resources, Investigation, Writing – review & editing. **Jacint Sala-Padró:** Resources, Investigation. **David Cucurell:** Methodology, Software, Data curation, Writing – review & editing. **Mercè Falip:** Resources, Writing – review & editing, Funding acquisition. **Antoni Rodríguez-Fornells:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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