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Correlation of individual differences in audiovisual asynchrony across stimuli and tasks: new constraints on Temporal Renormalization theory.

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Abstract

Sight and sound are out of synch in different people by different amounts for different tasks. But surprisingly, different concurrent measures of perceptual asynchrony correlate negatively (Freeman, Ipser et al, 2013. *Cortex* 49, 2875–2887): thus if vision subjectively leads audition in one individual, the same individual might show a visual lag in other measures of audiovisual integration (e.g. McGurk illusion, Stream-Bounce illusion).

This curious negative correlation was first observed between explicit temporal order judgements and implicit phoneme identification tasks, performed concurrently as a dual task, using incongruent McGurk stimuli. Here we used a new set of different of explicit and implicit tasks and congruent stimuli, to test whether this negative correlation persists across testing sessions, and whether it might be an artefact of using specific incongruent stimuli. None of these manipulations eliminated the negative correlation between explicit and implicit measures. This supports the generalisability and validity of the phenomenon, and offers new theoretical insights into its explanation.

Our previously proposed ‘temporal renormalization’ theory assumes that the timings of sensory events registered within the brain’s different multimodal sub-networks are each perceived relative to a representation of the typical average timing of such events across the wider network. Our new data suggest that this representation is stable and generic, rather than dependent on specific stimuli or task contexts, and that it may be acquired through experience with a variety of simultaneous stimuli. Our results also add further evidence that speech comprehension may be improved in some individuals by artificially delaying voices relative to lip-movements.

Keywords

Individual differences; multisensory integration; perceptual timing; speech perception

Public Significance Statement

Sight and sound are out of synch, by different amounts for different people and for different tasks. Yet curiously, we have found that the more an individual's vision lags their audition in the performance of one task (e.g. identifying speech sounds), the more their audition lags vision in other tasks (e.g. deciding whether lips followed or preceded the speaker's voice). Here we test the generality of this antagonistic phenomenon using a variety of previously untested implicit versus explicit subjective tasks involving audiovisual speech stimuli. Our results support a new theory of perceptual timing that can explain our results, while eliminating some competing accounts. Furthermore, our study suggests that speech comprehension can be improved in some individuals by artificially delaying voices relative to lip-movements, and provides automated tasks that might be used for on-line assessment of such benefits.

Introduction

When we see and hear a person speak, sensory signals travel independently from our eyes and ears through the brain, and converge within different multimodal areas of the brain that are sensitive to both auditory and visual information (Ghazanfar & Schroeder, 2006). These signals travel at different speeds via different routes from primary sensory areas, so information from each modality is likely to arrive at different multimodal areas at slightly different times (Efron, 1963; Halliday & Mingay, 1964; Keetels & Vroomen, 2012; Pöppel, 1988). Despite such temporal spreading of information in the brain, our ability to judge whether the original events were synchronous or not tends to be fairly veridical, at least on average across individuals (King, 2005). So how do we know when the original events occurred in relation to one another? This problem is a deep one, ultimately concerning the relationship between physical, neural and subjective timing (Dennett & Kinsbourne, 1995; Scharnowski, Rees, & Walsh, 2013; Zeki & Bartels, 1998). Researchers have often assumed that there are unifying mechanisms functioning to keep the brain's internal signals in synch, or to compensate for their asynchronies (Keetels & Vroomen, 2012). Recent studies, however, have begun to challenge this view with evidence that sight and sound are persistently out of synch in different people by different amounts, and even for different tasks (Ipser et al., 2017). More surprisingly, we previously found that some measures of audiovisual asynchrony can be anti-correlated (Freeman et al., 2013). For example, the more vision apparently leads audition for one given task in one individual, the more the same individual might show an opposite visual lag in other tasks. This phenomenon hints at a fundamental disunity of perceptual timing. However, this counterintuitive pattern has only been reported once to date. The aim of the present research was to test the replicability and generality of this phenomenon across a variety of tasks and stimuli, and to seek empirical constraints on a theoretical explanation for it.

The first hints that vision and hearing might not always be fully in synch for some people dates back to the birth of Experimental Psychology, when systematic discrepancies were discovered between astronomers in their judgments of the transit of celestial bodies relative to the sound of a ticking clock (Mollon & Perkins, 1996). Persistent individual differences in perceptual asynchronies have since been measured formally using explicit subjective temporal judgements and implicit tasks probing sensory integration (Grabot & van Wassenhove, 2017; Ipser et al., 2017; Love, Petrini, Cheng, & Pollick, 2013; Stone et al., 2001). It might be intuitively expected that different tasks might provide measures of

perceptual timing that are positively correlated. However some measures of perceptual asynchrony based on different explicit tasks such as simultaneity judgements and temporal order judgements do not show this predicted pattern (Fujisaki, Shimojo, Kashino, & Nishida, 2004; Love et al., 2013; Maier, Di Luca, & Noppeney, 2011; Petrini, Holt, & Pollick, 2010; Van Eijk, Kohlrausch, Juola, & Van De Par, 2008; Vatakis, Navarra, Soto-Faraco, & Spence, 2008; Vroomen & Stekelenburg, 2011). This inconsistency has been attributed to the effects of uncontrolled variability of decision criteria on explicit timing judgements (Schneider & Bavelier, 2003; Van Eijk et al., 2008; Yarrow, Jahn, Durant, & Arnold, 2011). However, some of our own data using implicit tasks also shows that different measures do not always correlate positively, even while each shows trait-like test-retest replicability (Ipser et al., 2017). Our conclusion was that such independent variability measured by implicit tasks is unlikely to be fully explained away by decision biases, but that it might still be reasonably explained by the assumption that sensory signals acquire independent temporal noise as they traverse different neural networks dedicated to different tasks. However this does not fully explain our previous evidence of negative correlations between different explicit versus implicit measures (Freeman et al., 2013).

