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RESEARCH ARTICLE

Phase-locking index and power of 40-Hz auditory steady-state response are not related to major personality trait dimensions

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Abstract Although a number of studies have demonstrated state-related dependence of auditory steady-state responses (ASSRs), the investigations assessing trait-related ASSR changes are limited. Five consistently identified major trait dimensions, also referred to as "big five" (Neuroticism, Extraversion, Openness, Agreeableness and Conscientiousness), are considered to account for virtually all personality variances in both healthy people and those with psychiatric disorders. The purpose of the present study was, for the first time, to establish the link between 40-Hz ASSR and "big five" major personality trait dimensions in young healthy adults. Ninety-four young healthy volunteers participated (38 males and 56 females; mean age ± SD 22.180 ± 2.75). The 40-Hz click trains were presented for each subject 30 times with an inter-train interval of 1–1.5 s. The EEG responses were recorded from F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 locations according to 10/20 electrode placement system. Phase-locking index (PLI) and event-related power perturbation (ERSP) were calculated, each providing the following characteristics: peak time, entrainment frequency, peak value and mean value. For assessing "big five" personality traits, NEO Personality Inventory Revised (NEO-PI-R) was used. No significant correlation between 40-Hz ASSR PLI or ERSP and "big five" personality traits was observed. Our results indicate that there is no dependence between 40-Hz ASSR entrainment and personality traits, demonstrating low individual 40-Hz variability in this domain. Our results support further development of 40-Hz ASSR as a neurophysiological marker allowing distinguishing between healthy population and patients with psychiatric disorders.

Keywords Auditory steady-state response (ASSR) · Gamma-frequency activity · 40-Hz ASSR · Personality traits · Phase-locking index (PLI) · Trait-related evoked response changes

Introduction

The auditory steady-state response (ASSR) is observed when periodically presented auditory stimuli produce electroencephalographic entrainment (Picton et al. 2003). As a consequence, the frequency of the ASSR approaches the frequency of presented auditory stimulation. The greatest magnitude of the ASSR is achieved when the stimuli are presented at 40-Hz frequency (referred to as 40-Hz ASSR) (Galambos et al. 1981). In the past years, 40-Hz ASSR has been used to test the ability of local cortical networks to generate gamma-frequency activity in patients with psychiatric disorders (Brenner et al. 2003; Light et al. 2006; Krishnan et al. 2009). Both gamma-band response and 40-Hz ASSR in particular have been proposed to serve as biomarkers of schizophrenia (Gandal et al. 2012; O'Donnell et al. 2013).

A number of studies argue that ASSRs are sensory responses, reflecting the integrity of auditory circuits (Teale et al. 2003; Brenner et al. 2009; Spencer et al. 2009; Hamm et al. 2011), that might be sensitive to state-related changes.

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Indeed, several state-related 40-Hz ASSR influences, such as sensitivity to controlled changes in general arousal (Jerger et al. 1986; Linden et al. 1987; Cohen et al. 1991; Griskova et al. 2007), activation level (Griskova et al. 2009; Griskova-Bulanova et al. 2011) and attentional demands (Ross et al. 2004; Skosnik et al. 2007; Gander et al. 2010), have been demonstrated.

At the same time, another group of studies supports the view of ASSRs as being a reflection of not merely sensory response, but rather global synchronization of neural activity with the external environment (Light et al. 2006; Koenig et al. 2012; Tada et al. 2014). Previous studies investigating gamma-band relation to personality traits have shown some associations between spontaneous gamma (Jausovec and Jausovec 2007) and early gamma-band responses evoked by visual stimuli (Kornmayer et al. 2015). Moreover, 40-Hz ASSR is regarded as a reflection of the cortical ability to generate gamma-band oscillations used in clinical studies (Brenner et al. 2009; O'Donnell et al. 2013; Hamm et al. 2015; Kim et al. 2015). Correlation of 40-Hz ASSR measures with working memory (Light et al. 2006) and attention (Tada et al. 2014) has been demonstrated, as well as with the sensitivity to concurring task load (Yokota and Naruse 2015) that is also observed in other SSR modalities (Kemp et al. 2002, Gray et al. 2003, Casey et al. 2010). These suggest that the 40-Hz ASSR might be an indicator of complex synchronization processes. A recent study by Escoffier et al. (2015) has suggested the model of entrainment of neuronal oscillations as a global mechanism that is used by the brain to optimize attention and stimulus perception (Escoffier et al. 2015)—a processes, associated with personality traits (Martel et al. 2014; Ledesma et al. 2015; Meyer and Morey 2015). Such model, due to its global intrinsic component, would imply possibility of complex inherent influences on steady-state response generation. However, up until now, the complex trait influences affecting ASSR generation, such as those related to personality traits (Bouchard and McGue 2003), have never been investigated. This hinders further development of ASSRs as a biomarker for psychiatric disorders, including schizophrenia.

