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Steady-State EEG and Psychophysical Measures of Multisensory Integration to Cross-Modally Synchronous and Asynchronous Acoustic and Vibrotactile Amplitude Modulation Rate

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Abstract

According to the *temporal principle* of multisensory integration, cross-modal synchronisation of stimulus onset facilitates multisensory integration. This is typically observed as a greater response to multisensory stimulation relative to the sum of the constituent unisensory responses (i.e., *superadditivity*). The aim of the present study was to examine whether the temporal principle extends to the cross-modal synchrony of amplitude-modulation (AM) rate. It is well established that psychophysical sensitivity to AM stimulation is strongly influenced by AM rate where the optimum rate differs according to sensory modality. This rate-dependent sensitivity is also apparent from EEG steady-state response (SSR) activity, which becomes entrained to the stimulation rate and is thought to reflect neural processing of the temporal characteristics of AM stimulation. In this study we investigated whether cross-modal congruence of AM rate reveals both psychophysical and EEG evidence of enhanced multisensory integration. To achieve this, EEG SSR and psychophysical sensitivity to simultaneous acoustic and/or vibrotactile AM stimuli were measured at cross-modally congruent and incongruent AM rates. While the results provided no evidence of superadditive multisensory SSR activity or psychophysical sensitivity, the complex pattern of results did reveal a consistent correspondence between SSR activity and psychophysical sensitivity to AM stimulation. This indicates that entrained EEG activity may provide a direct measure of cortical activity underlying multisensory integration. Consistent with the temporal principle of multisensory integration, increased vibrotactile SSR responses and psychophysical sensitivity were found for cross-modally congruent relative to incongruent AM rate. However, no corresponding increase in auditory SSR or psychophysical sensitivity was observed for cross-modally congruent AM rates. This complex pattern of results can be understood in terms of the likely influence of the *principle of inverse effectiveness* where the temporal

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principle of multisensory integration was only evident in the context of reduced perceptual sensitivity for the vibrotactile but not the auditory modality.

Keywords
Temporal processing, steady-state response, amplitude modulation detection, electroencephalography, psychophysics, cross-modal temporal congruence, auditory, vibrotactile

1. Introduction

The *temporal principle* of multisensory integration was initially described in research exploring the influence of stimulus features on the firing rate of multisensory neurons in the superior colliculus of the cat (Meredith *et al.*, 1987; Stein and Meredith, 1993). According to this principle, the cross-modal temporal coincidence or synchrony of stimulus onset enhances multisensory integration. This is evident where the magnitude of responses of multisensory neurons to cross-modally synchronous multisensory stimulation is greater than the arithmetic sum of responses to the constituent unisensory responses (i.e., 'superadditive') (Meredith *et al.*, 1987). The dependence of these superadditive multisensory enhancements on temporal synchrony suggests that cross-modal signals that are closer together in time are more likely to belong to the same perceptual source and therefore more likely to form an integrated percept. More recently, research in humans has provided confirmatory evidence of the temporal principle with cross-modal temporal congruence between auditory and visual stimuli found to enhance responses to multisensory stimuli using several different approaches including functional neuroimaging (Calvert, 2001; Lewis and Noppeney, 2010; Van Atteveldt *et al.*, 2007), electrophysiology (Lakatos *et al.*, 2007; Senkowski *et al.*, 2007) and perceptual studies (Diederich and Colonius, 2004; Wilson *et al.*, 2009).

Despite this growing body of research our understanding of the role of the cross-modal temporal synchrony has been largely restricted to stimulus onsets. Studies investigating the role of cross-modal temporal congruence for continuous or dynamic temporal properties of sensory stimulation suggest that these may also provide an important cue for multisensory integration. In a recent behavioural study participants were able to accurately match temporally congruent streams of acoustic and visual stimuli with lags of up to 200 ms, suggesting that it is the correspondence between the ongoing temporal structures of sensory stimuli which may be a more important predictor of multisensory integration than the relative timing of stimulus onsets (Denison *et al.*, 2013). Although behavioural research exploring auditory and tactile multisensory integration is limited, available evidence has also shown that cross-modal congruence of other stimulus features of acoustic and tactile stimuli, such as frequency, can dramatically influence performance on both detection and discrimination tasks (Ro *et al.*, 2009; Wilson *et al.*, 2010; Yau *et al.*, 2009).

Psychophysical studies using wide-band noise carriers have established that variations in amplitude modulation (AM) rate strongly influence the perceptual quality and salience of auditory and tactile stimulation. For both the auditory and tactile modalities AM stimulation at low rates (<10 Hz) results in each AM cycle being perceived as an individual perceptual event. At higher rates (10–50 Hz) the same acoustic or vibrotactile noise carrier creates a distinct flutter or 'motor-boating' perceptual quality, while AM rates greater than 50 Hz produce a more continuous tonal perception (Bendor and Wang, 2007; Nourski and Brugge, 2011; Saal *et al.*, 2016). Psychophysical sensitivity to both auditory and vibrotactile stimulation is also strongly influenced by AM rate. Viemeister (1979) used temporal modulation transfer functions (TMTF) to characterise auditory perceptual sensitivity to AM stimuli as a function of AM rate and showed that auditory sensitivity follows a low-pass function of AM rate. The TMTF revealed that the greatest sensitivity is evident for AM rates below 40 Hz and decreases at 3 dB per decade increase in AM rate. Similarly, perceptual sensitivity to vibrotactile AM stimulation is also strongly influenced by AM rate with sensitivity greatest at 20 Hz AM rate for a wide-band noise carrier and 40 Hz for a sinusoidal carrier (Weisenberger, 1986). This evidence indicates that AM rate is an important temporal property of auditory and vibrotactile stimulation and suggests that cross-modal synchrony of AM rate may play a key role in multisensory integration.

The dramatic influence of variations in AM rate on psychophysical sensitivity is paralleled by changes in entrained electroencephalography (EEG) and magnetoencephalography (MEG) to AM stimulation (Joris *et al.*, 2004; Nourski and Brugge, 2011; Rees *et al.*, 1986; Roß *et al.*, 2000). Entrained cortical activity to rhythmic stimulation can be measured using the steady-state response (SSR), which reflects oscillatory cortical activity driven by periodic sensory stimuli such as amplitude modulation. When analysed in the frequency domain the SSR typically shows a peak in activity at the EEG frequency corresponding to the AM stimulation rate. EEG studies using TMTFs to characterise the sensitivity of the auditory SSR to AM rate show a strikingly similar pattern to TMTFs reported in psychophysical research with auditory SSRs greatest in amplitude for AM rates of 40 Hz and below (Galambos *et al.*, 1981; Picton *et al.*, 1987; Rees *et al.*, 1986; Roß *et al.*, 2000). Similarly, EEG research examining the influence of AM rate on the magnitude of the vibrotactile SSR reveals a similar correspondence with psychophysical research where the maximal amplitude vibrotactile SSR is observed for AM rates between 20 and 30 Hz (Langdon *et al.*, 2011; Muller *et al.*, 2001; Snyder, 1992; Tobimatsu *et al.*, 1999). This apparent correspondence between psychophysical and EEG responses to AM suggest that the SSR may reflect cortical mechanisms that play a functional role in the perceptual processing of periodically modulated sensory stimulation (Rees *et al.*, 1986). The modality-specific sensitivity of the SSR to AM rate suggests it provides a unique neural measure of oscillatory cortical mechanisms involved in the processing of the temporal properties of sensory stimulation (Colon *et al.*, 2012; Rees *et al.*, 1986).

The sensitivity of the SSR to the temporal characteristics of unisensory stimulation has more recently been applied to better understand the neural mechanism underlying multisensory integration (De Jong *et al.*, 2010; Giani *et al.*, 2012; Nozaradan *et al.*, 2012; Porcu *et al.*, 2014). Using a ‘frequency tagging’ method, Nozaradan *et al.* (2012) examined whether the cross-modal temporal congruence between auditory and visual AM stimulation enhanced SSR activity. The results showed that the presentation of temporally congruent auditory and visual stimuli significantly enhanced both the magnitude and inter-trial phase coherence of both auditory and visual SSRs. The authors suggest that these enhancements reflect the oscilatory neural activity involved in the binding of multisensory stimulation. Using a similar frequency tagging approach, Giani *et al.* (2012) used SSRs to investigate how the brain integrates information both within and across the auditory and visual modalities. In contrast to the findings of Nozaradan *et al.* (2012) their results found evidence of enhanced SSR activity for within-modality stimulation but no evidence of multisensory SSR enhancements.