In Freeman et al. (2013), we presented videos of a person speaking single syllables, while participants performed two concurrent tasks. One implicit task measured the audiovisual asynchrony that was optimal for maximising the McGurk illusion (McGurk & MacDonald, 1976), where mismatching phonemes and lip movements can alter the phoneme that is heard. In the second task participants performed an explicit temporal order judgements (TOJ), indicating whether they heard the voice onset before or after the lip-movements. From this we measured the Point of Subjective Simultaneity (PSS) which represents the asynchrony at which 'voice-first' and 'voice-second' judgements were equally split. Curiously, we found that the more a participant required an auditory lag to maximise the McGurk illusion, the more the same participant required a visual lag to achieve subjective simultaneity.

This negative correlation pattern runs contrary to dominant theories which assume that temporal discrepancies between different brain networks can be either unified (Hanson, Heron, & Whitaker, 2008; Ivry & Spencer, 2004; Treisman, 1963), minimised via temporal ventriloquism (Freeman & Driver, 2008; Keetels & Vroomen, 2012; Morein-Zamir, Soto-Faraco, & Kingstone, 2003; Vroomen & de Gelder, 2004), adapted away (Fujisaki et al., 2004) or otherwise compensated for (Harris, Harrar, Jaekl, & Kopinska, 2008; Miyazaki,

Yamamoto, Uchida, & Kitazawa, 2006; Sternberg & Knoll, 1973; Yamamoto, Miyazaki, Iwano, & Kitazawa, 2012). Such theories would predict that measures of perceptual timing should correlate positively across different tasks, if at all, but never negatively. A negative correlation seems to point to a different kind of higher-order mechanism governing perceptual timing, which seem to preserve or even antagonise, rather than unify, discrepancies between individual measures. To explain the pattern, we have proposed a renormalization process by which the timings of sensory events registered in different multimodal brain mechanisms are each perceived relative to the average of a distribution of such timings across the ensemble (Freeman et al., 2013). The more one multimodal mechanism is subject to an auditory lag in a given individual, the more this will attract the average of this ‘reference’ distribution, relative to which other mechanisms may seem to have more of an opposite bias towards visual lags. The negative correlation then emerges given individual differences in the temporal discrepancies between mechanisms.

Before committing to this particular theoretical explanation, however, it is important to establish how replicable and generalizable this phenomenon is. Our previous study only used incongruent stimuli and a dual task, in which one implicit measure of audiovisual integration was tested concurrently with a explicit measure of perceived temporal order. This raises justifiable concerns that the pattern observed before is specific to those stimuli or tasks. The present study goes beyond our previous studies by using stimuli and task contexts never tested before in combination, to test several hypotheses that could explain away the negative correlation, and hypotheses concerning the nature of the proposed reference distribution construct, as follows.

Firstly, given the dual-task context, it is possible that responses to the second task were biased by the first. We tested this using a single-task context. This also provides a new test of whether the negative correlation reflects stable characteristics of the reference distribution that persist between testing sessions, or whether it is unique to the concurrent stimulation. If the latter stands, then a negative correlation might not manifest across non-concurrent single-task measurements. A second issue arises because of the prior use of incongruent auditory and visual stimuli, which was necessary to elicit the McGurk illusion. This might have introduced uncertainty over the precise temporal match between audiovisual features, and different tasks might have relied on matching different features. We tested this here using new sentence stimuli in which lip movements and phonemes are congruent. Thirdly, it is

uncertain whether the negative correlation is specific to task-contexts involving TOJ. This might have introduced competing processing demands. For example, the McGurk illusion is necessarily elicited when lip movements are integrated with potentially incongruent phonemes, while TOJ might require more selective unimodal processing of lip movements versus phonemes in order to compare their relative timing. We therefore used a new task in which participants rated the comprehensibility of sentences composed of congruent phonemes and lip movements, taken from the standardized IEEE collection of short ‘Harvard Sentences’. Like TOJ, this comprehensibility rating task still relies on explicit judgements, but it might more integrative rather than selective processing. We found the asynchrony for optimal comprehensibility of sentences, and correlated this against an implicit measure of optimal asynchrony based on a comprehension accuracy task, which also requires the integration of congruent auditory and visual streams, but for different stimuli composed of triplets of spoken numerals. This also provides a new test of whether the proposed reference distribution contains generic information about sensory timing rather than information unique to specific stimuli. If stimulus-specific, there should be no negative correlation between measures based on different stimuli. Altogether, the present study tested the following new stimulus/task combinations: Phoneme identification of syllables for the McGurk task and TOJ under single versus dual task conditions, and comprehension accuracy of Number Triplets versus comprehensibility rating of Harvard Sentences.

A secondary applied goal of this research was to develop an automated method to assess audiovisual asynchronies, for example using an internet-based application, and to assess whether comprehension of speech (either measured using implicit or explicit tasks) might actually improve in some individuals, by artificially desynchronising the stimuli to suit each individual’s personal sensory asynchrony. Whilst such procedures exist for assessing quality of purely auditory stimuli (Smits, Kapteyn, & Houtgast, 2004), to our knowledge none exist for audiovisual presentations with varying asynchrony.

Methods

Participants

Participants were recruited from the undergraduate population and from the local community, and received either course credits or payment as compensation. In the first experiment with McGurk and TOJ tasks, there were 40 participants, 14 male, average age 24.4 years, SD 4.58. In the second experiment with number triplets and Harvard sentences there was a separate group of 34 participants (14 male, average age 30 years, SD 13). These sample sizes were sufficient to measure Pearson's r correlations of $-.5$ (approximating values found in Freeman et al, 2013), with power of 0.8. We required that participants had normal, or corrected-to-normal eyesight, and normal hearing. For the speech comprehension tasks, we also required English language fluency. Procedures were approved by the local ethics committee at City, University of London.

