

Temporal attention and comodulation in multisensory causal inference

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ABSTRACT

Perception relies on inferences about the causal structure of the world provided by multiple sensory inputs. In ecological settings, multisensory events that cohere in time and space contribute to such inferential processes: the sound of flapping wings naturally paces the crowded vision of a flock of birds, and hearing while seeing a speaker enhances speech comprehension. Psychophysical and magnetoencephalography (MEG) studies suggest that the Human brain may synthesize multisensory temporal comodulation in some abstract form, which may benefit (as top-down predictions) the feedforward analysis of incoming sensory signals. For instance, recent findings have shown the emergence of large-scale phase synchronizations in high gamma (60-120 Hz) and beta (15-30 Hz) bands following the short experiencing of temporally comodulated multisensory signals. The coordinated engagement of prefrontal, parietal, and visual cortices suggests the possibility that a short experience of temporally comodulated stimuli signaling the same distal information may functionally re-route unisensory processing.

Keywords: Audiovisual, Comodulation, Magnetoencephalography

1. INTRODUCTION

Textbook descriptions of perception have classically addressed the senses in isolation, each concerned with the transduction, coding, and analysis of different kinds of physical signals. Increasingly however, empirical evidence from different fields of research have demonstrated that multisensory integration – *i.e.* the combination of multiple sensory signals – is the rule rather than the exception (1-3). Indeed, a few seconds of life are filled with a multitude of sensory inputs. Some sensory events pertain to the same perceptual episode such as the smell, the sight, the sound, and the anticipated taste of wine being poured in a glass; others, although constitutive of the same experienced scene, pertain to different experiential episodes such as the chattering crowd gathered around the waiter, each with dyads entertaining distinct conversations. How then does the brain selectively integrate and segregate multisensory information into a coherent, meaningful and intelligible story?

1.1 Causal Inference in Multisensory Perception

Since the seminal Fuzzy Logical Model of Perception (4-6) and the more recent Bayesian approaches of multisensory integration in behavior and in neurosciences (e.g. 7-10), the resolution of perceptual inference problems has been formulated as a weighted function of multisensory reliability so that the most reliable information outweighs other sensory inputs. This model entails the existence of multisensory priors shaped in the course of perceptual experiences (as posteriors). Hence, recent working hypotheses posit that the brain can infer the causal structure of the sensory environment by integrating multisensory signals originating from the same physical source and by segregating signals originating from different causes (11-15). Audiovisual speech perception was conceived as a case

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study for Bayesian inference (6) which likely follows similar Bayesian computational principles (16) mediated by predictive multisensory neural processes (17-20). Yet, what sensory cues are primordial in engaging multisensory integration is unclear, and whether multisensory integration is a default operating mode or not is likely determined by selective attention mechanisms.

1.2 Selective Attention

The role of (selective) attention is omnipresent in multisensory research (21). While neuroanatomical connectivity demonstrates that feedforward integration could occur early at different stages of the sensory hierarchy, the automaticity of behavioral integration effects is systematically put into question.

For instance, in a seminal study (22), behavioral evidence for early feature-based multisensory integration could not be found: using a visual search paradigm in which visual feature changes were temporally coherent or co-modulated with acoustic changes, the authors found no evidence of parallel search and concluded that audiovisual (AV) integration was mediated by attentional effects. To the contrary, Van der Burg and colleagues (23-24) used a conjunction visual search in which a horizontal or vertical bar (visual target) surrounded by distracters of various orientations changed colors (green, red) at a rate of 1 Hz. They showed that transient sounds synchronized with the visual target changes fastened participants' reaction times. As temporal coincidence was orthogonal to the feature space relevant for the task (here, the orientation of the visual bar) and yet, perceptual facilitation effects were observed, the authors suggested that the synchrony between the transient sounds and the visual changes was critical. This finding suggested that the feature of interest may have been the locus of temporal attention as cued by the sound.