Given the modality-specific sensitivity of the SSR to variations in auditory and vibrotactile AM rate, together with recent evidence indicating that the SSR may provide a unique measure of multisensory integration, the aim of the present study was to determine whether SSR magnitude covaries according to the cross-modal temporal congruence of AM rate. As prior research has been limited to examining cross-modal temporal congruence in the auditory and visual modalities, the present research also sought to extend this to the auditory and tactile modalities. Further, as reviewed above, prior EEG and psychophysical studies suggest a close correspondence between SSR and psychophysical measures of AM sensitivity; however, no research has undertaken a combined assessment of both measures. Therefore a second aim of the present study was to undertake a combined psychophysical and EEG study of the within-subject correspondence between EEG and psychophysical measures of AM sensitivity. This design also provided a means to examine the extent to which auditory and vibrotactile cross-modal congruence of AM rate is consistent with predictions based on the temporal principle of multisensory integration.

To achieve these aims, cross-modal congruence of auditory and vibrotactile AM rate was varied across three experimental conditions in separate EEG and psychophysical sessions: Unimodal AM (amplitude-modulated carrier in one modality only with an unmodulated carrier signal presented to the other), Congruent AM (AM stimulation in both modalities with the same AM rate) and

Incongruent AM (AM stimulation in both modalities at different AM rates). As previous psychophysical and SSR research has established a modality-specific sensitivity to AM rate each of the three conditions was presented at either 21 or 40 Hz AM rate to determine whether modality-specific sensitivity was also evident in multisensory contexts. If the temporal principle applies to cross-modal congruence of AM rate, we expected that psychophysical thresholds and SSR responses for cross-modally congruent AM conditions would be significantly lower (i.e., greater sensitivity) relative to thresholds in both the unimodal and incongruent AM rate conditions. Additionally, as neural and behavioural responses to multisensory stimuli have been shown to be superadditive, we expected that multisensory presentations of acoustic and vibrotactile AM stimuli would lead to superadditive enhancements of SSR activity. Further, as prior auditory studies suggest a potential correspondence between psychophysical and SSR measures of temporal processing we expected to observe a correspondence between SSR activity and psychophysical thresholds across all experimental conditions.

2. Materials and Methods

2.1. Participants

Thirty-two (18 females, mean age: 25.35 years old) participants from the University of Newcastle completed both a psychophysical and EEG session for the current study. Ethics approval for the study was provided by the Human Research Ethics Committee of the University of Newcastle. Informed consent was obtained from each participant prior to participation. No participants reported a history of hearing problems, current use of psychoactive medication, serious head injury leading to loss of consciousness, psychiatric illness, epileptic seizures or other neurological conditions were excluded from participating. Hearing levels of each participant were assessed with a standard audiometric procedure adjusted to the level of a young adult with 0 dB just audible (American National Standards Institute, 1978). Thresholds were measured over five octave frequencies between .5 and 8 kHz. Participants with any threshold less than 20 below 0 dB were excluded from participation.

2.2. Stimuli

Acoustic and vibrotactile signals used in the present study were created using MATLAB software (MathWorks, IL, USA, 2011b). Amplitude-modulated signals were created by multiplying a 1500 ms 440.5 Hz sinusoidal carrier signal by either an 21 or 40 Hz sinusoidal modulator represented by the formula: $A \sin(w_{\mathrm{c}} t)[1 + m \sin(w_{\mathrm{m}} t)]$, where w_{c} is the angular frequency of the carrier signal, w_{m} the modulation rate, A the amplitude of the carrier, t the time after signal onset (0 ms) and m the modulation depth. Cosine rise/fall ramps of

5 ms were applied across all modulated and unmodulated signals. As prior research has established a modality-specific sensitivity to AM rate (Galambos *et al.*, 1981; Muller *et al.*, 2001; Picton *et al.*, 1987; Rees *et al.*, 1986; Roß *et al.*, 2000; Snyder, 1992; Tobimatsu *et al.*, 1999), the inclusion of both 21 and 40 Hz AM rates allowed us to investigate whether multisensory integration of AM stimulation was also modality-specific.

Modulation depth varied between 0 and 100% during the psychophysical session and remained at 100% during the EEG session for all AM stimuli. In order to ensure that the intensity of the stimuli did not vary across the different AM rate conditions, the energy of each signal was normalised to the root-mean-square (RMS) amplitude of the unmodulated carrier signal. Acoustic stimuli were calibrated in intensity using an artificial ear and sound level meter (Bruel and Kajer: Type 3158 and 4100). Auditory stimuli were presented binaurally at 80 dB SPL. Vibrotactile stimuli were delivered bimanually to the left and right index fingers of the participant using 1.5 × 3 cm piezoelectric benders (MagDesign and Engineering, CA, US) that were held in place to the distal phalange using 15 mm rubber tubing. Sound generated by vibrotactile stimulation was eliminated using custom-built anechoic tubes placed on each arm of the participant. While the intensity of the vibrotactile stimuli was not calibrated, vibrotactile stimuli were adjusted throughout extensive pilot testing to ensure suprathreshold vibrotactile stimulation without audible sound was generated throughout the experiment.

2.3. Psychophysical Design and Procedure

2.3.1. Stimulus Design

The psychophysical session was designed to measure how the temporal congruence of AM rate between acoustic and vibrotactile stimuli influenced perceptual sensitivity to AM stimuli. To achieve this auditory and vibrotactile AM detection thresholds were estimated separately for both 21 and 40 Hz AM stimuli across the following auditory (AUD) and vibrotactile (VBT) conditions being either unimodal AM (i.e., AUD21Hz_VBT0Hz, AUD40Hz_VBT0Hz, AUD0Hz_VBT21Hz, AUD0Hz_VBT40Hz), multisensory AM stimulus conditions with congruent AM rates (i.e., AUD21Hz_VBT21Hz, AUD40Hz_VBT40Hz), or multisensory AM stimulus conditions with incongruent AM rates (i.e., AUD21Hz_VBT40Hz, AUD40Hz_VBT21Hz). Additionally, four unisensory conditions (i.e., AUD21HZ, AUD40Hz, VBT21Hz, VBT40Hz resulted in a total of 12 AM detection thresholds.

2.3.2. Psychophysical Procedure

All psychophysical thresholds were measured using a three-interval two-alternative forced choice procedure (3I–2AFC) and where auditory and vibrotactile thresholds were measured in separate 3I–2AFC procedures. During each trial participants were presented with simultaneous acoustic and vibrotactile stimuli across three sequential intervals (1500 ms duration) separated by 600 ms silent periods. The AM stimulus (i.e., either 21 or 40 Hz) was randomly presented in one of the three intervals (i.e., the target) and unmodulated carrier signal was presented in the two remaining intervals. The AM rate varied according to the three congruence conditions being either an unmodulated carrier signal, a congruent AM rate or an incongruent AM rate. After each trial the participant was asked to indicate, *via* a three-pedal foot response device, which of the three intervals contained the AM target stimulus (i.e., 1, 2 or 3). Participants were provided with feedback after each response and the subsequent trial commenced after a 1000 ms inter-trial interval.

To estimate AM detection thresholds an adaptive psychophysical procedure was used. During the first four trials the AM depth of the AM target remained at 100%. For subsequent trials AM depth was according to a virulent PEST rule (Findlay, 1978) using the WALD sequential likelihood test (Wald, 1943). This estimation procedure was governed by the following rules: (1) For each reversal in step direction; the step size was halved; (2) the second step in a given direction was the same step size as the first; and (3) the step sizes of the fourth and subsequent steps in a given direction were double the size of their predecessor. Each threshold estimation procedure was terminated when the step size reached a predetermined minimum change in AM depth for a 75% chance of detection. AM detection thresholds were recorded as the depth at the final step size and converted to a logarithmic scale (dB). Detection thresholds were estimated twice for each participant and the final threshold recorded was taken as the average of the two estimates. Prior to participation participants completed numerous practice trials for both auditory and vibrotactile detection.

Psychophysical thresholds for each participant and threshold attempt were modelled using the Palamedes Toolbox (Prins and Kingdon, 2009) in MATLAB. A cumulative normal function was fitted to the proportion of correct responses across each stimulus level (i.e., AM depth). The model was defined by four parameters: threshold α, slope β, guess rate γ and lapse rate λ. The guess and lapse rates of the models were fixed to 0.3 and 0.01, respectively, while the threshold and slope were set as free parameters and estimated using maximum likelihood estimation. Thresholds were defined as the AM depth corresponding to a 66.7% proportion correct. Data providing a poor fit to the model (i.e., pDevs < 0.05) were excluded (Kingdon and Prins, 2016). Thresholds estimates for the same condition for each participant were averaged.