Materials and Apparatus

Visual stimuli were presented on a Sony Trinitron HMD-A420 cathode ray tube monitor. Video mode was 1280 x 1024 pixels, with 85Hz refresh rate. Auditory stimuli were presented via two PC loudspeakers positioned on either side of the monitor. Experimental software was programmed using Psychtoolbox 3 (Brainard, 1997) for Matlab, running on a Mac Mini. Manual responses were made via a standard PC keyboard. Viewing distance was approximately 58cm, with head position constrained using a chin rest. Stimuli consisted of audiovisual movies depicting the lower half of a face speaking syllables, words or sentences. Sample images and dimensions are shown on Figure 1. An oscilloscope confirmed that audiovisual timing of simultaneous beep and flash signals presented through the same software and hardware had minimal bias.

Stimuli differed in their length and complexity, including from simple monosyllabic McGurk stimuli, triplets of bisyllabic numbers (Number Triplets task), and full sentences (Sentence Rating task). For an illustration of typical visual stimuli see Figure 1(a).

For the McGurk task, our choice of stimuli closely followed past studies which measured the McGurk illusion as a function of audiovisual asynchrony (Freeman et al., 2013; Munhall, Gribble, Sacco, & Ward, 1996; Soto-Faraco & Alsius, 2007). To rule out the possibility that our previous findings might be attributed to features specific to those stimuli, we constructed

a new set of stimuli, in which a different female speaker uttered phonemes /ba/ and /da/, which were paired with incongruent lip movements [ga] and [ba] respectively. To equalise response contingencies we also included congruent lip movements, but as these typically produce flat asynchrony functions they were not included in the final analysis. From pilot sessions, we had established that /ba/+[ga] could readily evoke the percept “da”, as the dominant McGurk fusion illusion, while for the /da/+[ba] pairing, the combination “bda” or “ba” percepts were most dominant, as reported in the above studies. For further consistency with those studies, white noise at 65dB sound pressure level was added to the voice stimulus, with a signal-to-noise ratio of 14dB, which might serve to enhance audiovisual interactions (Sumby & Pollack, 1954). A small white dot (0.2 deg) could appear with 50% probability on the speaker's tongue for 24ms when it was visible, which was used in the context of a secondary task to ensure subjects attended to the visual stimulus.

In the Number Triplets task, stimuli were composed of triplets of monosyllabic numbers (zero, pronounced ‘oh’, through nine excluding seven), spoken by a female as a continuous sequence. This restricted stimulus set was used for the convenience of inputting responses and coding errors (Smits et al., 2004), and also to minimise learning effects that might be found with less familiar stimuli (Vlaming, MacKinnon, Jansen, & Moore, 2014). The audio stream was embedded in background noise composed of Fourier phase-scrambled original speech (65dB sound pressure level), which contained the same frequencies and temporal structure within each frequency band, but which was not recognisable as speech. The signal-to-noise ratio (SNR) was set for each individual in a prior staircase sequence (see Procedure). In the main task, average signal-to-noise ratio was -17dB (SD1.5).

The sentence comprehension task used the standard Harvard Sentences (sets 1 to 26) developed for telecommunications research (IEEE, 1969), which balance the frequency of occurrence of all common speech sounds. The speaker was male.

Design

One group of 40 participants completed the McGurk task (McGurk/TOJ Dual), concurrently with TOJ, and also with each in separate runs of trials (McGurk/TOJ Single). The design distinguished between congruent and incongruent audiovisual pairings. A second group of 34 participants performed the Number Triplets and Harvard Sentences Comprehension tasks. In all tasks, audiovisual asynchrony was manipulated between trials, sampling equally from nine

equally spaced levels from 500ms auditory lead to 500ms auditory lag, including simultaneous (0ms, ± 125 ms, ± 250 ms, ± 375 ms, ± 500 ms).

Procedure

Order of tasks was counterbalanced. All conditions were run in one session, in counterbalanced order. Each task began with at least 15 practice trials. No performance feedback was given in either task. In the McGurk task, each trial commenced with a fixation display. Following a key press and a blank interval (duration randomly selected from the range $1000\text{ms} \pm 500\text{ms}$), a movie was displayed for 3000ms. Each presentation began with a variable period during which the speaker was shown with mouth closed. The onset of the actual speech event (both visual and auditory) was timed to start on average at 1500ms from the start of the movie, with random jittering of ± 500 ms. Note that this variable was independent of the asynchrony on each trial. On each trial the stimulus pairing was selected pseudo-randomly. In an attempt to control for cognitive load, attention and visual fixation in the ‘single-task’ conditions, we included a secondary task involved detecting a dot, which appeared with a probability of 50% on the speaker’s tongue at 800ms following movie onset (taking into account the jitter described above). The visual probe was introduced to encourage participants to direct their gaze and attention towards the visual lip movements, in case they become disengaged when lip-movements were highly asynchronous. Participants were instructed to attend to the mouth of the speaker in order to detect the dot, and to listen to what the speaker said. At the end of the movie, in the dual-task context, participants were first visually prompted to decide if they had heard the voice before or after the lip-movements, and then prompted to indicate whether they had heard the phonemes /ba/, /bda/, or /da/. In the single task context, the second prompt was for the presence or absence of the central dot. Responses were made using the arrow keys on a keyboard. In common with previous studies of temporal functions for McGurk illusion (Munhall et al., 1996; van Wassenhove, Grant, & Poeppel, 2007) we presented this limited number of options, representing the percepts most typically reported for the present audiovisual combinations (Soto-Faraco & Alsius, 2007, 2009), to simplify coding of percepts that were visually-driven versus auditory-driven, and thus to construct a single temporal response function. After the McGurk response, participants were then prompted to indicate whether or not they had detected a dot.

Participants completed a total of 288 trials, comprising 8 repetitions of each of the four lip/voice combinations for each of 9 asynchronies.