A follow-up study by an independent group tested whether behavioral facilitation in visual conjunction search would show temporal selectivity in the predicted range of neurophysiological reports. Neurophysiological evidence had suggested that selective attention may be implemented as the slow regulation of neuronal activity (25-27) in the delta band (1-2 Hz) across auditory and visual sensory modalities. More recent neurophysiological evidence further supports a selective enhancement of sensory information processing in multisensory populations as well as sensory cortices (28), and this can be observed for speech content as well (29-30).

The paradigm of Van der Burg and colleagues (23) was extended by measuring reaction times (RT) and performance at varying rates of AV presentation as well as insuring that no temporal correlation survived between the sound and the visual target in a control condition (31). Below 2 Hz, faster RTs and improved performances were observed for temporally congruent AV stimuli, whereas slower and worse performances were observed for temporally incongruent AV stimuli as compared to the visual condition alone. These results provided evidence that AV interactions in visual search were temporally-dependent and that automaticity in multisensory integration was mediated by selective temporal attention. In a similar vein, Parise and colleagues (32) presented a train of white noise clicks and Gaussian blobs at different spatial locations. The authors showed that spatial localization was more precise when AV stimuli were temporally correlated than when they were not; however, temporally uncorrelated AV stimuli were still more precise than the best unisensory condition. As mentioned by the authors, even when stimuli were "uncorrelated", they still presented some correlations at larger temporal scales which likely accounted for the lack of replication of the differences observed between correlated and uncorrelated effects reported in the previous study (31).

Altogether, these psychophysical studies suggest that the temporal comodulation of sensory inputs is a crucial cue for engaging selective attention in multisensory integration by increasing the salience in time of incoming sensory inputs. A recent model (15) relying on temporal coincidence further suggested that temporal coherence may be sufficient to determine very early on in the sensory hierarchy whether signals are causally related or temporally segregated.

1.3 Audiovisual Comodulation

The comodulation or temporal coherence of multisensory sources could be seen as a 'common-fate' Gestalt principle so that features sharing the same dynamics in different sensory modalities are inferred to belong to the same perceptual object (32), just as can be observed within vision (33-35) and within audition (36, 37). The temporal comodulation of sensory signals helps building the representation of complex perceptual scenes and in the context of multisensory integration, may enable a feedforward volley of multisensory cueing. This is particularly relevant for speech processing in which the acoustic envelope of the speech signal and the movements of the lips show high temporal correlation or comodulation (38) in the spectral range that is relevant for speech

feature categorization *i.e.* the F2/F3 formants region (39,40). These correlations have been argued to support multisensory integration even when visual speech information is consciously suppressed (41). Hence, an interlocutor's mouth movements temporally coherent with the envelope of the acoustic speech signals provide the listener with strong binding cues for predictive inferences (17, 18, 38, 42, 43). These general considerations motivated a research program which explored whether AV comodulation may also subsequently help visual perceptual discrimination (44, 45). We report below a partial set of results from one study, which will be presented at the conference.

2. MATERIALS & METHODS

2.1 Participants

36 healthy human participants (16 females) were recruited for the study (22.1 \pm 2 y.o). All participants were right-handed, had normal hearing and normal or corrected-to-normal vision. Before the experiment, all participants provided a written informed consent in accordance with the Declaration of Helsinki (2008) and the local Ethics Committee on Human Research at NeuroSpin (Gif-sur-Yvette, France). Prior to the MEG acquisition, participants were randomly split into 3 experimental groups (V, AV, and CTRL) as detailed below.

2.2 Task

The behavioral task consisted in discriminating which of a red or green cloud of dots moved in the most coherent way (**Figure 1**). While being recorded with magnetoencephalography (MEG), participants were tested with the visual task for 12 minutes before and after a short training (PRE, POST, respectively). The training was 20 minutes long (4 blocks, 5 minutes each) using visual stimuli only (V group; N=12), congruent or incongruent audiovisual stimuli (AV and CTRL group, respectively; each with N=12). In PRE and POST, individuals' visual discrimination thresholds were drawn from their individual psychophysical discrimination curve testing 7 strengths of motion coherence (15%, 25%, 35%, 45%, 55%, 75% and 95%; 28 trials each). Each MEG recording block was followed by a 5 minutes rest block.