The study by Boyette et al. (2013) suggested that personality traits can be of high clinical relevance in studies related to psychiatric disorders because they may: (1) contribute to the vulnerability of developing the disorder; (2) influence the course of illness; (3) be associated with specific symptoms (although findings supporting this last statement are inconsistent). In all the above-mentioned conditions, application of biomarkers is favorable. Moreover, behavior problems (Lewis et al. 2014) and clinical personality disorders (Stone 1993; Widiger and Costa 1994) are viewed as manifestations of extreme variation along normal personality trait dimensions. Several studies have demonstrated that personalities of individuals with schizophrenia differ from those without it, even before the psychiatric symptoms have manifested (Van Os and Jones 2001; Lonnqvist et al. 2009; Cuesta et al. 2015).

Five consistently identified major trait dimensions, also referred to as "big five" (Neuroticism, Extraversion, Openness, Agreeableness and Conscientiousness), are considered to account for virtually all personality variances in both healthy people and those with psychiatric disorders (Stone 1993; Moldin et al. 1994). These major trait dimensions are also found to have a strong genetic contribution (Briley and Tucker-Drob 2012). The "big five" have shown to be stable across lifetime and cultures and have been identified in multiple studies using different instruments (John and Srivastava 2001).

Interestingly, compared with other personality trait dimensions, Neuroticism appears to be correlated with a wider range of mental and physical health problems (Saulsman and Page 2004; Malouff et al. 2006, 2007). Neuroticism is operationally defined by items referring to irritability, anger, sadness, anxiety, worry, hostility, self-consciousness and vulnerability that have been found to be substantially correlated with one another in factor analyses (Costa and McCrae 1992; Goldberg 1993; Costa et al. 2014). Higher Neuroticism scores in schizophrenia patients (Gurrera et al. 2014; Suslow et al. 2014) and bipolar disorder (Naragon-Gainey and Watson 2014) are commonly observed. In addition to Neuroticism, the dimension of Agreeableness deserves close attention. According to meta-analysis by Saulsman and Page (2004), the dimension of Agreeableness might be virtually as informative with respect to association with psychiatric disorders as the dimension of Neuroticism. Importantly, along with increased Neuroticism, Agreeableness was reported to be reduced in schizophrenia (Lysaker et al. 2003; Lindner et al. 2014).

The purpose of the present study was, for the first time, to establish the relationship between 40-Hz auditory steady-state response and "big five" major personality trait dimensions in healthy young people. Based on the known reduction of 40-Hz ASSR in schizophrenia, where high Neuroticism levels and low Agreeableness levels are observed (Lysaker et al. 2003; Gurrera et al. 2014; Lindner et al. 2014; Suslow et al. 2014), we expected to see negative relationship between 40-Hz ASSR measures and Neuroticism scores and positive relationship between 40Hz ASSR measures and Agreeableness scores, respectively.

Methods

Subjects

The study was approved by the Lithuanian Bioethics Committee, and all participants gave their written-informed consent. Ninety-four healthy young adults participated (38 males and 56 females; mean age 22.18 ± 2.75). Study volunteers were requested to abstain from alcohol for 24 h and from nicotine and caffeine for 2 h prior to testing. Each participant was given a brief description of the procedure. Exclusion criteria for the study consisted of any reported neurological disorder or known hearing problems. Twenty participants were left-handed, as evaluated by Edinburgh Handedness Inventory Short Form (Veale 2014).