The Triplets and Harvard Sentences tasks were each administered on separate days. In the Triplets task, the order of numerals was pseudo-randomised with the constraints that each number was presented 18 times in each of the three possible positions, each sequence was unique, and there were no repetitions of a number within each sequence. At the end of each sequence, participants were prompted to identify the numbers that had been presented by typing in three numbers using the computer keyboard. The full set of possible numbers (0 to 9, excluding 7) were displayed during the response period. The next sequence followed once the response was submitted using the 'return' key. There were 162 trials in total. The appropriate SNR for each observer was established in a calibration task performed just before the main task. Here, participants were presented with triplets in the auditory modality only, and the amplitude of the speech was adjusted relative to phase-scrambled background noise, using a one-up one-down adaptive staircase procedure with step sizes of 1dB, over 24 trials. The final threshold was calculated by averaging the speech amplitudes over the last 5 trials of each set, and used to set the SNR for the main task.

In the Harvard Sentences task participants were prompted after each sentence presentation to rate its comprehensibility, by typing in a single number from 1 to 5. The on-screen options displayed after the stimulus presentation were as follows: '1: *Totally incomprehensible*, 2: *Mostly incomprehensible*, 3: *Many words unclear and gist unclear*, 4: *Some words unclear but gist comprehensible*, 5: *Perfectly comprehensible*'. An adaptive procedure was used in the main trial sequence (rather than in a prior sequence as for the Triplets task), where the signal amplitude was increased by 1dB if the response rating was less than or equal to three, or otherwise decreased by the same amount. Participants completed 200 trials.

Analysis

For the TOJ task, we obtained the proportion of 'voice second' responses for each asynchrony. We estimated the PSS, from a logistic function fitted to the raw data for each participant using a maximum likelihood algorithm.

For the McGurk task we obtained the percentage of incongruent trials in which the reported phoneme was influenced by the lip movements, for each of the 9 asynchrony conditions. We

coded trials as visually influenced when a ‘ba’ or ‘bda’ response was made to /da/ + [ba] (12% and 46% of responses respectively) and a ‘da’ or ‘bda’ response was made to /ba/ + [ga] (37% and 9% respectively). We combined responses to both stimulus types into an averaged measure of visual bias. For the Number Triplets task, we computed the percentage of correct word identifications for each asynchrony. In both tasks these performance variables tended to rise to a peak and then fall as asynchronies varied from auditory lead to lag (Figure 1b). For the Harvard Sentences task, we used the threshold S/N ratio for each asynchrony, which fell to a minimum at the optimal asynchrony for comprehensibility.

A function-fitting analysis aimed to interpolate the data points using a non-monotonic asymmetric function, and to read off from this a precise estimate of the asynchrony at which this function reached a peak, or minimum in the case of the Harvard Sentences data. We refer to the asynchrony for maximum visual influence as ‘tMax’. For the McGurk task, we fitted functions individually to data from the fusion and combination illusions, and to the average of these, following Freeman et al. (2013), and then averaged tMax values estimated from these fits. Goodness of fit was then estimated for the averaged fitted functions.

We adopted a previously used non-monotonic asymmetric function (Yarrow et al., 2011) to model task performance y depending on audiovisual asynchrony (t) as follows:

$$y(t, M, \sigma) = \Phi_1(t, M_1, \sigma_1) - \Phi_2(t, M_2, \sigma_2)$$

This equation is composed of two Gaussian cumulative density sub-functions $\Phi(t)$, each with its own mean M and standard deviation σ . The characteristic bell-shaped asymmetrical curve is created by subtracting one of these sub-functions from the other. The four free parameters M_1, σ_1, M_2 , and σ_2 in this equation control the width, height, asymmetry and horizontal shift of the resultant bell-curve. To avoid confusion, it should be understood that we did *not* fit the two separate cumulative Gaussians sub-functions to the data, but the resulting asymmetrical bell-curve.

Results

Our statistical analyses excluded participants for whom tMax and PSS values exceeded a plausible range (± 400 ms, based on our experience that values beyond this range are typically due to poor fitting, plus past literature on the plausible range of audiovisual asynchronies) or rare cases where the raw data were too noisy to fit reliably. There were 3 exclusions for each of the TOJ tasks, and 1 exclusion for each of the McGurk tasks, leaving 35 complete datasets across these conditions. R^2 values were consistent across all tasks (Mean 0.74, SE 0.015, see Table 1).

Descriptive statistics for tMax and PSS are shown in Figure 1

a) Still image from movie stimulus, with dimensions and timing information; b) Illustration of typical data, plotting accuracy for number triplet identification as a function of auditory lag; results from two example participants shown as blue dots; fitted functions shown as continuous lines; vertical dotted lines show how tMax is derived from the fitted functions; grey arrows illustrate how the benefit of desynchronising speech is derived from the empirical data.

Figure 2

Individual participant fits of responses to different tasks and stimuli, all plotted against auditory lag, in seconds. (a-b) proportion of McGurk responses in single and dual task contexts; (c) proportion of correct identifications of number triplets; (d-e) proportion of ‘sound later’ responses in temporal order judgements, for single versus dual tasks; (f) signal to noise ratio in decibels, for maximal comprehensibility ratings for Harvard sentences. Average fit in red, with 95% confidence intervals shaded in grey.

Figure 3 for each condition and Table 1. On average, tMax from McGurk and Number Triplets tasks were biased towards auditory lags by 103ms, SE 0.8ms, and were significantly different from zero [mean McGurk: $t(34) = 5.92$, $p < 0.001$, Cohen's $D = 1.414$; Triplets: $t(33) = 5.87$, $p < 0.001$, Cohen's $D = 1.423$]. However, tMax for the Harvard Sentences was veridical on average [-1ms, SD 74ms; $t(33) = -0.72$, $p = 0.477$, Cohen's $D = -0.175$] and the PSS from the TOJ tasks was also near veridical [-12ms, SE 22ms; $t(34) = -0.48$, $p = 0.633$,

Cohen's $D = -0.115$]. In the McGurk tasks, PSS and tMax values were significantly different from each other [single: $t(34) = 2.15$, $p=0.039$, Cohen's $D = 0.608$; dual: $t(34) = 3.19$, $p=0.003$, Cohen's $D = 0.90$]; tMax values for the Number Triplets versus Harvard Sentences tasks were also significantly different [$t(33) = 4.56$, $p<0.001$, Cohen's $D = 1.298$]. There were no significant differences between PSS values for dual and single TOJ tasks, nor between tMax values for the McGurk tasks. Differences were also non-significant between average tMax values for the McGurk tasks and Number Triplets tasks, and between average PSS values for the TOJ tasks and Harvard Sentences.

