A comparison of spectral magnitude and phase-loc ing value analyses of the frequency-following response to complex tones

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 $(\text{Re } \varepsilon \cdot \varepsilon)$ 25 J $_2$ 2012; $\varepsilon \cdot \varepsilon$ 7 A $_2$ 2013; $\varepsilon \cdot \varepsilon$ 23 A $_2$ 2013)

Two experiments, both presenting differential distribution of e and e fundamental e fundamental e conducted to explore the envelope-relations e the frequency-following response $(\rm{FFR}_{EN}$), a e function synchronous, subcortical neural activity evoked by a periodic input. Experiment is directed to compute the magnitude spectrum analysis methods, computing the magnitude spectrum of ϵ $e^{i\theta}$, $e^{-i\theta}$, $e^{i\theta}$ (PL). Bootstrapping if $e^{i\theta}$ is $e^{-i\theta}$ FFREN from $e^{i\theta}$ eer modernesstatistically above the noise floor \mathbb{R}^n for approaches. Across and conditions, the two methods produced highly correlated results. The two methods produce H e.e., PL and R and R is regular produce readily interpretable readily interpretable readily interpretable results. M ee, et e fee te n . PL eet e ee t f than spectral magnitudes. Having established the advantages of ϵ and ϵ and ϵ of the approach was functions function $\mathfrak{g}_\mathbb{C}$ in the cousting \mathbb{R}^n contribution to ϵ FFRENV, and ϵ responses to complex to compute ϵ for different actions computed of the composition of different acoustic ϵ for different acoustic ϵ is a composition of different acoustic $\$ h (f 100 H (E_{xp}eriment 2). Results show that the FFRENT response is dominated by the FFRENT response is domin p and p and p auditory channels responding to \mathbb{R} to unresponding to \mathbb{R} de de la solved harmonics also contribute the utility of the PLV for the utility of the PLV for the Utility of the PLV for the PLV for the Utility of the PLV for the PLV for the PLV for the Utility of the PLV for the PLV f ϵ ϵ \mathbf{v}_i ϵ FFR_{EN} acoustical Society of America. $\frac{1}{4}$: $\frac{1}{4}$. $\frac{10.1121}{1.4807498}$ PACS $_{\rm e}$ (): 43.64.R TD Pesses 1384–395

I. INTRODUCTION

The frequency-following response (FFR), measured as a $e \circ e \circ \psi$ reflects $e \in \mathbb{R}$. portions of the audio pathway encoder periodic periodic periodic periodic periodic periodic periodic periodic **b** in $k = 0.5$, [Krishnan, 1999](#page-11-0); G
 $\frac{1}{N}$ $\frac{1}{2005}$; A and the et al., 200 et al.[, 2000;](#page-11-0) Kraus **and Nicol, 2005**; [Akhoun](#page-10-0) et al., 2008; D et al.[, 2011](#page-11-0)). Muniches the FFR $f_{\rm c}$ on the FFR $f_{\rm c}$ on the e e_1 are phase e_1 are phase e_1 are phase of the input stimes of the input stimaulus (FFRENV; the portion of the response that is the same $f \circ \mathcal{C}$ and $f \circ \mathcal{C}$ part because many artifacts and non-neural signals (such as e $\mathbf{c} = \mathbf{c} \cdot \mathbf{m}$ minimate that contains the measure that contains $\mathbf{c} = \mathbf{c} \cdot \mathbf{c}$ $\begin{array}{ccccc} \epsilon & \epsilon & \bullet & \epsilon & \epsilon \\ \epsilon & \epsilon & \epsilon & \epsilon & \epsilon \end{array}$ FFR_{EN}V., et [2011\)](#page-11-0). The ε is extremely in ε is correlated with percep- \mathcal{C} is a range of tasks, including at the level of \mathcal{C} individual of \mathcal{C} individual of individual of \mathcal{C} indi vidual subjects (e.g., [Krishnan](#page-11-0) et al., 2010; ϵ B_4 , 2007; B_{ur}et al., 2008; C [2011;](#page-10-0) ℓ e H m₃, 1980; K_{rig} et al., 2012; R_e et al.[, 2011;](#page-11-0) R ϵ et al., 2012). This ϵ and personal $c_{\ell,m}$ in some tasks has lead to recent surge of in ee FFR_{EN}.
M fig e $e^{\int_{\mathbf{M}_{\mathbf{R}}}}$ different methods have been proposed for $e \longrightarrow e \longrightarrow e \longrightarrow e \longrightarrow e$