2.3 Stimuli

Visual stimuli were isoluminant green and red clouds of dots (**Figure 1A**). Dots (0.2° radius) were presented within an annulus of 4° to 15° of visual angle. The motion flow was 16.7 dots/deg²/s with a speed of 10°/s. The direction of motion was constrained to 45°-90° around the azimuth. Both colors (red, green) and directions (up, down) of the most coherent cloud were counterbalanced and pseudo-randomized across trials. The V group underwent training using visual only stimuli. The CTRL group underwent training with acoustic noise fully uncorrelated with the coherent motion to test specificity of AV associations. The AV group was tested with temporally comodulated AV associations (**Figure 1B**). We used parametrized acoustic textures (46) so that each visual dot was paired with a linear frequency-modulated acoustic sweep whose slope depended on the direction of the visual dot (see 44; Fig. 1A; $f_s = 44.1$ kHz, 0.2 - 5 kHz). The maximal slope was 16 octaves/s corresponding to motion directions of 82.9°-90°. A visual dot moving upwards (downwards) was associated with an upward (downward) acoustic ramp. The duration of a ramp was identical to the life-time of a dot.

2.4 Magnetoencephalography (MEG)

Electromagnetic brain activity was recorded in a magnetically shielded room using a 306 MEG system (Neuromag Elekta LTD, Helsinki). MEG signals were sampled at 2 kHz and band-pass filtered between 0.03-600 Hz. Four head position coils (HPI) measured the head position of participants before each block; three fiducial markers (nasion and pre-auricular points) were used during digitization as a reference for coregistration of anatomical MRI (aMRI) immediately following MEG acquisition. Electrooculograms (EOG) and electrocardiogram (ECG) were recorded simultaneously with MEG. Five minutes of empty room recordings was acquired before each block for the computation of the noise covariance matrix.