We analysed correlations between these tMax measures of optimal asynchrony (Figure 1

a) Still image from movie stimulus, with dimensions and timing information; b) Illustration of typical data, plotting accuracy for number triplet identification as a function of auditory lag; results from two example participants shown as blue dots; fitted functions shown as continuous lines; vertical dotted lines show how tMax is derived from the fitted functions; grey arrows illustrate how the benefit of desynchronising speech is derived from the empirical data.

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Figure 3

tMax (asynchrony for maximal visual influence over auditory responses) and PSS (point of subjective simultaneity), averaged across participants for each task, with error bars indicating one unit of standard error of the means.

Figure 4a-d). A negative correlation was found between tMax for McGurk versus TOJ, in the dual task [$r(33) = -0.44$, $p = 0.009$, 95% CI -0.66, -0.09], replicating our previous study. This effect generalised to the single task context [$r(33) = -0.43$, $p = 0.011$, 95% CI -0.66, -.11]. The correlation between tMax for Triplets versus Sentences tasks was also significantly negative [$r(32) = -0.42$, $p = 0.014$, 95% CI -0.66, -0.09]. Correlations across single and dual contexts were significantly positive for the TOJ task [$r(33) = 0.73$, $p < 0.001$, 95% CI 0.52, 0.85] and for the McGurk task [$r(33) = 0.48$, $p = 0.003$, 95% CI 0.18, 0.70]. These positive correlations indicate that the tMax and PSS estimates could be measured reliably, such that similar values could be obtained for each individual on different replications of the same task. As a more conservative analysis, we replicated the above pattern of significant correlations ($p < .05$) after filtering out participants with poor function fits (i.e. $R^2 < 0.5$). As a comparison, we have replotted data from Ipser et al (2017) plotting tMax for a McGurk task against tMax for the Number Triplet task, for which there was no significant correlation (Figure 4f, see Discussion for commentary).

A further analysis assessed how much comprehension might benefit from desynchronising audio and video. For the Number Triplets task, we found each individual's empirical peak accuracy for number identification, and subtracted accuracy measured with veridically synchronous stimuli (see Figure 1b for an illustration). Mean benefit was 11.6% (SD 8.9). For the Harvard Sentences task, at each individual's optimal asynchrony there was only a modest average improvement in comprehensibility, quantified as a mean decrement in the signal-to-noise ratio required for a threshold level of subjective comprehensibility of 0.26dB (SD 0.42dB). Nine percent of participants had a decrement of at least 1dB. Such small effects are likely to be due to the tight clustering of tMax values around veridical for this measure. Histograms for the distribution of benefits are shown in Table and figure legends

Table 1

Descriptive statistics for average auditory lag (sec) for optimal influence of visual stimulation on audition (tMax) and for the point of subjective simultaneity (PSS), with average R^2 values for the goodness of function fits.

Figure 1

a) Still image from movie stimulus, with dimensions and timing information; b) Illustration of typical data, plotting accuracy for number triplet identification as a function of auditory lag; results from two example participants shown as blue dots; fitted functions shown as continuous lines; vertical dotted lines show how tMax is derived from the fitted functions; grey arrows illustrate how the benefit of desynchronising speech is derived from the empirical data.

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Figure 3

tMax (asynchrony for maximal visual influence over auditory responses) and PSS (point of subjective simultaneity), averaged across participants for each task, with error bars indicating one unit of standard error of the means.

Figure 4

Scatterplots of different measures of audiovisual timing, for three different task contexts. a) Point of subjective simultaneity (PSS) in a temporal order judgement task (TOJ, vertical axis) against an implicit measure of asynchrony for maximal visual influence in the McGurk effect (tMax, horizontal axis), both measured concurrently in a dual task; b) same variables but measured in separate tasks; c) asynchrony for minimum threshold signal/noise ratio for explicit Harvard Sentence comprehensibility ratings, against implicit asynchrony for

maximum accuracy in Number Triplet identification, for a separate participant group; d) TOJ results for single versus dual tasks; e) McGurk results for single vs dual tasks; f) Data replotted from Ipser et al (2017) showing a null correlation between two implicit measures of optimal timing for McGurk illusion and degraded-speech word identification.

Figure 5.

Discussion

The present experiments examined a newly discovered phenomenon whereby different measures of perceptual asynchrony correlate with each other negatively (Freeman et al., 2013). We have established the generality and validity of this phenomenon across a variety of task contexts and stimuli never previously tested in combination, and gained new insights into the underlying mechanisms, while helping to discount the role of response biases, stimulus incongruities, or attentional demands. While current theories of perceptual timing would predict a positive or null correlation, our results provide fresh support for higher-order mechanisms which may function to renormalize, rather than minimise discrepancies in sensory event timing across the brain.

In our previous study we used a dual-task paradigm (Freeman et al., 2013) to measure the audiovisual asynchrony required to elicit maximum McGurk illusion (tMax) and the asynchrony necessary for perception of simultaneity (PSS). We found that the greater the auditory delay an individual required to maximise the illusion, the more that same individual tended to require an opposite visual lag to explicitly perceive the auditory and visual streams as being simultaneous. This counterintuitive negative-correlation phenomenon might be highly informative about the mechanisms underlying our perception of event timing, but first, a number of alternative explanations remained to be excluded. One possibility is that responses to one task might have been biased by previously responding to another task in the same trial, or that individual differences in selective attention to one concurrent task versus the other might have led to apparently antagonistic measures of perceptual timing. To exclude this possibility, here we tested McGurk task and Temporal Order Judgement task (TOJ) as separate single tasks, in which no such potential biases were present. Because we found similar negative correlations between McGurk-tMax and TOJ-PSS under both single and dual-task conditions, biases from performance of concurrent tasks cannot explain away the negative correlation. The stability of our measures across testing episodes also helps to reject the possibility that our measures are dependent on the participant's current state or on the specific combination of tasks that they are concurrently performing: we found negative correlations between explicit (e.g. PSS) and implicit measures (e.g. tMax) obtained from single tasks, administered separately within an experimental session, and positive correlations between the same measures obtained from separate single-task and dual-task contexts (e.g. tMax-single against tMax-Dual and PSS-single against PSS-Dual, Figure 1