2.4. *Psychophysical Statistical Design and Analysis*

To investigate the impact of AM rate and AM congruence on perceptual sensitivity to acoustic and vibrotactile AM stimuli a psychophysical analysis was performed using custom MATLAB scripts and SPSS software (IBM SPSS Statistics, Armonk, NY). Auditory and vibrotactile threshold estimates were submitted to a three-way 2 (Modality: Auditory and Tactile) × 2 (AM rate: 21 and 40 Hz) × 3 (AM temporal congruence: unimodal, same AM rate, different AM rate) repeated-measures ANOVA. *Post-hoc t*-tests were used to explore differences in thresholds between the AM rate and temporal congruence conditions for both auditory and vibrotactile thresholds.

2.5. EEG Design and Procedure

2.5.1. Stimulus Design

Transducers and stimulus conditions used during the EEG recordings were identical to those used in the psychophysical session. During the EEG recording three additional conditions were presented that included presenting a carrier signal to either the auditory or tactile modality alone or simultaneously to both modalities. Modulation depth of acoustic and vibrotactile AM stimuli during the EEG recordings was maintained at 100%.

2.5.2. EEG Data Acquisition

EEG was recorded using 64-pin-type sintered silver-silver chloride (Ag/AgCl)-tipped scalp active electrodes attached to an elastic Biosemi 64 + 2 channel (CMS, DRL) electrode cap (extended 10–20 system). Signals were recorded using a BioSemi ActiveTwo amplifier (BioSemi, Amsterdam, Netherlands) with a 512 Hz sampling rate (24 bits DC) and with a common average reference. For the Biosemi ActiveTwo system the Common Mode Sense (CMS) and Driven Right Leg (DRL) electrodes served as the ground. Horizontal eye movements (HEOG) were recorded with two flat non-scalp electrodes that were placed on the outer canthus of both the left and right eye. Vertical eye movements (VEOG) were recorded by placing flat non-scalp electrodes approximately 2.5 cm above and below the centre of the right eye. Additional flat non-scalp electrodes were also placed at the mastoid prominence behind the left and right ears as well on the tip of the nose. EEG signals were acquired using ActiView data acquisition software (Version 7.06, Cortech Solutions, Wilmington, NC, USA). All electrode offsets remained at ±25 mV during the recording process. Stimulus combinations during the EEG session were randomly presented *via* a PC with Presentation software (Version 10.1.13, Neurobiological Systems Inc., Albany, CA, USA.). Inter-stimulus intervals (onset to offset) ranged between 1000 to 1500 ms in order to reduce time-locking of successive stimuli. During the EEG recordings stimuli were presented passively to participants as they viewed a silent nature documentary presented *via* a PC monitor. Each recording took place over a 90-min session with a break halfway. Recorded EEG activity was stored offline for later analysis.

2.5.3. EEG Processing and Analysis

Custom MATLAB scripts (MathWorks, IL, USA, 2015b), Fieldtrip (Oostenveld *et al.*, 2011) and statistical parametric mapping SPM12 (http://www.fil.ion.ucl.ac.uk/spm/software/spm12/) were used to process and analyse EEG data offline. Data was filtered between 0.1 and 80 Hz using a 5th-order Butterworth filter as well as notch filtered (Bandstop: 49 to 51 Hz) to reduce 50 Hz main power artefact. Electrooculogram (EOG) activity was corrected using a MATLAB- based EOG regression procedure (http://www.fil.ion.ucl.ac.uk/spm/software/spm12/). Epochs of 2000 ms were extracted from the continuous recordings and included the 500 ms pre-stimulus onset and ended 2000 ms post-stimulus onset. Epochs were zeroed by subtracting the mean amplitude over the entire epoch. Peak-to-peak amplitude jumps exceeding 200 μV or sample-to-sample differences exceeding 200 μV were rejected. Epochs were averaged according to the 11 stimulus conditions and baseline corrected over the 500 ms pre stimulus period. Grand average event-related potentials (ERPs) were calculated for each of the 11 conditions across the 64 electrode sites for all participants.

2.5.4. Steady-State Response Activity

An aim of the EEG session was to examine how the temporal congruence of AM rate influenced the entrainment of cortical oscillatory activity (i.e., the steady-state response). In order to do this EEG power was estimated using a Fast Fourier Transformation (FFT) for each participant across all sites and conditions resulting in bin sizes of 0.5 Hz. The FFT response was calculated between 300 and 1500 ms post stimulus in order to remove the influence of onset responses. To measure how congruence influenced steady-state response, activity power (μV^2) at each of the frequency bins on either side of the SSR frequency of interest (i.e., 21 and 40 Hz) was averaged and then extracted from the spectrum across each of the 11 stimulus conditions.

The frequency spectrum for each condition was adjusted according to a de-noising procedure (Nozaradan *et al.*, 2011, 2012, 2013). To effect this the average amplitude of the two neighbouring frequency bins either side of the bin of interest were subtracted. This procedure is based on the assumption that the amplitude of closely located frequency bins should be similar in the absence of a steady-state response. This resulting noise-corrected FFT data was then submitted to the statistical analyses.

To obtain separate auditory and vibrotactile SSR measures, sites eliciting maximal amplitude responses at both the 21 and 40 Hz EEG frequencies were selected according to the unimodal conditions. EEG power at both the 21 and 40 Hz EEG frequencies was then averaged across these sites according to unimodal SSR topographies. This allowed us to create separate auditory and vibrotactile SSR measures for both 21 and 40 Hz SSR frequencies in order to investigate the potential influence of temporal congruence and AM rate on auditory and vibrotactile SSRs.

2.6. SSR Statistical Design and Analysis

2.6.1. Steady-State Response Entrainment

To determine whether the SSR demonstrated entrainment at the respective AM stimulation rate a 2 (SSR frequency: 21 and 40 Hz) × 3 (AM condition: Carrier Only, 21 Hz AM, 40 Hz AM) repeated-measures ANOVAs was performed separately for the auditory and somatosensory SSR measures.

2.6.2. Superadditivity

To determine whether SSR activity to multisensory stimulation demonstrated superadditivity the purpose of the current analysis was to determine whether the magnitude of the SSR elicited by congruent multisensory AM stimuli was greater than the sum of SSR elicited by the constituent unimodal AM conditions (unimodal auditory AM + unimodal vibrotactile AM). A 2 (SSR frequency: 21 and 40 Hz) × 2 (modality: simultaneous and summed) repeated-measures ANOVA was performed separately for both the auditory and somatosensory SSR measures.

2.6.3. Cross-Modal AM Congruence

A 2 (SSR frequency: 21 and 40 Hz) × 2 (Cross-Modal AM Congruence: Congruent and Incongruent) repeated-measures analysis was performed separately on the auditory and vibrotactile SSR measures in order to investigate whether congruent multisensory AM stimuli led to enhanced SSR activity relative to incongruent AM stimuli.

3. Results

3.1. Psychophysical Results

The three-way repeated-measures general linear model ANOVA was performed to investigate how the factors of modality (auditory and tactile), AM rate (21 and 40 Hz) and AM temporal congruence (unimodal AM, congruent AM and incongruent AM) influenced AM depth detection thresholds. The results revealed a significant three-way interaction between modality, AM rate and temporal congruence [$F(2, 62) = 7.34$, $p = 0.001$, $\eta^2 = 0.19$]. Subsequently, the analysis was split into two separate two-way repeated-measures ANOVAs investigating the effects of AM rate and temporal congruence on auditory and vibrotactile AM detection thresholds separately.