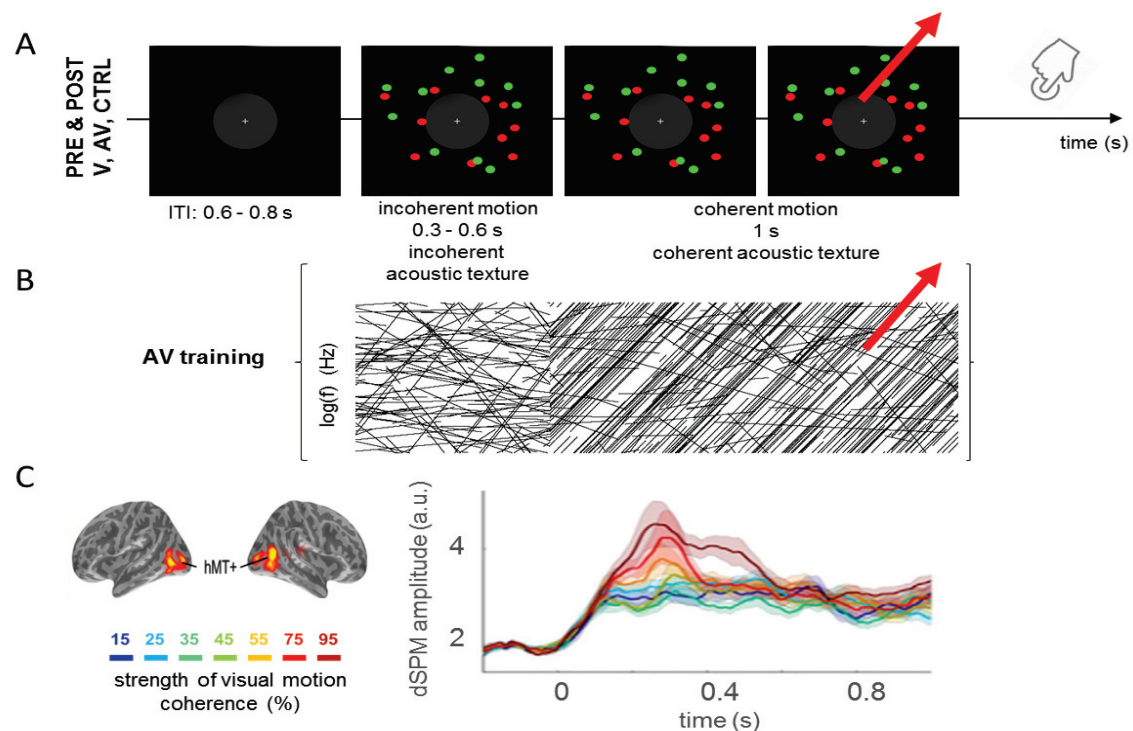


Figure 1 – A: In a single trial of the main experimental task used for all participants (V, AV and CTRL groups in the PRE and POST experimental blocks), a red and a green cloud of dots were intermixed. All dots were fully incoherent for up to 0.6 s. Then, one of the clouds (here, red) became more coherent for 1 s. Participants were asked to report the color of the most coherent cloud. **B:** During training, the AV group heard a coherent acoustic texture paired with the most coherent cloud (here, red). **C:** Illustration of the source-estimated Human motion area (hMT+; left panel) activity in response to the presentation of visual motion coherence of increasing strength (blue to red color). The stronger the coherence of visual motion, the stronger the source amplitude estimated with MEG (right panel). Samples of the video trials are provide as Movies S1 and S2 in Zilber et al (44).

2.5 Main Analyses

The analysis of the MEG used the MNE-python toolbox (47). After applying an anti-aliasing FIR filter (low-pass cutoff frequency at 130 Hz), MEG data were down-sampled to 400 Hz, and preprocessed to remove external and internal interferences. Signal Space Separation (SSS) was applied with MaxFilter to remove exogenous artifacts and noisy sensors (48). Ocular and cardiac artifacts (eye blinks and heart beats) were removed using Independent Component Analysis (ICA) on raw signals (49; https://github.com/mne-tools/mne-python/blob/master/tutorials/plot_artifacts_correction_ica.py). The functional interaction between brain regions was assessed by evaluating the similarity of brain activity across remote brain regions, namely functional connectivity (FC) of oscillatory activity using the weighted Phase Lag Index (PLI) (50, 51). All statistics were corrected for multiple comparisons.

3. MAIN RESULTS

All participants improved their performance during training (**Figure 2, left column**). Performing the visual discrimination task was accompanied by the activation of a large network of brain regions encompassing sensory and multisensory cortices (44). Of interest, we found a selective implication of prefrontal regions for those motion coherence strengths that improved after training (**Figure 2, middle column**). Herein, we solely focused on the PRE and the POST functional networks, when participants from all three groups performed the task on visual motion coherence only in the absence of any other

stimuli. 28 cortical regions were considered following source reconstruction. All statistical contrasts were based on non-parametric permutation t-tests. Only phase coupling values showing significant differences ($p < 0.01$) are being highlighted.

3.1 Alpha (8-12 Hz) Networks (De)Synchronization

The functional connectivity pattern observed in resting-state was subtracted from the PRE and POST networks. A significant uncoupling of the alpha oscillatory network during both PRE and POST was found as compared to resting-state. The observed alpha desynchronization was modulated by the training (i.e. the sensory history) experienced by participants. Consistent with the alpha desynchronization, a general task-related decrease of node degree from resting-state to PRE was found in parietal, occipital, and temporal regions for the alpha network. Additionally, a relative increase in synchronization from PRE to POST was observed mainly in the V and CTRL groups (**Figure 2**).