a) Still image from movie stimulus, with dimensions and timing information; b) Illustration of typical data, plotting accuracy for number triplet identification as a function of auditory lag; results from two example participants shown as blue dots; fitted functions shown as continuous lines; vertical dotted lines show how tMax is derived from the fitted functions; grey arrows illustrate how the benefit of desynchronising speech is derived from the empirical data.

Figure 2

Individual participant fits of responses to different tasks and stimuli, all plotted against auditory lag, in seconds. (a-b) proportion of McGurk responses in single and dual task contexts; (c) proportion of correct identifications of number triplets; (d-e) proportion of ‘sound later’ responses in temporal order judgements, for single versus dual tasks; (f) signal to noise ratio in decibels, for maximal comprehensibility ratings for Harvard sentences. Average fit in red, with 95% confidence intervals shaded in grey.

Figure 3

tMax (asynchrony for maximal visual influence over auditory responses) and PSS (point of subjective simultaneity), averaged across participants for each task, with error bars indicating one unit of standard error of the means.

Figure 4d-e). This provides further evidence that each individual’s preference for different lags for different tasks may constitute a relatively stable trait-like characteristic of their perception (Grabot & van Wassenhove, 2017; Ipser et al., 2017).

Our new implicit tasks using naturalistic congruent speech stimuli further reinforce the validity and generality of our findings. Participants in our previous study (Freeman et al., 2013) performed phoneme identification and a TOJ task with McGurk stimuli in which one phoneme (e.g. /ba/) was incongruently paired with lip movements belonging to another phoneme (e.g. /ga/). While this mismatch is essential for eliciting the McGurk illusion (e.g. /da/), the task of judging temporal order of such incongruent stimuli is necessarily susceptible

to error, as there is no veridical match between auditory and visual features. Furthermore, in contrast with the integrative McGurk task, the TOJ task might also specifically require comparing the features of distinct auditory and visual events to judge their respective onsets. Discrepancies between the asynchronies that are optimal for each task might therefore arise due to differences in weighting of different features in the two tasks. It is also arguable that the McGurk paradigm, which depends on an illusory deviation from veridical, also lacks validity as an assay of the physical asynchrony that is actually best for audiovisual integration. These concerns were all addressed here by using congruent stimuli, and implicit measures of audiovisual integration based on accuracy of speech identification such as that provided by our Triplets task. We again found evidence of negative correlations between the asynchrony for optimal Triplets identification versus optimal subjective comprehensibility of Harvard Sentences, which supports the generality and validity of our measures of this phenomenon.

So far we have only discussed tests involving speech stimuli, which might be uniquely susceptible to errors of audiovisual feature matching. However, we have previously also replicated the negative correlation for a combination of TOJ with the Stream-Bounce illusion (Sekuler, Sekuler, & Lau, 1997), in which the trajectory of a moving visual stimulus can be altered by an appropriately timed sound (Freeman et al., 2013). Thus the negative correlation phenomenon can be found in non-speech as well as speech stimuli, and in both directions of influence, from vision to audition and vice versa. However it remains to be tested whether measures derived from non-speech stimuli correlate negatively with those derived from speech-based stimuli, or whether measures from three modalities might show transitive relationships to each other (Machulla, Di Luca, & Ernst, 2016). It also remains to be tested whether alternative subjective measures of timing such as simultaneity judgements (SJ) might show similar results. Previous studies have noted that measures derived from SJ and TOJ do not tend to correlate either positively or negatively (Fujisaki et al., 2004; Love et al., 2013; Maier et al., 2011; Petrini et al., 2010; Van Eijk et al., 2008; Vatakis et al., 2008; Vroomen & Stekelenburg, 2011). One reason may be that SJ encourages a broader and more variable mix of strategies, focusing not only on the temporal relationship between the discrete events to be judged (similar to TOJ) but independently also on the quality of temporal binding between them (thus perhaps more similar to our present measures of integration). Each of these would be subject to different weightings and response criteria (Yarrow et al., 2011), and would thus

present a variable combination of influences that might correlate both negatively and positively with TOJ, resulting in an overall null correlation.

As outlined in the Introduction, leading theoretical accounts have often assumed that discrepancies in sensory event timing across different brain areas are either statistically independent, or that they may be minimised, compensated for or unified (Freeman & Driver, 2008; Fujisaki et al., 2004; Hanson et al., 2008; Harris et al., 2008; Ivry & Spencer, 2004; Keetels & Vroomen, 2012; Miyazaki et al., 2006; Morein-Zamir et al., 2003; Sternberg & Knoll, 1973; Treisman, 1963; Vroomen & de Gelder, 2004; Yamamoto et al., 2012). These accounts would predict either a positive or null correlation of different measures of perceptual asynchrony. The counterintuitive negative correlation between our implicit and explicit measures of perceptual timing points to a different kind of higher-order mechanism governing perceptual timing whereby such discrepancies are instead normalized relative to each other. Although such a mechanism might appear to antagonise rather than minimise disparities in perceptual timing between tasks, we have previously proposed that this actually reveals a strategy by which the brain maximises certainty about the timing of multisensory events in the world (Freeman et al., 2013).