The results of the auditory AM detection threshold analysis revealed no significant interaction between AM rate and AM temporal congruence conditions ($p > 0.05$). In contrast, the impact of temporal congruence on vibrotactile thresholds was found to be dependent on AM rate (AM rate × AM temporal

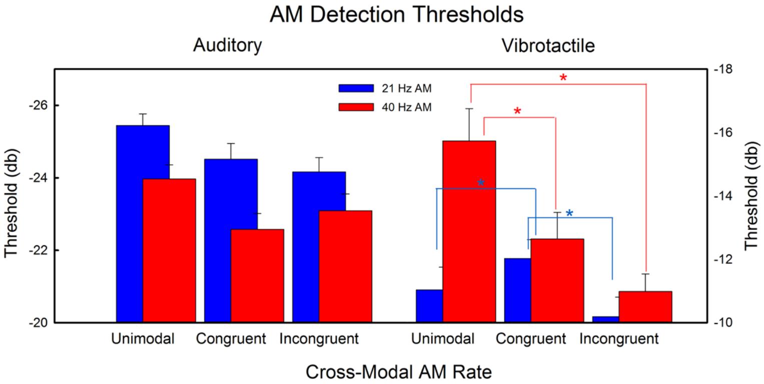

Figure 1. Mean auditory and vibrotactile psychophysical thresholds ($n = 32$, error = s.e.m.) for AM depth detection thresholds for 21 and 40 Hz AM stimuli across AM temporal congruence conditions (i.e., unimodal, congruent AM rates and incongruent AM rates). Asterisks highlight significantly different *post-hoc* pariwise comparisons between vibrotactile thresholds for each AM rate ($^{*}p < 0.05$). Note: The more negative the threshold the greater the perceptual sensitivity.

congruence interaction: $F(2, 62) = 9.15,\ p < 0.001,\ \eta^2 = 0.23$). As evident in Fig. 1 and confirmed by Bonferroni-corrected *post-hoc* comparisons, 21 Hz vibrotactile thresholds in the congruent AM condition were significantly lower (i.e., greater sensitivity) relative to the incongruent condition ($p = 0.04$) while differences between the other conditions were non-significant ($p > 0.05$). The 40 Hz AM vibrotactile thresholds were significantly lower in the unimodal condition relative to both the congruent and incongruent multisensory AM conditions (*ps* < 0.05). Overall both auditory (main effect of AM temporal congruence: $F(2, 62) = 9.92,\ p < 0.001,\ \eta^2 = 0.24$) and vibrotactile (main effect of AM temporal congruence: $F(2, 62) = 11.21,\ p < 0.001,\ \eta^2 = 0.27$) thresholds significantly varied across the AM temporal congruence conditions. As illustrated in Fig. 1 and confirmed by Bonferroni-corrected *post-hoc* t-tests, auditory sensitivity in the unimodal AM condition was significantly lower relative to both the multisensory congruent and incongruent AM condition (*ps* < 0.05). Overall vibrotactile thresholds in the incongruent condition were significantly higher relative to both the unimodal and congruent AM rate conditions (*ps* < 0.05). AM rate was also found to significantly influence auditory (AM rate main effect: [$F(1, 31) = 40.01,\ p < 0.001,\ \eta^2 = 0.56$] and vibrotactile [AM rate main effect: $F(1, 31) = 18.18,\ p < 0.001,\ \eta^2 = 0.37$] thresholds. Auditory thresholds were found to be significantly lower for 21 Hz AM stimuli relative to 40 Hz, in contrast vibrotactile thresholds were lower for 40 Hz AM stimuli relative to 21 Hz.

Additional separate two-way repeated-measures ANOVAs were conducted with the factors AM rate (21 and 40 Hz) and AM temporal congruence (congruent AM and incongruent AM) on both auditory and vibrotactile thresholds to explore differences between the multisensory AM conditions. The results revealed no significant interaction between AM rate and temporal congruence or significant main effect of temporal congruence (*ps* > 0.05); however, auditory thresholds were again found to be significantly lower for 21 Hz AM stimuli relative to 40 Hz [AM rate main effect: $F(1, 31) = 19.36$, $p < 0.001$, $\eta^2 = 0.38$]. Vibrotactile thresholds were significantly higher for the congruent AM conditions relative to incongruent AM conditions (temporal congruence main effect: $F(1, 31) = 8.31$, $p = 0.007$, $\eta^2 = 0.21$). Both the main effect of AM rate and the interaction between AM rate and AM temporal congruence for vibrotactile thresholds were non-significant (*ps* $>$ 0.05).

3.2. EEG Results

3.2.1. Steady-State Responses

Figure 2 shows the grand average ERP waveforms and corresponding frequency spectrums for both auditory and vibrotactile SSRs for the Carrier Only, 21 Hz and 40 Hz unisensory AM stimulation conditions. Each ERP waveform shows a tri-phasic onset response (P1-N1-P2) between 50 to 250 ms post-stimulus onset. Also evident is oscillatory activity from approximately 250 ms post stimulus onset; it appears as part of a pronounced negative shift (i.e., sustained potential) for the duration of stimulation (i.e., 1500 ms) and is followed by an offset response. The frequency of the oscillatory activity corresponds to the rate of AM stimulation as apparent from the corresponding FFT spectrums, which show ERP waveforms in the frequency domain. As evident in Fig. 2, the FFTs for both auditory and vibrotactile AM stimulation show clear peaks in power at EEG frequencies corresponding to the AM rate of the stimulus and the harmonics. These AM rate-dependent increases in EEG power are consistent with EEG entrainment and indicate both auditory and vibrotactile SSRs were obtained in the present experiment.

Figure 3 shows the grand average scalp topographies for EEG power across the 21 and 40 Hz SSR frequencies for the Carrier Only, 21 Hz and 40 Hz unisensory AM conditions. The auditory SSR topographies show a distinct topography with maximum power across frontocentral electrodes and inferior-parietal and mastoid electrodes which is consistent with auditory sensory activity (Näätänen and Picton, 1987). A different topography was found for vibrotactile SSR activity, which appears to vary depending on AM rate. As illustrated in Fig. 3, the 21 Hz SSR topography for the 21 Hz vibrotactile AM stimulation condition shows maximal power across a more frontal distribution

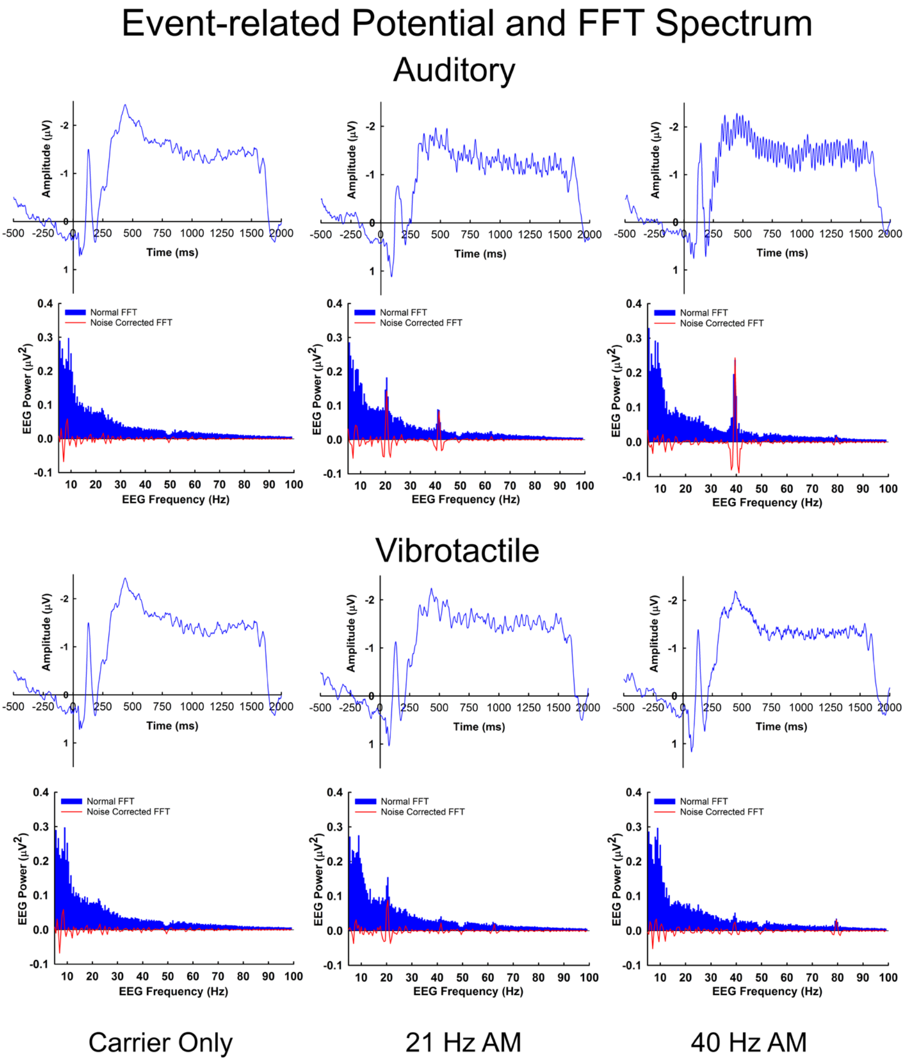

Figure 2. Grand average ($n = 32$) event-related potential waveforms (top row) and the corresponding frequency spectrums (bottom row) for the AM conditions (Carrier Only, 21 Hz AM and 40 Hz AM) for both auditory and vibrotactile stimulation (FCz). The grand average frequency plots display both the uncorrected (blue) and noise-reduced (red) frequency spectrums for each waveform for the time period between 300 to 1500 ms post stimulus onset.