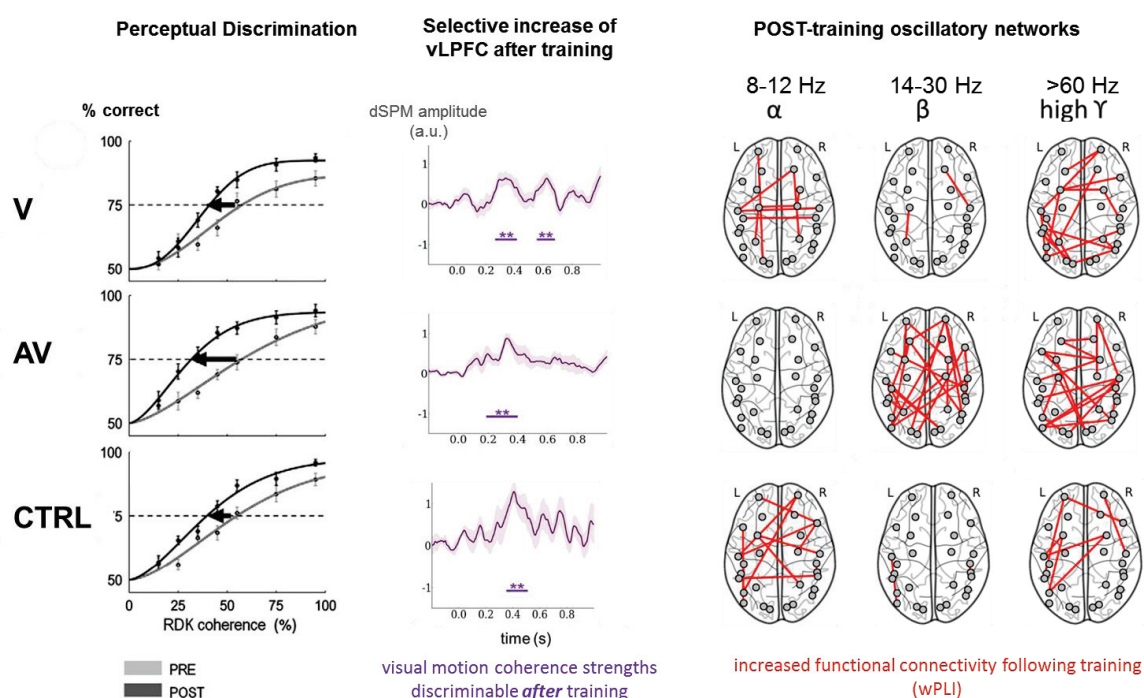


Figure 2 – Perceptual Discrimination (left column): all three groups (V, AV and CTRL) significantly improved their performance (significant decrease of perceptual threshold) after the short training. **An increased activity in ventro-lateral Prefrontal Cortices (vLPFC)** was found in response to visual motion coherence stimuli, which became discriminable after training (44; middle column). This observation suggested that the temporal comodulation of sensory signals may be represented in an abstract (sensory-independent) format. **Post-training oscillatory networks** showed the notable emergence of beta and high-gamma oscillatory activity in the AV group (45; left column).

3.2 Beta (14-30 Hz) and High Gamma (> 60 Hz) Networks

A similar analysis performed for the beta and gamma oscillatory regimes showed an increase of large-scale coupling from resting-state to task (both PRE and POST; **Figure 2**, right column). The beta network was found in all groups and implicated vLPFC, Intra-Parietal Sulcus (IPS) and hMT+. A significant strengthening of the beta network following training was solely observed in the AV group, who had experienced AV comodulated signals. A significant increase of functional connectivity in high gamma was also found in the AV group between auditory regions and pSTS. Further, the node degree value of beta oscillatory networks decreased with training in all three experimental groups. Conversely, the right mSTS region increased following training in all three groups. This observation suggested the implication of the mSTS during training, the synchronization of which got stronger and more extensive following all trainings.