A useful analogy for our proposed mechanism is to consider estimating the correct time in a roomful of clocks: we might not know whether each clock is correct, or randomly slow or fast, but these errors can be minimised if we take an average across clocks. However if one clock is particularly slow, it will attract the average so that other unaffected clocks actually appear fast. To translate the analogy to perceptual timing, it may be assumed that different measures of timing (e.g. tMax and PSS) probe different sub-networks in the brain, each subject to different neural delays, which may vary between individuals for functional and anatomical reasons. Each sub-network therefore suffers the ambiguity of not knowing how much the timing of its incoming neural signals reflects the actual timing of external events and how much it reflects internal delays (Scharnowski et al., 2013). This uncertainty might be reduced by normalising each local asynchrony relative to the distribution of all such asynchronies across the different parts of the network. Note that rather than assuming a single centrally-stored representation, each sub-network might share and jointly represent timing information with others in its local network. The central tendency of this distribution represents the asynchrony that relates the most reliably to the actual timing of the external events rather than internal delays. The timing of the stimuli in each local sub-network is then perceived relative to this average. When one sub-network is subject to a particularly large

auditory lag (for example), it will attract the average so that the events registered in other sub-networks will be perceived as tending to have an auditory *lead*. Thus, the more the local timing estimates for one task deviate from the central tendency in a given individual, the more other local estimates relevant to other tasks will seem to be biased in the opposite direction. Renormalization therefore explains why individual differences in the lags measured for one task may anti-correlate with lags measured for other tasks. To summarize the general idea of this theory of Temporal Renormalization: *the event timing within one sub-network is perceived relative to the distribution of event timings across the ensemble*.

It is notable that some participants show biases towards auditory lags in both measures, however such a distribution is predicted by this theory given that each of our two timing estimates is renormalized not only relative to the other, but also relative to other implicit sources of temporal variability which are not currently measured. In our first paper (Freeman et al., 2013, supplementary materials) we simulated this phenomenon assuming two measured ‘clocks’ and one hidden one, and a similar distribution of datapoints was generated with some showing biases with the same sign.

An important aim of the present study was to provide new constraints on the proposed renormalization theory, regarding the nature of the reference representation relative to which perceptions are renormalized. One possibility is that a unique distribution of neural event timings is generated across the brain instantaneously by each incoming stimulus (Mauk & Buonomano, 2004). If so, then we might expect the negative correlation to be found only when two tasks are based on the same stimuli evoking the same distribution. This could explain the results obtained from the dual-task paradigm, in which McGurk and TOJ tasks were performed on the same stimuli in a dual-task context. It might also explain the negative correlation observed in the single-task context with McGurk stimuli, if we assume that the same stimuli presented on separate occasions evoke the same neural distribution. However a negative correlation was also found for stimuli which were not physically identical, in the case of Triplets and Sentences. This supports an alternative possibility that there is a stable record of this distribution against which incoming stimuli can be later compared, and that this distribution records somewhat generic rather than stimulus-specific timing information. Overall, our evidence supports the theory that the perceptual timing of each new stimulus is compared with a stable and generic representation of the distribution of timing of neural events across the whole network, which we might acquire with exposure to a wide variety of different veridically simultaneous multimodal stimuli.

An additional constraint is suggested by a comparison of implicit versus explicit tasks. All the tasks considered so far here have combined an implicit measure of integration efficiency (based on syllable or word identification), with an explicit measure of subjective perceptual timing (TOJ) or comprehensibility (Harvard Sentences). It is therefore unclear from the present data alone whether it is critical to have the contrast between explicit versus implicit tasks in order to obtain the negative correlation effect. However, we have previously compared two implicit measures of optimal asynchrony (tMax) for McGurk with tMax for verbal identification of degraded speech of single bisyllabic words (Ipser et al., 2017). In this case, there was no significant correlation between these measures (see Figure 1

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Figure 2

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Figure 3

tMax (asynchrony for maximal visual influence over auditory responses) and PSS (point of subjective simultaneity), averaged across participants for each task, with error bars indicating one unit of standard error of the means.

Figure 4f, replotting data from the previous study), even though there were reliable within-task positive correlations across testing sessions. We had initially speculated that the negative correlation had been abolished because the two tasks were based on physically rather different stimuli, i.e. single syllables versus words. However this seems less likely given that here we have obtained a negative correlation between triplets of words versus whole sentences, which were also rather different in length and content. An alternative constraint might therefore be that the negative correlation effect manifests specifically when explicit subjective measures are included in the analysis, such as TOJ and comprehensibility ratings. Paradoxically, the consequence of this phenomenon might be that an asynchrony that is optimal for accurate word identification in the Triplets task may seem subjectively asynchronous, leading to reduced ratings of sentence comprehensibility.

The difference between implicit and explicit tasks receives further support from our finding of marked average preferences for auditory lags in our implicit measures, but no such bias on average for our subjective measures of temporal order and the speech comprehensibility ratings. As a further constraint to our explanatory account, we therefore propose that renormalization may be most effective for adjusting the subjective perception of timing, providing one mechanism for maintaining simultaneity constancy (Harris et al., 2008; Kopinska & Harris, 2004) and subjective unity of multisensory events (Vatakis & Spence, 2007) despite variable neural latencies in signal processing. In contrast, implicit measures may reflect more literally the relative latencies for physically propagating and processing signals from audition and vision as they converge on a relevant integration site. Such latencies may be intrinsically hard to adjust or minimise, while the translation from such latencies to the subjective perception of event timing might be more labile, and dependent on renormalization. In other words, explicit measures might be renormalized relative to implicit measures which themselves remain fixed. This might explain why a negative correlation was only found between pairings of explicit versus implicit tasks, but not between the two implicit tasks measured in our previous study (Ipser et al., 2017, Figure 5 here). However the apparent robustness of our implicit measures to renormalization contrasts with evidence from the literature on temporal ‘recalibration’, from which there is some evidence to suggest that both explicit measures and implicit measures of the point of perceptual simultaneity (e.g. based on stream-bounce illusion or McGurk effect) can shift following adaptation to a auditory lead or lag (Fujisaki et al., 2004; Yuan, Bi, Yin, Li, & Huang, 2014). The possibility

that implicit measures are susceptible to temporal recalibration but not renormalization suggests that these may be distinct mechanisms.