 f_{eff} are not integrated artifacts of the noise at multiples of the multiples of a contribution electrical current to broadband neuro-electrical cur noise. This makes interpretation of the absolute spectral ϵ magnitude r magnitude results consider the channel r c_1 in the response are defined by the acoustic input, the noise floor, which is not flat, must be estimated and ϵ e results normalized appropriately. In direct contrast, the unit $e \cdot \text{PL}$ metric (for instance) is directly interpretable, with out e in the noise for the noise floor in the measures. M ee, e \mathcal{F}_s in the simplest number of \mathcal{F}_s . that the measurement phase at any given frequency is uni f_{max} distributed by π and π (e.g., the equation \mathcal{E} , has a distribution that depends on \mathcal{E} , \mathcal{E} and \mathcal{E} on the number of samples going into the calculation of samples $\mathfrak{c}_{\mathfrak{m}}$ in particulation. In particular, t_{max} , t_{max} is independent of both frequency and both frequency and t_{max} and t_{max} and t_{max} \mathbf{c} and \mathbf{c} , \mathbf{c} sources contributing to the noise sources contributi we assured responses in the contractors in the contract of I and ϵ is flat al., 2007 resulting the set of \mathcal{P}_1

the onset of T_{eff} the stimuli were presented with alternative with alternative with alternative with alternative with alternative with T_{eff} and T_{eff} and T_{eff} and T_{eff} are presented with alternativ nation starting polarities, so that half of \mathbf{f} all trials were presented in one polarity and the other half inverted to the $\mathcal{O}_\mathcal{F}$ opposite polarity. The polarity $\mathcal{O}_\mathcal{F}$

C. Equipment

 A, e , we all aspect e the experimental all aspects of the experimental all aspects of the experimental aspects of the experimental all aspects of the experimental all aspects of the experimental all aspects of the exp \mathbf{c} , including triggering triggering sound delivery and storing data. $S_{\mathcal{O}}$, we can be sound-control hardware (System 3 real-time singlet processing systems, including D/A conversion and D/A amplification; $T \in D$, $T \in D$, $T \in C$, $C \in C$, $C \in R$, F presented sound through insert phones (ER-1, E $_{\rm c}$, E_R G e_me, IL) g f_ce, FFR_{EN} e, e e e \blacksquare e recorded using a BioSemi A ℓ T S ℓ $(B$ \mathcal{L} $, A$ ℓ $, N$ ℓ $, N$ sample of 16.384 KH $_2$. \mathcal{A}_n . \mathcal{A}_n Bio \mathcal{B}_n e. \mathcal{S}_n specialistics, high-impedance electrodes optimized for \mathcal{S}_n $e^{\frac{i}{2}}$ recording subcortical responses, $e^{\frac{i}{2}}$ responses, $e^{\frac{i}{2}}$ responses, $e^{\frac{i}{2}}$ responses conductive A-A C_n , c_n ee c. Te FFR $_{EN}$ e. eele ϵ from active electrode ϵ \mathbf{e} (e.e.c. m.), EOG) eer monitored with two monitored with two monotored with two monotored with two monotones \mathbf{e} $e^{\frac{1}{2} \mathbf{w}_1}$ external electrodes. Prior to data acquisition, we ensured that e ϵ field ϵ and ϵ each ϵ and ϵ <20 mV.