relative to the auditory topography. This is consistent with the scalp topography of vibrotactile SSR activity reported in prior research (Porcu *et al.*, 2014). While the topography of auditory 21 and 40 Hz SSR activity was consistent for both 21 and 40 Hz AM stimulation, respectively, vibrotactile SSR topography was only clearly apparent for the 21 Hz vibrotactile SSR, which is consistent

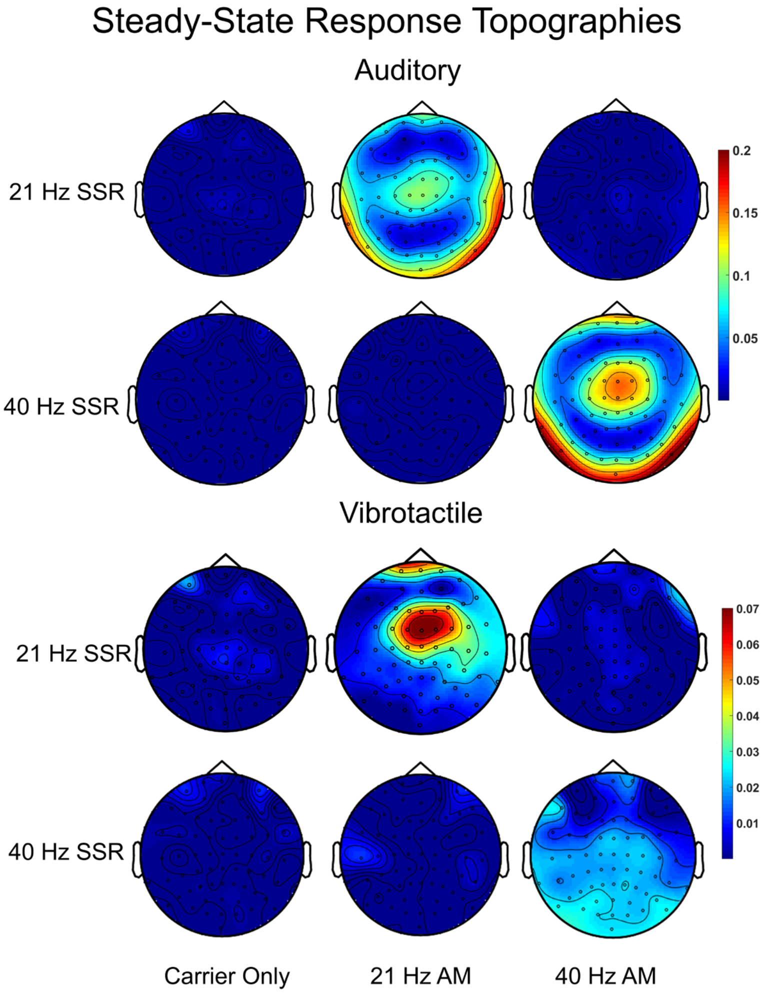

Figure 3. Grand average ($n = 32$) steady-state response (SSR) scalp topographies for both 21 Hz and 40 Hz noise reduced SSRs for the AM stimulation conditions (Carrier Only, 21 Hz AM and 40 Hz AM) for both auditory (top panel) and vibrotactile (bottom panel) stimulation.

with prior research showing the vibrotactile SSR is maximal at 21 Hz stimulation (Tobimatsu *et al.*, 1999). In order to best measure the modality-specific topographies of SSR activity a region-based analysis was undertaken to derive separate measures of auditory and vibrotactile responses. To achieve this, SSR activity at sites eliciting the maximum responses according to unisensory AM conditions were averaged (i.e., auditory SSR: FC1, FC2, FCz, Cz, P9, P10, M1 and M2 and vibrotactile SSR: FC3, FC1, FCz, FC2 and FC4). These across-electrode averaged auditory and vibrotactile SSR responses were then submitted separately to the following statistical analyses.

3.3. Steady-State Response Entrainment

The results of the 2 (SSR Frequency) × 3 (AM rate) repeated-measures ANOVAs showed that SSR frequency varied significantly according to AM rate for both the auditory (EEG frequency × AM condition interaction: $F(2, 62) = 201.56$, $p < 0.001$, $\eta^2 = 0.87$) and vibrotactile (EEG frequency × AM stimulation interaction: $F(2, 2) = 17.27$, $p < 0.001$, $\eta^2 = 0.36$) SSR measures. *Post-hoc* Bonferroni-corrected comparisons showed that this reflects greater SSR power for conditions where SSR frequency corresponded to AM rate (i.e., entrainment). As illustrated in Fig. 4, 21 Hz SSR power was significantly greater for the 21 Hz AM auditory stimulus relative to both the auditory Carrier Only and the 40 Hz AM conditions ($ps < 0.001$). In contrast, no difference between the Carrier Only and 40 Hz AM conditions ($ps > 0.05$) was found for auditory 21 Hz SSR power. Similarly, auditory 40 Hz SSR power for the 40 Hz AM stimulus condition was significantly greater than both the Carrier Only and 21 Hz AM conditions ($ps < 0.001$). Additionally, 40 Hz SSR activity in the 21 Hz AM condition was significantly lower relative to the Carrier Only condition ($p < 0.001$). *Post-hoc* t-tests also showed that vibrotactile EEG power for the 21 Hz SSR was significantly greater relative to both the Carrier Only condition ($p = 0.001$) and 40 Hz AM ($p = 0.003$) with no difference between the Carrier Only and 40 Hz AM condition. Vibrotactile 40 Hz EEG power for the 40 Hz AM condition was also significantly greater

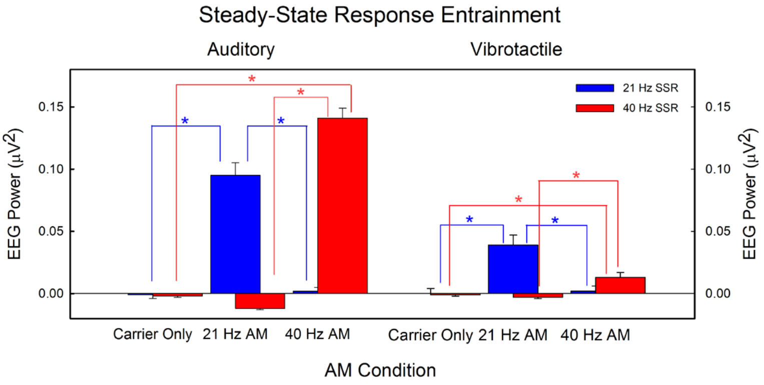

Figure 4. EEG power ($n = 32$, error = s.e.m.) for 21 and 40 Hz auditory steady-state responses (SSRs) (electrode sites: FC1, FC2, FCz, Cz, P9, P10, M1 and M2) and vibrotactile SSRs (electrode sites: FC3, FC1, FCz, FC2 and FC4) for unimodal AM stimulation conditions (i.e., Carrier Only, 21 Hz and 40 Hz AM). Consistent with EEG entrainment, increases in SSR power were found to be dependent on AM rate with greater activity at SSR frequencies matching the AM rate of the stimulus. Asterisks highlight significantly different *post-hoc* pairwise comparisons for SSR power for the across AM conditions for both 21 and 40 Hz auditory and vibrotactile SSR measures ($^*p < 0.05$). Note: Negative Fast Fourier Transformation values are the result of the noise correction procedure.

relative to both the Carrier Only and 21 Hz AM conditions ($p = 0.002$). There was no significant difference between the Carrier Only condition and the 21 Hz AM condition. This correspondence between AM rate and SSR frequency observed in the current study for both the auditory and vibrotactile SSR measures is indicative of EEG entrainment and the steady-state response.