Procedures

Neo-PI-R

To evaluate individual personality differences, we have chosen revised NEO Personality Inventory (NEO-PI-R) (Costa and McCrae 1992), which is one of the most widely used instruments for the assessment of "big five" personality domains. The NEO-PI-R is based on a hierarchical model, where each of the five major personality factors comprises several related facets as a self-administered questionnaire, consisting of 240 items rated on a five-point response scale (from "strongly disagree" to "strongly agree"). This is an instrument with well-established reliability and validity for evaluation of Neuroticism, Extraversion, Agreeableness, Openness and Conscientiousness personality trait dimensions.

Stimulation

Stimuli were 500-ms 40-Hz trains, consisting of 20 identical clicks (1.5 ms burst of white noise), interspersed with 20-Hz stimuli (these 20-Hz data have been collected for the purposes outside the scope of the current study and are aimed to become a subject of a separate publication), delivered binaurally through the headphones (peak SPL of 60 dB). Each 40-Hz train was presented 30 times in a pseudo-randomized order with an inter-train interval set at 1–1.5 s. Participants were instructed to let their thoughts wander during the presentation of auditory stimuli and to focus their gaze at a fixation cross approximately 1.5 m in front of them.

Recordings

The electroencephalographic (EEG) signal was recorded with an EEG amplifier (ANTneuro, the Netherlands) from F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 sites (International 10-20 System) by using Ag/AgCl electrodes. Averaged mastoid electrodes served as reference; the ground electrode was attached close to Fz. The impedance was kept below 5 kΩ. The recorded signal was digitized at 512 Hz.

Data analysis

The NEO-PI-R scores were expressed as *T*-scores (statistical differences) from the age- and gender-adjusted population mean, according to published instructions (Costa and McCrae 1992).

The off-line processing of EEG data was performed in EEGLAB and ERPWAVELAB for MATLAB©. The power-line noise was removed using multi-tapering and Thomas *F*-statistics implemented in CleanLine plugin for EEGLAB. The epochs containing muscle artifacts were manually rejected. The eye-movements correction was performed using independent component analysis (ICA). The epochs of 700 ms were created starting at 100 ms prior to the stimulus onset and lasting for 600 ms post-stimulus onset. The data were baseline-corrected to the mean of the pre-stimulus period. After the data preprocessing, minimum 28 responses were averaged for each study participant.

A wavelet transformation (WT; complex Morlet wavelet from MATLAB© Wavelet Toolbox; frequencies represented from 1 to 80 Hz, 1-Hz intervals between each frequency) was performed. More details on inter-trial phase coherence (also known as phase-locking index, PLI) can be found in Morup et al. (2007). The PLI was selected as it is the least sensitive to noise (Kalcher and Pfurtscheller 1995; Griskova et al. 2009; Rojas et al. 2011) and the most reliable (McFadden et al. 2014) parameter among other ASSR measures. The random phase coherence, a constant depending on the number of epochs, was subtracted from the post-stimulus PLI measures. The event-related power perturbation (ERSP), indicating event-related changes in power relative to a pre-stimulus baseline, was also used, as this measure is commonly applied in clinical SSR-related studies. Further, PLI was decomposed through nonnegative multi-way factorization (NMWF), indicating the activity that is the most common across subjects (Morup et al. 2006). The NMWF results in the identification of the common recorded activity components, where each component can be described by a signature of the maximal activity in time, frequency and location domains (Arnfred et al. 2008), thus providing three characteristics (signatures) of the measure of interest: the time of the maximal entrainment, the frequency of the entrainment and the value of the measure (PLI/ERSP). Such approach resembles manual peak detection of event-related potentials (ERPs) that is determined by inspection of the grand average of the data or according to previous findings in the literature. Based on previous ASSR studies (Griskova et al. 2009; Griskova-Bulanova et al. 2011), the window for mathematical decomposition of ASSRs was set to 36–46 Hz range with +200- to +400-ms time interval. Additionally, commonly applied in other studies time-averaged PLI and ERSP measures were calculated, further referred in the text as