D. Procedures

After electrodes \mathcal{A} $\mathfrak{e}\mathfrak{e}$ and $\mathfrak{e}\mathfrak{e}$ and $\mathfrak{e}\mathfrak{e}$ and $\mathfrak{e}\mathfrak{e}$ and $\mathfrak{e}\mathfrak{e}$ $\left(\begin{array}{ccc} \mathbf{c}-\mathbf{c} & \mathbf{E} & \mathbf{c}\end{array}\right.$ C-14 booth, C_{app} e, MA). T is defined a silent, participants watched a silent, captioned movie of the acoustic stimulity o $\text{E}[\mathbf{M}_1, \dots, \dots, \text{E}]$, $e \in e - 1$, $e \in \mathbb{R}$, $e \in \mathbb{R}$ or experimental session of 2 h, including setup and data collec t_{max} e.g., $e \to e$ is 1 stimulus $e \circ e$ repeated 1 4000 ee each in ϵ . The ee $e e$ \blacksquare ⁸ blocks of 1000 trials each, alternation each, alternation and alternation e noise conditions from block to block t \mathbf{b} block). Stimulus polarity alternation from the trial to tri dominate e , e , $\sqrt{200}$ e, e , f \mathbf{t} is (that is, 2000 e.e. each of 2 polarities and 2 polaritie $2 \bullet$ \bullet E ach participant in Experiment 2 performed for E \mathbf{e} ssions (\mathbf{e} , \mathbf{e}), each lasting 1.5 h, maximum \mathbf{e}), each lasting 1.5 h

 $i_n = e^{i_n t}$ setup and data collection. The four setup and data collection. The four sessions each collections each collection. The four setup and i_n eee et et thee \ldots (LO, MID, HIGH, BROAD, ee e_mf_ensel is eⁿ

The \mathbf{r}_i field \mathbf{e}_i extending the PLVs significantly above the \mathbf{r}_i noise floor occur at f the input stimulus, as f the input stimulus, as f expected. The experimental trends described in the spectral magnetic spectral magnetic magnetic spectral magnetic \cdot equalities are also seen in the PLV e_{\cdot} results. In the \cdot $\rm{FFR}_{\rm{EN}}$

FIG. 4. C_{omp} of PL₂, equation of PL₂ m agnitude responses in ϵ in ϵ in ϵ and in ϵ as associated in ϵ \mathbf{a}_i fermer efect (E, e e 1). () Across-subject average PLV $(\blacksquare_3 \varepsilon)$ and spectral magnitudes in ε (circles) as $z_z = e - (e_{\rm m})$ ce e ϵ , error bars show the across- ϵ standard deviation, ϵ obscuring consistent differences between the \cdot () Te e. e een PLV \mathbf{w}_i become spectral magnitude z- ε . $(\varepsilon_n - \varepsilon_n - \varepsilon_n \varepsilon_n \varepsilon_n - \varepsilon_{n-1} \varepsilon_n \varepsilon_n)$ for z-scores exceeding a value of 4, $e \rightarrow e \rightarrow e$ subjects, and frequency $e \cdot F$ and $e \cdot e$ and $e \cdot e$ and $e \cdot g$ $c_1 \cdot F$ $c_2 \cdot c_3 \cdot c_4 \cdot c_5 \cdot c_6 \cdot c_7 \cdot c_8 \cdot c_8 \cdot c_9$ σ than spectral magnitude z-scores.

on c_n results that are significantly above that are significantly above the noise floor of a significant above the noise floor of a significant above the noise floor of a significant above the noise floor of a significa e c in e in e and e e e e e e e e e rather than the noise, we include in the analysis only the analysis only the analysis only the analysis only t values that we state that we state \mathcal{C} $\mathfrak{e}\circ \mathfrak{e}$ magnitude analysis and the PLV analysis for an \mathbf{c} condition, harmonic, \mathbf{c} , \mathbf{c} and subject. 16 ϵ f FFRENV 100 H_j(ϵ other harmonics, there has hardonics, the ϵ number of points was lower; at some of the highest harmon i there end and with responses that e not enough subjects with e above the noise floor to allow a meaningful comparison. We are e for every harmonic and condition that for every harmonic and condition that condition the ϵ enough data points to allow a direct assessment, spectral $m \cdot e \cdot e$ are $v \cdot e$ and $v \cdot e$ are very strongly correlated (see T_{B} E I).