Overall SSR activity for both the auditory (AM condition main effect: $F(2, 62) = 96.36$, $p < 0.001$, $\eta^2 = 0.76$) and vibrotactile (AM stimulation main effect: $F(2, 31) = 7.53$, $p = 0.001$, $\eta^2 = 0.20$) SSRs were found to vary according to AM stimulation condition. *Post-hoc* t-tests revealed that auditory SSR power for the 40 Hz AM condition was significantly greater relative to both the Carrier Only and 21 Hz AM conditions (*ps* < 0.001). Additionally, SSR power in the 21 Hz AM stimulus condition was significantly greater relative to the Carrier Only condition ($p < 0.001$). In contrast *post-hoc* comparisons showed that overall vibrotactile EEG power in the 21 Hz AM condition was only significantly greater relative to the Carrier Only condition ($p = 0.001$). Both auditory (EEG frequency main effect: $F(1, 31) = 7.21$, $p < 0.001$, $\eta^2 = 0.19$) and vibrotactile SSR activity significantly varied according to EEG frequency with greater overall 40 Hz SSR activity for the auditory SSR and greater 21 Hz SSR activity for the 21 Hz SSR.

In order to explore the modality-specific nature of the SSR, additional paired t-tests were performed to separately compare the magnitudes of 21 and 40 Hz SSRs for both auditory and vibrotactile stimulation. As shown in Fig. 4, the 40 Hz auditory SSR for a 40 Hz AM rate was significantly larger relative to the 21 Hz SSR for 21 Hz AM [$t(31) = 4.24$, $p < 0.001$] while 21 Hz vibrotactile SSR activity was significantly larger relative 40 Hz [EEG frequency main effect: $F(1, 31) = 10.64$, $p = 0.003$, $\eta^2 = 0.26$]. This pattern of results provides evidence of a modality-specific sensitivity of the SSR to AM rate.

3.4. Superadditivity

In order to examine whether temporally congruent multisensory AM stimulation led to enhancements in auditory or vibrotactile SSR activity (i.e., superadditivity), repeated-measures ANOVAs were performed with factors EEG frequency (i.e., 21 and 40 Hz) and Modality (i.e., summed or simultaneous). As illustrated in Fig. 5 auditory SSR activity for the summed conditions was significantly larger relative to the multisensory presentation conditions (main effect of modality $F(1, 31) = 7.40$, $p = 0.01$, $\eta^2 = 0.20$). Auditory SSR activity was also found to be significantly larger for the 40 Hz SSR relative to the 21 Hz [EEG frequency main effect: $F(1, 31) = 7.12$, $p = 0.01$, $\eta^2 = 0.19$]. The interaction between EEG frequency and modality was non-significant ($p > 0.05$). Also evident in Fig. 5 and following a similar pattern to the auditory responses, vibrotactile SSRs for simultaneous AM stimulation were significantly lower in power relative to the summed SSRs [main effect of

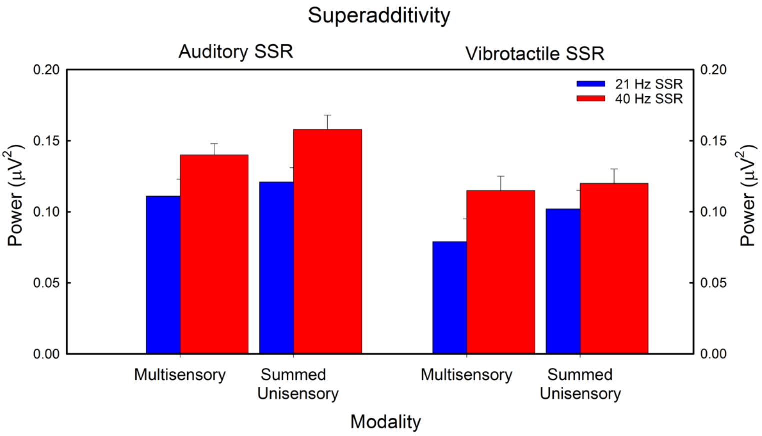

Figure 5. Auditory (left panel) (electrode sites: FC1, FC2, FCz, Cz, P9, P10, M1 and M2) and vibrotactile (electrode sites: FC3, FC1, FCz, FC2 and FC4) (right panel) EEG power for 21 and 40 Hz steady-state response frequencies for the multisensory congruent conditions and the sum of constituent unimodal conditions (e.g., unimodal auditory 21 Hz AM + 21 Hz vibrotactile AM).

modality: $F(1,31) = 5.34$, $p = 0.03$, $\eta^2 = 0.15$]. The analysis also revealed a trend for EEG frequency with greater 40 Hz SSR power relative to 21 Hz [$F(1,31) = 4.718$, $p = 0.05$, $\eta^2 = 0.12$]. The interaction between EEG frequency and modality was non-significant ($p > 0.05$). These results suggest that rather than leading to superadditive SSRs, multisensory AM stimulation led to subadditive responses for both auditory and vibrotactile SSR measures.

3.5. *Cross-Modal AM Congruence and the Steady-State Response*

A repeated-measures ANOVA with the factors SSR frequency (i.e., 21 and 40 Hz) and cross-modal AM congruence (i.e., congruent AM or incongruent AM) was performed on the auditory and vibrotactile SSR measures to investigate whether congruent AM stimuli enhanced SSR magnitude relative to incongruent AM stimulation. As evident in Fig. 6 there was no significant interaction between SSR frequencies and AM congruence or main effect of AM congruence on auditory SSR activity (*ps* > 0.05). The analysis did reveal that the magnitude of auditory SSR was significantly greater for the 40 Hz SSR frequency relative to 21 Hz [main effect of SSR frequency: $F(1,31) = 9.51$, $p = 0.004$, $\eta^2 = 0.26$].

As illustrated in Fig. 6 the influence of AM congruence on vibrotactile SSR measures varied according to SSR frequency [EEG frequency × cross-modal AM congruence interaction $F(1,31) = 22.30$, $p < 0.001$, $\eta^2 = 0.42$]. This was confirmed by Bonferroni-corrected *post-hoc* comparisons where EEG power in the temporally congruent conditions was significantly greater for both the 21 ($p = 0.003$) and 40 Hz SSRs ($p < 0.001$) with a noticeably bigger

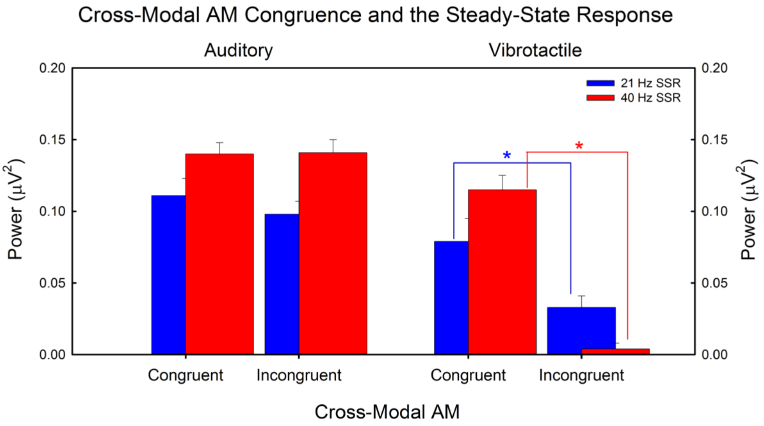

Figure 6. EEG power for 21 and 40 Hz steady-state response (SSR) frequencies for the multisensory cross-modal AM congruence conditions ($n = 32$, error = s.e.m.). AM congruence had no effect on the auditory SSR responses (left panel) (electrode sites: FC1, FC2, FCz, Cz, P9, P10, M1 and M2); however, congruent AM rates appeared to enhance the vibrotactile SSR activity (right panel) (electrode sites: FC3, FC1, FCz, FC2 and FC4). Asterisks highlight significantly difference *post-hoc* pairwise comparisons for 21 and 40 Hz vibrotactile SSR measures across the AM congruence conditions ($^* p < 0.05$).

difference for the 40 Hz SSR. The overall vibrotactile SSR activity was also found to be significantly larger for the congruent AM rate condition relative to incongruent [cross-modal AM congruence main effect: $F(1, 31) = 52.54$, $p < 0.001$, $\eta^2 = 0.63$]. There was no significant main effect of EEG frequency ($p > 0.05$). This pattern of results suggests a modality-specific influence of temporal congruence with AM congruence enhancing vibrotactile SSR measures but having no effect on auditory SSR measures.