3.3 Beta (14-30 Hz) network and perceptual decision-making

The functional network patterns emerged in a training-selective manner in the beta band for the AV group, suggesting that comodulated AV stimuli affected the functional organization of cortical interactions during visual discrimination task. Both beta and gamma long-range interactions in POST-specific networks were found to predict an individual's confidence rating trained with AV comodulation ($r=0.72$, $p=0.011$, $N=12; 45$).

4. DISCUSSION

A series of psychophysical work and recent MEG data (44, 45) suggest that comodulated audiovisual stimuli are crucial for multisensory perception. Comodulated sounds while performing a motion coherence discrimination task seem to strengthen subsequent perceptual decision-making through the regulation of large-scale oscillatory synchronizations in the Human brain. A functional connectivity analysis quantifying the degree of oscillatory phase-coupling across brain regions showed a global decrease of alpha (8-12 Hz) phase synchronization from rest to task. This global decrease was indicative of an enhanced attentional state when performing the task. Importantly, we observed the selective emergence of the long-range beta (15-30Hz) and gamma (60-120 Hz) synchronization networks in the AV group, that is the group having experienced coherent multisensory stimulation. Altogether, our results suggest that temporal comodulation is an important ecological cue for solving the seminal correspondence problem in multisensory research.

5. CONCLUSIONS

In sum, this body of work aims at exploring the interplay of bottom-up (temporal comodulation) and top-down (abstraction) selectivity in the integration and segregation of multisensory information during perception.

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REFERENCES

1. Stein BE, Meredith MA. The merging of the senses. The MIT Press; 1993.
2. Wallace MT, Ramachandran R, Stein BE. A revised view of sensory cortical parcellation. *Proceedings of the National Academy of Sciences*. 2004 Feb 17;101(7):2167-72.
3. Ghazanfar AA, Schroeder CE. Is neocortex essentially multisensory?. *Trends in cognitive sciences*. 2006 Jun 1;10(6):278-85.
4. Massaro DW. Attention and perception: An information-integration perspective. *Acta Psychologica*. 1985 Dec 1;60(2-3):211-43.
5. Massaro DW, Cohen MM. Evaluation and integration of visual and auditory information in speech perception. *Journal of Experimental Psychology: Human Perception and Performance*. 1983 Oct;9(5):753.
6. Massaro DW, Palmer SE. *Perceiving talking faces: From speech perception to a behavioral principle*. Mit Press; 1998.
7. Ernst MO, Banks MS. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*. 2002 Jan;415(6870):429.
8. Fetsch CR, Pouget A, DeAngelis GC, Angelaki DE. Neural correlates of reliability-based cue weighting during multisensory integration. *Nature neuroscience*. 2012 Jan;15(1):146.
9. Angelaki DE, Gu Y, DeAngelis GC. Multisensory integration: psychophysics, neurophysiology, and computation. *Current opinion in neurobiology*. 2009 Aug 1;19(4):452-8.
10. Ma WJ, Beck JM, Latham PE, Pouget A. Bayesian inference with probabilistic population codes. *Nature neuroscience*. 2006 Nov;9(11):1432.
11. Parise CV, Spence C, Ernst MO. When correlation implies causation in multisensory integration. *Current Biology*. 2012 Jan 10;22(1):46-9.