 $T \epsilon \epsilon$, the ϵ_{max} show that the PLV analysis is in the PLV analysis is in the PLV analysis is in the PLV analysis in the PLV and T $\begin{array}{ccccc} \epsilon & \epsilon & \epsilon & \epsilon & \epsilon \end{array}$, see that $\begin{array}{ccccc} \epsilon & \epsilon & \epsilon & \epsilon & \epsilon & \epsilon \end{array}$ \blacksquare FFR_{EN} ε , ε ε the two approaches yield comparable patterns of results. T e e focus on $f(x)$ results.

4. Statistical effects of additive acoustic noise

 T correctly the effect of e and e and e and e and e \mathbb{R} . pared the across-subject average PLVs. First we found those FFR_{EN} components that we statistically above that we statistically above the noise the noise term of \mathbf{c} \mathbf{I} in the inner in both conditions (based on a Tukey's post hoc \mathbf{e} ; $\frac{1}{2}$ 100, 200, 300, 400, 500 H), central theorem entry computed the computed text computed the computation of ϵ fiere (e.e. PL i.e. e.e. PLV, e). \mathbf{c} then found then found the noise floor that we reflect that \mathbf{c} in the condition, but below the noise floor in the condition 600, 700, 800 H $; f \bullet e$,

 e and difference between the measured the measured value in e $g \in \mathbb{N}$ is a $f \in \mathbb{R}$ in \mathbb{R}^n in \mathbb{R} at the noise floor e and e is a generous estimate of the latter is a generous estimate of the latter is a generous estimate of the latter is a generous extension of the latter is a generous extension of the latter is phase locking evoked by the stimulus in e). As seen in \texttt{T} g \texttt{II} , \texttt{e} , $\texttt{FFR}_{\texttt{EN}}$ harmonic frequencies of 200,300, \sim 800. Heep ϵ , ϵ e ϵ
the noise noise noise ϵ is the noise noise in the noise ϵ is the noise in the noise in the noise in the noise is the noise in the noise in the noise ϵ cause ϵ e PL $100 \,\mathrm{H}$.

TABLE I. C e_n en e even spectral magnitude (B SNR) and PLV m easures across c and c in Experiment 1 for each n fundamental fundamental frequency. To be included in the analysis, a subject had to have \mathbb{R}^n both a spectral magnitude and PLV $e \cdot e$ is tatistically significant;

B. Experiment 2

 $E \nvert \xi = 2$ ever FFR_{EN} ε is $\varepsilon = \varepsilon$ for $\varepsilon = 1$ ferent actions in \mathbb{R}^n in put signals, each consisting of different \mathbb{R}^n f combinations of 100 H \cdot F \cdot e 5 shows the e across-subject average e of e \mathbf{r} average to the \mathbf{r} for $c \in \mathcal{E}$ complex to \mathcal{E} . $\blacktriangledown_{\text{E}}$ in Eq. 1, FFR_{EN} tends to be strongest at F₀ \mathbf{c} and \mathbf{c} in put stimulus—even for the input stimulus—even for \mathbf{c} \mathbf{c} is \mathbf{c} at the \mathbf{c} frequency is the frequency of \mathbf{c} e ie the magnitude of the magnit f_{max} of \mathbf{M}_1 \mathbf{M}_2 \mathbf{P} and \mathbf{P} and \mathbf{P} \mathbf{H}_1 are FFR_{EN} components at f_0 can be defined by f_0 $\mathbf{b}_\mathbf{c}$ and $\mathbf{c}_\mathbf{c}$, $\mathbf{c}_\mathbf{c}$, span c_n ing a range of c_n in c Acoustic Inputs **LOW** 0.30 $||$ $||$ $||$.
100 – 500 Hz 0.1 stimulus narmonies 0.3 \blacksquare $^{0.2}$ 600 11 1000 Hz $\frac{1}{2}$ · sumulus na · 一副GE 1200 – 1600 Hz \$ i pao $\frac{1560}{1500}$ $\frac{1500}{1500}$ ாமி Li de Legen de Meural Resourse France (Hz FIG. 5. Phase-locking value across subjects as a function of e in the neural subjects as a function of $f(x)$ response from the four different action of the function f in f deament 100 H (Experiment 2). For all stimuli, the envelope e_n erelate FFR are e_{n} and e_{n} and low-order harmonics at e_{n} of the fundamental, even for stimuli that do not contain acoustic energy F_0 .