4. Discussion

The primary aim of the current study was to determine whether temporal congruence of acoustic and vibrotactile AM rate resulted in psychophysical and EEG enhancements of multisensory stimulation. Accordingly, both perceptual sensitivity to AM stimuli and EEG entrainment (i.e., SSR) were measured while the congruence of AM rates for acoustic and vibrotactile stimuli were varied cross-modally. Additionally, as unisensory literature suggests a relationship between psychophysical and SSR measures of AM sensitivity (Nourski and Brugge, 2011; Rees *et al.*, 1986; Roß *et al.*, 2000), we also aimed to explore any correspondence between our psychophysical and SSR measures.

4.1. Psychophysics

The results of the current study revealed that multisensory presentations of acoustic and vibrotactile AM stimuli decreased AM perceptual sensitivity for both 21 and 40 Hz auditory AM stimuli and 40 Hz vibrotactile AM stimuli relative to multisensory AM conditions. This finding was relatively unexpected and conflicts with prior research reporting that multisensory acoustic and tactile stimulation enhances performance on perceptual tasks. For example, using a simple detection task Ro *et al.* (2009) showed that simultaneously presenting task-irrelevant 500 Hz pure-tone auditory stimuli through speakers significantly enhanced the detection accuracy of an electric tactile stimulus presented to the middle finger. Similarly, Wilson *et al.* (2009) reported that detection accuracy for 250 Hz pure-tone auditory–tactile multisensory stimuli was significantly greater relative to the detection accuracy for unisensory auditory or tactile stimuli.

Interestingly, the decrease in AM perceptual sensitivity observed in the current study is more broadly consistent with findings from very early perceptual research using detection tasks to explore the auditory and tactile interactions. Gescheider and Niblette (1967) examined how sensitivity to auditory clicks and tactile pulses varied according to the timing and intensity of stimuli presented in the corresponding modality (i.e., tactile pulses for auditory detection and auditory clicks for tactile detection). Although no quantitative statistical analysis was provided, their results suggested that sensitivity to tactile stimuli decreased as the intensity of simultaneously presented auditory stimulus increased. Importantly, their findings showed that the decrease in tactile sensitivity was greatest when the task-irrelevant auditory stimulus was presented synchronously. They also report a similar pattern for auditory detection accuracy with the presentation of a task-irrelevant tactile stimulus decreasing auditory detection but to a lesser extent. This decrease in sensitivity observed by Gescheider and Niblette (1967) is consistent with the decrease in AM perceptual sensitivity observed in the current study and suggests that multisensory auditory and tactile multisensory stimulation impairs perceptual sensitivity relative to unisensory stimulation.

One notable aspect of the current study is that all conditions in the psychophysical session were inherently multisensory in nature, as the unimodal AM conditions presented an unmodulated carrier signal to the other modality. Subsequently, as thresholds in the multisensory AM conditions were significantly worse relative to the unimodal AM conditions, it suggests that the decrease in sensitivity results from the temporal nature of the stimulus presented to the corresponding modality rather than multisensory stimulation alone.

Stimulus congruence between acoustic and tactile stimuli has previously been shown to improve performance on behavioural tasks (Ro *et al.*, 2009; Wilson *et al.*, 2010). Accordingly, we expected that cross-modal temporal congruence between acoustic and vibrotactile AM rates would increase perceptual sensitivity to AM stimuli, relative to cross-modal incongruence. Our results provided evidence of a modality-specific influence of temporal congruence on perceptual sensitivity to AM stimulation. AM congruence was found to have no significant effect on auditory AM thresholds, suggesting no effect of temporal congruence on auditory AM sensitivity. In contrast, congruent AM vibrotactile thresholds were significantly better (i.e., lower thresholds) relative to incongruent AM thresholds, suggesting that AM congruence enhanced vibrotactile AM perceptual sensitivity.

Prior research examining cross-modal temporal congruence on auditory and tactile multisensory integration is relatively limited; however, evidence shows that congruence can influence behavioural performance on both detection and discrimination tasks. Ro *et al.* (2009) explored how the frequency of a task-irrelevant auditory stimulus influenced the ability to discriminate between the frequencies of consecutively presented tactile stimuli. They found that performance was frequency dependent with greater congruence between acoustic and tactile stimuli leading to greater discrimination accuracy while decreasing congruence led to decreased accuracy. Wilson *et al.* (2010) measured how the corresponding frequencies of acoustic and tactile stimuli influenced accuracy on auditory, tactile and multisensory (audio-tactile combined) detection tasks. Their results revealed that accuracy was significantly greater when the frequencies of the acoustic and vibrotactile stimuli were the same or similar. Prior research has also found that increased correspondence between the frequency components of acoustic and vibrotactile stimuli can disrupt perceptual processing. Yau *et al.* (2009) measured how the frequency of task-irrelevant acoustic stimuli influenced participants' performance on a tactile frequency discrimination task. They found that the ability of participants to discriminate between the frequencies of consecutive tactile stimuli was significantly impaired when simultaneously presented acoustic stimuli shared the same or a similar frequency. The vibrotactile findings of the current study support the findings of Wilson *et al.* (2010) and Ro *et al.* (2009) with vibrotactile sensitivity increasing when a simultaneous auditory stimulus shared the same AM rate.

The multisensory principle of *Inverse Effectiveness* may provide a potential explanation for the modality-specific influence of temporal correspondence observed in the current study. According to inverse effectiveness, multisensory enhancements are typically more pronounced for weaker or less effective multisensory stimuli (Holmes and Spence, 2005; Stein and Meredith, 1993). Gillmeister and Eimer (2007) examined the influence of task-irrelevant tactile stimuli on both auditory detection and intensity judgement tasks while varying both stimulus onset asynchrony and stimulus intensity. Multisensory enhancements were observed for both tasks with synchronous audio-tactile stimuli enhancing auditory detection accuracy and intensity ratings. Interestingly, the multisensory enhancements were reported to be larger for less intense auditory stimuli, consistent with inverse effectiveness. The results of the current study may also be in line with inverse effectiveness. Vibrotactile AM sensitivity was noticeably lower relative to thresholds in the auditory modality, suggesting less effective stimuli. Subsequently, the decreased sensitivity for the tactile modality may mean a greater or more pronounced multisensory enhancement resulting from temporal congruence.

The current study also provided further evidence of a modality-specific sensitivity to AM rate. Auditory thresholds were found to be significantly better for 21 Hz AM stimuli relative to 40 Hz suggesting greater sensitivity to 21 Hz AM stimuli. This is in line with prior research examining psychophysical sensitivity to auditory AM rate (Viemeister, 1979). Vibrotactile thresholds were also found to be AM rate-dependent with thresholds greater for 40 Hz AM stimuli relative to 21 Hz, suggesting greater sensitivity to 40 Hz stimuli. This AM rate-dependent sensitivity of the tactile modality is consistent with the findings of Weisenberger (1986) who revealed that perceptual sensitivity to pure-tone AM stimuli was greatest at around 40 Hz.

4.2. EEG Steady-State Response

The analysis of the unimodal AM stimulation conditions produced similar findings for both the auditory and vibrotactile SSRs with significantly greater increases in SSR magnitude when SSR frequency corresponded to the AM rate of stimulation. This relationship between the temporal rate of the stimulus and frequency components of the SSR is consistent with prior research and reflects the entrainment of oscillatory activity to the temporal features of sensory stimulation (Colon *et al.*, 2012; Rees *et al.*, 1986). Furthermore, SSRs observed in the current study appeared to be modality-specific with a maximal auditory SSR response for a 40 Hz AM rate and larger vibrotactile SSR for a 21 Hz AM rate. This modality specificity of the SSR is consistent with unisensory EEG research where the auditory SSR has been shown to be maximal for a rate of 40 Hz (Galambos *et al.*, 1981; Picton *et al.*, 1987; Rees *et al.*, 1986; Roß *et al.*, 2000) and vibrotactile SSRs for rates between 20 and 30 Hz (Muller *et al.*, 2001; Snyder, 1992; Tobimatsu *et al.*, 1999).