12. Rohe T, Noppeney U. Cortical hierarchies perform Bayesian causal inference in multisensory perception. *PLoS Biology*. 2015 Feb 24;13(2):e1002073.
13. Kayser C, Shams L. Multisensory causal inference in the brain. *PLoS biology*. 2015 Feb 24;13(2):e1002075.
14. Deroy O, Spence C. Crossmodal correspondences: four challenges. *Multisensory research*. 2016 Jan 1;29(1-3):29-48.
15. Parise CV, Ernst MO. Correlation detection as a general mechanism for multisensory integration. *Nature communications*. 2016 Jun 6;7:11543.
16. Magnotti JF, Beauchamp MS. A causal inference model explains perception of the McGurk effect and other incongruent audiovisual speech. *PLoS computational biology*. 2017 Feb 16;13(2):e1005229.
17. van Wassenhove V, Grant KW, Poeppel D. Visual speech speeds up the neural processing of auditory speech. *Proceedings of the National Academy of Sciences*. 2005 Jan 25;102(4):1181-6.
18. van Wassenhove V. Speech through ears and eyes: interfacing the senses with the supramodal brain. *Frontiers in psychology*. 2013 Jul 12;4:388.
19. Arnal LH, Morillon B, Kell CA, Giraud AL. Dual neural routing of visual facilitation in speech processing. *Journal of Neuroscience*. 2009 Oct 28;29(43):13445-53.
20. Arnal LH, Wyart V, Giraud AL. Transitions in neural oscillations reflect prediction errors generated in audiovisual speech. *Nature neuroscience*. 2011 Jun;14(6):797.
21. Talsma D, Senkowski D, Soto-Faraco S, Woldorff MG. The multifaceted interplay between attention and multisensory integration. *Trends in cognitive sciences*. 2010 Sep 1;14(9):400-10.
22. Fujisaki W, Nishida SY. Feature-based processing of audio-visual synchrony perception revealed by random pulse trains. *Vision research*. 2007 Apr 1;47(8):1075-93.
23. Van der Burg E, Olivers CN, Bronkhorst AW, Theeuwes J. Pip and pop: nonspatial auditory signals improve spatial visual search. *Journal of Experimental Psychology: Human Perception and Performance*. 2008 Oct;34(5):1053.
24. Van der Burg E, Cass J, Olivers CN, Theeuwes J, Alais D. Efficient visual search from synchronized auditory signals requires transient audiovisual events. *PLoS One*. 2010 May 14;5(5):e10664.
25. Lakatos P, Karmos G, Mehta AD, Ulbert I, Schroeder CE. Entrainment of neuronal oscillations as a mechanism of attentional selection. *science*. 2008 Apr 4;320(5872):110-3.
26. Gomez-Ramirez M, Kelly SP, Molholm S, Sehatpour P, Schwartz TH, Foxe JJ. Oscillatory sensory selection mechanisms during intersensory attention to rhythmic auditory and visual inputs: a human electrocorticographic investigation. *Journal of Neuroscience*. 2011 Dec 14;31(50):18556-67.
27. Besle J, Schevon CA, Mehta AD, Lakatos P, Goodman RR, McKhann GM, Emerson RG, Schroeder CE. Tuning of the human neocortex to the temporal dynamics of attended events. *Journal of Neuroscience*. 2011 Mar 2;31(9):3176-85.
28. Kayser C, Logothetis NK, Panzeri S. Visual enhancement of the information representation in auditory cortex. *Current Biology*. 2010 Jan 12;20(1):19-24.
29. Golumbic EM, Ding N, Bickel S, Lakatos P, Schevon CA, McKhann GM, Goodman RR, Emerson R, Mehta AD, Simon JZ, Poeppel D. Mechanisms underlying selective neuronal tracking of attended speech at a “cocktail party”. *Neuron*. 2013 Mar 6;77(5):980-91.
30. Golumbic EM, Poeppel D, Schroeder CE. Temporal context in speech processing and attentional stream selection: a behavioral and neural perspective. *Brain and language*. 2012 Sep 1;122(3):151-61.
31. Kösem A, Van Wassenhove V. Temporal structure in audiovisual sensory selection. *PLoS One*. 2012 Jul 19;7(7):e40936.
32. Parise CV, Spence C, Ernst MO. When correlation implies causation in multisensory integration. *Current Biology*. 2012 Jan 10;22(1):46-9.
33. Lee SH, Blake R. Detection of temporal structure depends on spatial structure. *Vision research*. 1999 Sep 1;39(18):3033-48.
34. Blake R, Lee SH. The role of temporal structure in human vision. *Behavioral and cognitive neuroscience reviews*. 2005 Mar 1;4(1):21-42.
35. Kandil FI, Fahle M. Purely temporal figure-ground segregation. *European Journal of Neuroscience*. 2001 May;13(10):2004-8.
36. Turgeon M, Bregman AS. Ambiguous musical figures. *Annals of the New York Academy of Sciences*. 2001 Jun 1;930(1):375-81.
37. George MF, Bregman AS. Role of predictability of sequence in auditory stream segregation. *Perception & psychophysics*. 1989 Jul 1;46(4):384-6.