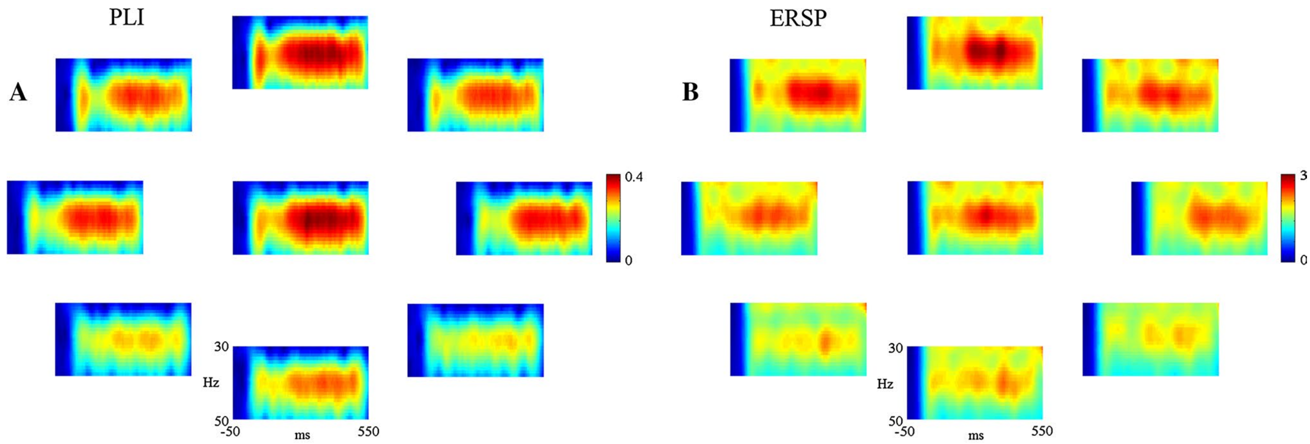

Fig. 1 Topographical plot of 40-Hz ASSR. Maximal activity, consistent across subjects, was identified at the Fz electrode, with the largest entrainment in 250- to 350-ms window for both phase-locking index (PLI, **a**) and event-related spectral perturbation (ERSP, **b**)

mean PLI/ERSP. The averaging was performed for 0- to 500-ms time period within 38–42 Hz range.

Statistics

The means and standard deviations of all measures were calculated. Inter-correlations among the five NEO-PI-R major domain scores were analyzed by using Pearson's correlation coefficients. This analysis aimed to help with the comparison of the current study results with the results that have been previously reported. After Bonferroni correction, *P*-values at 0.005 were regarded as significant.

The canonical correlation analysis was performed to estimate potential correlation of phase-based and power-based 40-Hz ASSR measures (PLI signatures—time, frequency and PLI value; ERSP signatures—time, frequency and ERSP value) with NEO-PI-R major factors (Neuroticism, Extraversion, Agreeableness, Openness and Conscientiousness). For PLI signatures: (1) as a criterion set—time, frequency and PLI value of individual responses were entered; and (2) as a predictor variable set—NEO-PI-R major factor estimates were utilized. The ERSP signatures were analyzed accordingly. *P* values smaller than 0.05 were regarded as significant. Relationship between the personality traits and the mean PLI/ERSP values was assessed by using Pearson's correlation with *P*-values at 0.01 regarded as significant after Bonferroni correction.

Results

Auditory steady-state responses

We were able to identify ASSRs in all subjects, except for four of them, whose data were later excluded from the analyses. To ensure the inclusion of both PLI and ERSP data from the same subject, we have removed the data of six subjects from further analyses due to their poor ERSP (a measure particularly sensitive to the noise) results. The final sample consisted of 84 subjects. Similarly to the previously reported results (Griskova-Bulanova et al. 2013), the non-negative multi-way factorization decomposition of PLIs and ERSPs resulted in the observation of a single component that was maximal over Fz. Topographical plots of PLI and ERSP are presented in Fig. 1. The peak entrainment of the PLI was observed at 303.15 ms (SD 67.85) at 40.2 Hz (SD 1.63) following 40-Hz stimulation (40-Hz ASSR) (Fig. 1). Mean peak PLI of 40-Hz ASSR was 0.32 ± 0.14; mean value of PLI in 0–500 ms time window was 0.28 ± 0.12. The peak entrainment ERSP was estimated at 314.15 ms (SD 63.90) at 39.73 Hz (SD 2.70). The mean peak ERSP of 40-Hz ASSR was 3.15 ± 1.28, and mean value of ERSP in the 0–500 ms time window was 1.56 ± 0.9.