Prior research exploring SSR scalp distributions are fairly limited with earliest recordings limited to one to four electrodes (Rees *et al.*, 1986; Tobimatsu *et al.*, 1999). However, consistent with the current study available evidence reports a maximal fronto-central response for the auditory SSR (Picton *et al.*, 2003; Rees *et al.*, 1986) and a maximal frontocentral response for the vibrotactile SSR (Giabbiconi *et al.*, 2004; Kelly and Folger, 1999; Nangini *et al.*, 2006). These modality-specific SSR topographies have more recently been confirmed in a study examining the impact of selective attention on auditory, vibrotactile and visual SSRs (Porcu *et al.*, 2014). Similar to the findings of the current study, a 40 Hz auditory SSR was found to produce maximal response at fronto-central electrodes (i.e., Fz, F2, F4, FCz, FC2, FC4) while a 22 Hz tactile SSR was also found to have maximal responses at more frontal electrodes (i.e., Fz, FCz, F1, F2, FC1, FC2). Although the relationship between the SSR and transient responses is still debated, one perspective suggests that the SSR reflects stimulus-driven oscillatory activity of particular networks as they become entrained to the temporal features of temporally modulated stimuli. This perspective is supported by the modality-specific sensitivity of the SSR as it is proposed to reflect resonance characteristics of different neuronal networks as they encode the temporal features of sensory stimuli (Colon *et al.*, 2012).

The presentation of multisensory auditory and tactile stimuli has been reported to elicit enhanced neurophysiological responses (Brett-Green *et al.*, 2008; Foxe *et al.*, 2000, 2002). Typically, the magnitude of these enhancements is larger than the sum of the constituent unisensory responses or superadditive and is interpreted to reflect the integration of multisensory information. Accordingly, we expected that if the SSR provides a sensitive measure of activity underlying the integration of acoustic and vibrotactile temporal information then SSR responses for the congruent AM multisensory conditions should be significantly larger relative to the sum of constituent unisensory conditions. Our results provided no evidence to support superadditive enhancements of SSR activity. In contrast the magnitude of multisensory SSR responses for both auditory and vibrotactile SSRs was found to be significantly lower relative to summed SSR responses or subadditive.

The subadditive SSRs observed in the current study are inconsistent with prior research that has shown that multisensory auditory and tactile stimulation can produce superadditive neurophysiological enhancements. For example, Foxe *et al.* (2000) used EEG to compare event related potentials (ERPs) to unisensory pure-tone auditory stimuli, median-nerve electrical tactile stimulation and combined audio-tactile stimulation. Presentations of simultaneous auditory and tactile stimuli led to significantly larger ERP responses relative to summed responses (i.e., superadditivity), suggesting the integration of auditory and tactile multisensory information. Similarly, Brett-Green *et al.* (2008) also identified superadditive ERP responses for simultaneous auditory and tactile stimulation in children. Functional magnetic resonance imaging (fMRI) has also been used to further demonstrate auditory and tactile superadditive responses. Foxe *et al.* (2002) examined blood oxygenation level-dependent

(BOLD) responses to the presentation of auditory broadband stimuli, tactile responses to the rotation of a wooden roller applied to the index and middle finger and combined audio-tactile stimulation. They showed that the combined audio-tactile stimuli led to superadditive BOLD responses in the superior temporal sulcus, a proposed multisensory region.

Neurophysiological research suggests that temporal congruence between multisensory stimuli facilitates multisensory integration (Calvert, 2001; Calvert *et al.*, 2000; Noesselt *et al.*, 2007). In line with this we expected that multisensory presentations of acoustic and vibrotactile stimuli with congruent AM rates would lead to greater enhancements in the magnitude of SSRs relative to incongruent stimuli. Findings from the current study provided mixed results as the influence of temporal congruence was found to vary according to modality. The presentation of temporally congruent auditory and vibrotactile AM stimuli had no effect on auditory SSRs; however, it did enhance the magnitude of vibrotactile SSR activity.

Research examining temporal congruence of acoustic and vibrotactile stimuli using the SSR is limited; however, temporal congruence between auditory and visual stimuli has previously been shown to increase SSR activity. Using a different approach Nozaradan *et al.* (2012) used the sensitivity of the SSR to ‘frequency tag’ auditory and visual responses, using an 11 Hz auditory stimulus and a 10 Hz change in luminance for visual stimuli. In order to explore temporal congruence, the impact of temporal congruence on the SSR stimuli was additionally modulated. Auditory stimuli were modulated at either 2.1 or 2.4 Hz while the horizontal back and forth movement of the visual stimuli was modulated at 2.1 or 2.4 Hz. Multisensory presentations of the auditory and visual stimuli were either temporally congruent (e.g., auditory: 2.4 Hz and visual: 2.4 Hz) or incongruent (e.g., auditory: 2.4 Hz and visual: 2.1 Hz). Consistent with the vibroactile results of the current study the magnitude of auditory and visual SSRs was significantly enhanced for presentations of the temporally congruent stimuli. Subsequently, these enhancements may reflect the binding of cross-modal sensory streams which share similar temporal dynamics.

The modality-specific influence of temporal congruence on SSR activity may also be consistent with the principle of inverse effectiveness, where multisensory enhancements are greater for weaker or less effective stimuli (Senkowski *et al.*, 2011; Stein and Meredith, 1993). In line with this, the magnitude of vibrotactile SSRs is noticeably lower relative to auditory SSRs. Subsequently, the impact of temporal congruence on multisensory integration may be more pronounced for these relatively weak vibrotactile SSRs. Alternatively, a notable constraint of the current study is the similar scalp distributions of the auditory and vibrotactile SSRs. Due to these similar topographies, sites used to estimate auditory and vibrotactile SSRs overlapped. The correspondence between the auditory and vibrotactile SSR measures may mean that rather than reflecting a multisensory SSR enhancement, the increased vibrotactile SSR activity potentially reflects a contribution to SSR activity resulting from auditory AM stimulation. This limits the conclusions that can be drawn from the congruence findings.

4.3. Psychophysics and Steady-State Measures of AM Sensitivity

Auditory unisensory research suggests a correspondence between psychophysical and SSR measures of AM sensitivity as auditory AM rate has a similar influence on AM perceptual sensitivity and SSR magnitude (Joris *et al.*, 2004; Liegeois-Chauvel *et al.*, 2004; Rees *et al.*, 1986; Roß *et al.*, 2000). A relationship between these neurophysiological and psychophysical measures suggests that the entrained oscillatory activity underlying the SSR has a functional role in the perceptual analysis of sensory temporal information. Subsequently, we aimed to further explore any potential relationship between our psychophysical and EEG measures.

The results of the current study provide evidence to further support a relationship between the SSR and AM perceptual sensitivity. One notable finding from our psychophysical results was the decrease in AM perceptual sensitivity for multisensory AM stimulation, relative to unisensory sensitivity. Interestingly, auditory and vibrotactile SSRs for the multisensory AM stimulation conditions were found to be significantly lower relative to the sum of constituent unisensory responses, or subadditive. These subadditive SSRs potentially suggest that multisensory AM stimulation may inhibit multisensory integration, consequently leading to a decrease in AM perceptual sensitivity.

The modality-specific influence of temporal congruence may also provide evidence of a relationship between psychophysical and SSR measures of AM rate. The psychophysical and SSR results provided no evidence to support enhancements effects of AM temporal congruence on auditory psychophysical or SSR measures. Interestingly, AM temporal correspondence was found to enhance both AM perceptual sensitivity and SSR magnitude in the tactile modality. Furthermore, this may indicate that the vibrotactile SSR enhancements reflect a multisensory enhancement rather than a contribution of auditory SSR activity. This correspondence supports the relationship between EEG entrainment and perceptual sensitivity to AM reported in unisensory literature, further suggesting a role of oscillatory EEG entrainment in the perceptual processing of temporally modulated stimuli.

5. Conclusion

The current study revealed that multisensory AM stimulation leads to a decrease in perceptual sensitivity relative to unimodal AM sensitivity. We also provide further evidence to support a modality-specific sensitivity to AM rate across both psychophysical and EEG measures. We observed that the impact of AM temporal congruence varied according to modality with congruence, enhancing perceptual sensitivity and SSR magnitude for the tactile modality alone. Interestingly, the tactile enhancements resulting from temporal congruence were observed across both psychophysical and EEG measures. This apparent correspondence between the psychophysical and SSR measures further supports the relationship between EEG entrainment and perceptual sensitivity to AM reported in unisensory literature. The modality-specific results observed in the current study may also provide evidence of inverse effectiveness. Vibrotactile AM thresholds and SSRs were both noticeably lower relative to those for the auditory modality, suggesting relatively less effective vibrotactile stimuli. Subsequently, the impact of temporal congruence may abide by inverse effectiveness whereby multisensory enhancements are more pronounced for weaker or less effective multisensory stimuli. These results indicate that the role of temporal dimension in multisensory integration extends beyond stimulus onset synchrony and proposes the need to extend our current understanding of the temporal principle.

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