 $r_{\rm c}$ in the lowest harmonics tends to be weakest for the the theorem tends to be weakest for the total tends to be LO ϵ fFFR $_{\rm EN}$ ϵ $\frac{d}{dx}$ stimulity stimulate the average PLV at 100 Hz e fig. \blacksquare different conditions (see Fig. 6). The LOW stimulus (see Fig. 6). The LOW stimulus of \blacksquare p c c e PLV than the other three $\begin{array}{ccc} \mathbf{c}, & \mathbf{c}, & \mathbf{M} \mathbf{D}, & \mathbf{H} \mathbf{I} \mathbf{G} \mathbf{H}, & \mathbf{BROAD} \end{array}$ stimuli and \mathbf{c} produced by \mathbf{c} $e^{-\mathbf{w}_1}$ similar values. These observations we performed e paired to the term Bonferrence of $p < 0.05/6$ $\begin{array}{ccc} \epsilon & \overline{a}_{\text{tr}} & \text{B} & \text{fe} & \text{c} & \text{(p} < 0.083) \\ 0.0083) & \text{m} & \text{c} & \text{f} & \text{m} & \text{T} & \text{c} & \text{c} \end{array}$ $c \to e$ f FFR_{EN} R_{ON} is significant of $F1$ \mathbf{f} \mathbf{HIGH} BROAD $t(1, 19)$ $4.0 \bullet p \quad 0.001$ $t(1, 19)$ 3.2, p 0.005, ϵ , ϵ ϵ , ϵ ϵ ϵ ω ϵ ω ϵ ϵ ω ω ϵ ω ω ϵ ω ω ω ϵ ω ω ω ω ω e LO_w stimulus f e MID 2.9, p 0.009, which is e^{i} and e^{i} e Big $e^{\mathbf{w}}$; (), of PL α are statistically significantly significantly significantly significantly different from α e e e e MID, HIGH, BROAD MID HIGH: t(1, 19) 0.5, p 0.632; MID BROAD: $t(1, 19)$ 0.6, p 0.544; HIGH BROAD: $t(1, 19)$ 0.1, $p \ 0.891$.

IV. DISCUSSION

A. Advantages of PLV analysis

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 e , e to the stimulus. Of e , the frequency e content of the resulting electrical signal will not be purely signal will not be purely signal will not be pure $n=1$ is the audience response is half-wave rectified, \mathbf{c}_i and \mathbf{c} includes a significant DC component [\(Pickles,](#page-11-0) [1982\)](#page-11-0). Mere, the federal as it programs is the contraction of e through the brainstead of ϵ is a sum of ϵ measure is a sum of ϵ activity along the mass A and e , \mathbb{F}_p , ee . There may be a result, there may be a result, there may be a result, then $\mathcal{C} \times \mathcal{C}$ is FFR $_{\text{EN}}$ in \mathcal{C} in response to the LOW stimulus, even in response to the LOW stimulus, even in \mathcal{C} is a set of the LOW studies of the LOW studies of the LOW studies of the LOW studies of t \mathbf{t}_1 to dominant auditory nerve response is \mathbf{t}_2 to \mathbf{t}_3 to \mathbf{t}_4 to \mathbf{t}_5 to \mathbf{t}_6 to \mathbf{t}_7 to \mathbf{t}_8 to \mathbf{t}_7 to \mathbf{t}_8 to \mathbf{t}_8 to \mathbf{t}_9 to \mathbf{t}_8 to \mathbf{t}_9 to \math

4. Statistical significance of spectral magnitude results

- distortion-product otoacoustic emissions, or other sinusoids, \mathbf{c} acoust. \mathbf{J} , \mathbf{A} acoust. $S.A. 100, 22362246.$
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