Neo-PI-R

The mean age- and gender-adjusted *T* scores of the NEO-PI-R facets were in the healthy population range (Table 1). Inter-correlation between NEO-PI-R facets after Bonferroni correction revealed significant positive inter-correlation between Neuroticism and Conscientiousness, as well as between Openness and Extraversion, which is in line with the previously published results (Costa et al. 1991; Yoon et al. 2002; Sosic-Vasic et al. 2012). Inter-correlation results of NEO-PI-R scores are summarized in Table 2.

Correlation

To evaluate the multivariate shared relationship between the five major personality factors and measures of 40-Hz

Table 1 Descriptive statistics of T scores of age- and gender-adjusted NEO-PI-R facets

NEO-PI-R facets	Mean	SD
Neuroticism	50.54	10.77
Extraversion	52.04	11.38
Openness	58.76	9.50
Agreeableness	45.51	10.32
Conscientiousness	49.12	11.76

ASSR, separate canonical correlation analyses were performed using five major personality dimension variables (Neuroticism, Extraversion, Agreeableness, Openness and Conscientiousness) as predictors of the PLI and ERSP signatures (time, frequency and PLI/ERSP value). The full models across all functions for both PLI and ERSP signatures were insignificant using the Wilks's λ as criterion representing the variance unexplained by the model: for PLI signature Wilks's $\lambda = 0.811$, $F(15, 210.20) = 1.11$, $P = 0.35$; for ERSP signature Wilks's $\lambda = 0.852$, $F(15, 210.20) = 0.84$, $P = 0.64$. For more results, illustrating the absence of such relationship, bivariate Pearson's correlation coefficients of PLI and ERSP signatures (time, frequency, peak value and mean value) with NEO-PI-R facets and corresponding *P* values of the relationship assessment are presented in Table 3. Pearson's correlation coefficients of mean PLI and mean ERSP with personality traits are also presented in Table 3. No significant correlations were observed.

Discussion

In this study, we aimed to determine, for the first time, whether brain's ability to generate synchronous gamma-band activity, as measured by 40-Hz ASSR, is related to major personality trait dimensions in young healthy subjects. Contrary to our initial hypothesis to find a negative relationship between 40-Hz ASSR phase-locking and power measures with Neuroticism scores, as well as positive relationship between 40-Hz ASSR phase-locking and power measures with Agreeableness scores, no correspondence between ASSR measures and personality traits was observed.

Although, to our knowledge, the current study is the first one to investigate the relationship between "big five" personality traits and 40-Hz auditory steady-state response, a study evaluating the link between "big five" and gamma-frequency band of spontaneous EEG activity was previously performed by Jausovec and Jausovec (2007). The authors have reported less complex EEG patterns and higher power of gamma activity focused at parieto-occipital areas in the neurotic type. Additionally, a very recent study by Kornmayer et al. (2015) showed positive association between the schizotypal personality traits and power of the early visual gamma response, suggesting larger power values in more schizotypal subjects. The authors discussed the results in light of differential effects of disinhibition versus effortful control of attention that need to be considered more carefully in the research of gamma oscillations, especially in relation to positive symptomatology. The

Table 2 Inter-correlation coefficients between NEO-PI-R major domain scores and corresponding *P* values

	Neuroticism	Extraversion	Openness	Agreeableness	Conscientiousness
Neuroticism					
r	1.00				
P					
Extraversion					
r	−0.19	1.00			
P	0.08				
Openness					
r	0.03	**0.40***	1.00		
P	0.76	**<0.001**			
Agreeableness					
r	0.03	−0.17	0.07	1.00	
P	0.76	0.13	0.55		
Conscientiousness					
r	**−0.54***	0.14	−0.21	0.05	1.00
P	**<0.001**	0.19	0.05	0.65	

* Significant correlations are marked in bold; based on Bonferroni correction, *P* values at 0.005 were regarded as significant

Table 3 Correlation coefficients between 40-Hz ASSR parameters and NEO-PI-R major domain scores and corresponding *P* values