38. Grant KW, Seitz PF. The use of visible speech cues for improving auditory detection of spoken sentences. *The Journal of the Acoustical Society of America*. 2000 Sep;108(3):1197-208.
39. Grant KW, Greenberg S. Speech intelligibility derived from asynchronous processing of auditory-visual information. In *AVSP 2001-International Conference on Auditory-Visual Speech Processing* 2001.
40. Grant KW, Bernstein JG. Toward a Model of Auditory-Visual Speech Intelligibility. In *Multisensory Processes* 2019 (pp. 33-57). Springer, Cham.
41. Alsius A, Munhall KG. Detection of audiovisual speech correspondences without visual awareness. *Psychological science*. 2013 Apr;24(4):423-31.
42. Nahorna O, Berthommier F, Schwartz JL. Audio-visual speech scene analysis: characterization of the dynamics of unbinding and rebinding the McGurk effect. *The Journal of the Acoustical Society of America*. 2015 Jan;137(1):362-77.
43. Maddox RK, Atilgan H, Bizley JK, Lee AK. Auditory selective attention is enhanced by a task-irrelevant temporally coherent visual stimulus in human listeners. *Elife*. 2015 Feb 5;4:e04995.
44. Zilber N, Ciuciu P, Gramfort A, Azizi L, Van Wassenhove V. Supramodal processing optimizes visual perceptual learning and plasticity. *Neuroimage*. 2014 Jun 1;93:32-46.
45. La Rocca D, Ciuciu P, Engemann DA, Van Wassenhove V. Emergence of β and γ networks following multisensory training. *bioRxiv*. 2019 Jan 1:560235.
46. Overath T, Kumar S, Stewart L, von Kriegstein K, Cusack R, Rees A, Griffiths TD. Cortical mechanisms for the segregation and representation of acoustic textures. *Journal of Neuroscience*. 2010 Feb 10;30(6):2070-6.
47. Gramfort A, Luessi M, Larson E, Engemann DA, Strohmeier D, Brodbeck C, Goj R, Jas M, Brooks T, Parkkonen L, Hämäläinen M. MEG and EEG data analysis with MNE-Python. *Frontiers in neuroscience*. 2013 Dec 26;7:267.
48. Taulu S, Simola J. Spatiotemporal signal space separation method for rejecting nearby interference in MEG measurements. *Physics in Medicine & Biology*. 2006 Mar 16;51(7):1759.
49. Gramfort A, Luessi M, Larson E, Engemann DA, Strohmeier D, Brodbeck C, Parkkonen L, Hämäläinen MS. MNE software for processing MEG and EEG data. *Neuroimage*. 2014 Feb 1;86:446-60.
50. Stam CJ, Nolte G, Daffertshofer A. Phase lag index: assessment of functional connectivity from multi channel EEG and MEG with diminished bias from common sources. *Human brain mapping*. 2007 Nov;28(11):1178-93.
51. Vinck M, Oostenveld R, Van Wingerden M, Battaglia F, Pennartz CM. An improved index of phase-synchronization for electrophysiological data in the presence of volume-conduction, noise and sample-size bias. *Neuroimage*. 2011 Apr 15;55(4):1548-65.