	Neuroticism	Extraversion	Openness	Agreeableness	Conscientiousness
PLI					
Time					
r	0.03	0.18	−0.03	0.08	0.11
P	0.80	0.09	0.81	0.48	0.31
Frequency					
r	−0.14	0.03	0.10	0.04	−0.05
P	0.20	0.78	0.36	0.70	0.64
Peak value					
r	0.13	0.10	0.02	−0.17	−0.00
P	0.24	0.35	0.89	0.13	0.97
Mean value					
r	0.15	0.04	0.05	−0.13	−0.02
P	0.16	0.71	0.367	0.25	0.83
ERSP					
Time					
r	0.03	−0.02	0.11	0.00	−0.04
P	0.76	0.89	0.31	0.99	0.71
Frequency					
r	−0.07	−0.13	−0.05	0.13	0.08
P	0.55	0.23	0.67	0.25	0.46
Peak value					
r	−0.07	−0.19	0.01	0.01	0.17
P	0.51	0.09	0.93	0.95	0.13
Mean value					
r	−0.05	0.00	0.11	−0.08	0.12
P	0.64	0.98	0.32	0.50	0.27

difference of our study from those by Jausovec and Jausovec (2007) as well as Kornmayer et al. (2015) is that these studies have investigated spontaneous and sensory evoked gamma brain activity, respectively, whereas in our study, the entrainment effect at 40-Hz gamma frequency has been evaluated. Therefore, the entrainment capabilities of the brain may be more stable across different individual personality domains than the brain's ability to generate spontaneous or transient sensory gamma activity. This speculation is supported by the fact that our study results are in agreement with several previous studies demonstrating the relationship between "big five" personality traits and brain abilities to entrain at lower frequencies. After a study by Rosenfeld et al. (1997) suggested that the ability to entrain at alpha and beta frequencies may depend on individual differences, the relationship between "big five" personality traits and brain entrainment to photic driving at 26 and 30 Hz (Stough et al. 2001) and to binaural beat at 16 Hz (Goodin et al. 2012) has been investigated; however, no significant effects were observed. The lack of correspondence between 40-Hz ASSR peak time together with phase-locking index and individual personality scores in our study suggests that, similar to previous studies by Stough et al. (2001) and Goodin et al. (2012) in lower-frequency bands, the entrainment abilities in the 40-Hz gamma-range are not dependent on major personality traits.

The lack of dependence of the 40-Hz PLI and ERSP on "big five" personality traits found in our study adds to the body of literature exploring the individual variability of ERPs, which is essential when considering them as potential specific biomarkers for psychiatric disorders. Previously, the state-related sensitivity of 40-Hz ASSR has been demonstrated, including subjects with ultra-high risk of developing schizophrenia (Tada et al. 2014). Our data suggest that 40-Hz ASSR, while being state-sensitive, is not trait-sensitive. Importance of low variability of ERP-based biomarkers in healthy population is vital when assessing the risk of developing the disorder (e.g., schizophrenia) in healthy population (Light and Swerdlow 2015; Naatanen et al. 2015). Individual variability of ERP-related measures can interfere with determining the cutoff value of healthy physiological response from the pathological one. For example, as discussed by Matsubayashi et al. (2008), Javitt et al. (1995) reported that 29 out of 30 of their studied schizophrenia patients as well as 5 out of 10 of their studied healthy controls had similar mismatch negativity (MMN) amplitude.

There are limitations to this study. Sample size, though comparable to the studies of clinical ASSR application, may be considered small by the personality research standards. The age representation of the sample was narrow (around 24 years), and thus the results may not generalize to other age ranges. We did not evaluate neurocognitive abilities of our subjects, although few studies have observed relationships between the neuropsychological performance and personality variance in non-psychiatric samples (Gurrera et al. 2005; Williams et al. 2010). Moreover, the recent study by Gurrera et al. (2014) has demonstrated a negative relationship between attention/planning and neuroticism, as well as a positive association between memory and openness in their control group—neuropsychological factors, such as attention (Tada et al. 2014) and working memory (Light et al. 2006), that were shown to correlate with 40-Hz ASSR measures. The relationship between 40-Hz ASSR parameters and neurocognitive functioning requires further investigation.

In conclusion, the lack of personality-related variability of both phase and power measures of 40-Hz ASSR demonstrated in current study suggests that the entrainment abilities in the 40-Hz gamma-range are independent from the major personality trait dimensions. This observation together with previously reported state-related sensitivity of the 40-Hz ASSR prompts further development of its clinical application as a neurophysiological biomarker aiming at differentiating between patients with psychiatric disorders and healthy population.

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