A secondary aim of this research was to test a novel automated method for measuring speech integration as a function of audiovisual asynchrony, which could be administered over the internet or via an ‘app’, without supervision. Such a method could have several benefits. For example, previous studies have suggested that abnormalities in the window of integration might be associated with schizotypal personality traits, autism spectrum traits, and dyslexia (Foss-Feig et al., 2010; Hairston, Burdette, Flowers, Wood, & Wallace, 2005; Martin, Giersch, Huron, & van Wassenhove, 2013), but it is not yet clear whether there are also associations with the actual asynchrony of audiovisual integration. An automated on-line test could potentially be used to extend research into such associations, and ultimately as a diagnostic tool to detect shifts of the optimal audiovisual asynchrony for integration, or differences in the width of the windows of integration. Our results with the Triplets task shows that this automated method generates data that are reliable enough to correlate significantly (albeit negatively) with other measures, such as the Harvard Sentences task.

Our results also suggest that word identification accuracy is typically suboptimal in the Triplets task when presented at natural synchrony, and that it can improve by 12 triplets in every 100 on average (SD 7.5%), when the stimuli are presented at each individuals’ optimal asynchrony. If performance is suboptimal for some individuals with synchronous stimuli, this suggests that once an individual’s personal audiovisual asynchrony has been measured (e.g. using our automated procedure), their comprehension of speech while watching multimedia presentations (e.g. in streaming video, or language learning software) might be improved boosted by individually delaying the auditory or visual stream. An automated test of the kind we have constructed might be used to estimate the lag that can optimise an individual’s comprehension. Such an auditory lag could then be incorporated into multimedia streaming software, personal hearing aids and cockpit communication systems (to take just a few examples), to optimise comprehension. However it is notable that benefits were much greater for the implicit task than the explicit speech comprehensibility task. Optimal asynchronies in the subjective task were centred tightly around zero (veridical), so there was typically little difference between the dependent measure sampled at the peak of the asynchrony function relative to at zero asynchrony. Thus there appears to be less quantitative benefit of desynchronising the stimuli for the subjective quality of speech comprehensibility, than for implicit measures based on accuracy. It remains to be determined whether comprehension of

whole sentences can be similarly improved when measured using an implicit task rather than the subjective comprehensibility rating task used here. Given the apparent dissociation between implicit measures of comprehension accuracy and explicit comprehensibility ratings or simultaneity, a further new implication is that for some individuals with large perceptual asynchronies, an auditory or visual delay that fully optimises their comprehension accuracy might actually feel uncomfortably asynchronous if this delay is outside their window for subjective simultaneity.

Conclusion

In this study we have successfully generalised a curious finding from our previous study to a variety of different tasks with more complex speech stimuli. In each case, we found that subjective measures of audiovisual synchronisation correlated negatively with measures of the optimal asynchrony for integration, even when these were tested at different times. Our results support and provide new constraints for our proposed theory of Temporal Renormalization, which explains the negative correlation: we propose that audiovisual stimuli evoke a generic signature distribution of asynchronous activity around the brain, and that the subjective timing of these stimuli is perceived in relation to this distribution. Our results are also encouraging for future research and development of technologies that might improve speech comprehension by individually measuring and delaying audition or vision.

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Table and figure legends

Table 1

Descriptive statistics for average auditory lag (sec) for optimal influence of visual stimulation on audition (tMax) and for the point of subjective simultaneity (PSS), with average R^2 values for the goodness of function fits.

Figure 1

a) Still image from movie stimulus, with dimensions and timing information; b) Illustration of typical data, plotting accuracy for number triplet identification as a function of auditory lag; results from two example participants shown as blue dots; fitted functions shown as continuous lines; vertical dotted lines show how tMax is derived from the fitted functions; grey arrows illustrate how the benefit of desynchronising speech is derived from the empirical data.

Figure 2

Individual participant fits of responses to different tasks and stimuli, all plotted against auditory lag, in seconds. (a-b) proportion of McGurk responses in single and dual task contexts; (c) proportion of correct identifications of number triplets; (d-e) proportion of ‘sound later’ responses in temporal order judgements, for single versus dual tasks; (f) signal to noise ratio in decibels, for maximal comprehensibility ratings for Harvard sentences. Average fit in red, with 95% confidence intervals shaded in grey.

Figure 3

tMax (asynchrony for maximal visual influence over auditory responses) and PSS (point of subjective simultaneity), averaged across participants for each task, with error bars indicating one unit of standard error of the means.

Figure 4

Scatterplots of different measures of audiovisual timing, for three different task contexts. a) Point of subjective simultaneity (PSS) in a temporal order judgement task (TOJ, vertical axis) against an implicit measure of asynchrony for maximal visual influence in the McGurk effect (tMax, horizontal axis), both measured concurrently in a dual task; b) same variables but measured in separate tasks; c) asynchrony for minimum threshold signal/noise ratio for explicit Harvard Sentence comprehensibility ratings, against implicit asynchrony for maximum accuracy in Number Triplet identification, for a separate participant group; d) TOJ results for single versus dual tasks; e) McGurk results for single vs dual tasks; f) Data replotted from Ipser et al (2017) showing a null correlation between two implicit measures of optimal timing for McGurk illusion and degraded-speech word identification.

Figure 5

Distribution of benefits from individually desynchronising audio and video. SNR: Signal to noise ratio.

Table 1

Column1	mean	SE	N
Dual McG (tMax)	0.097	0.019	35
R^2	0.750	0.035	
Dual TOJ (PSS)	-0.035	0.030	35
R^2	0.711	0.043	
Single McG (tMax)	0.093	0.019	35
R^2	0.807	0.031	
Single TOJ (PSS)	0.010	0.027	35
R^2	0.729	0.047	
Number Triplets (tMax)	0.119	0.020	34
R^2	0.757	0.031	
Sentences (tMax)	-0.009	0.013	34
R^2	0.716	0.039	

Figure 1

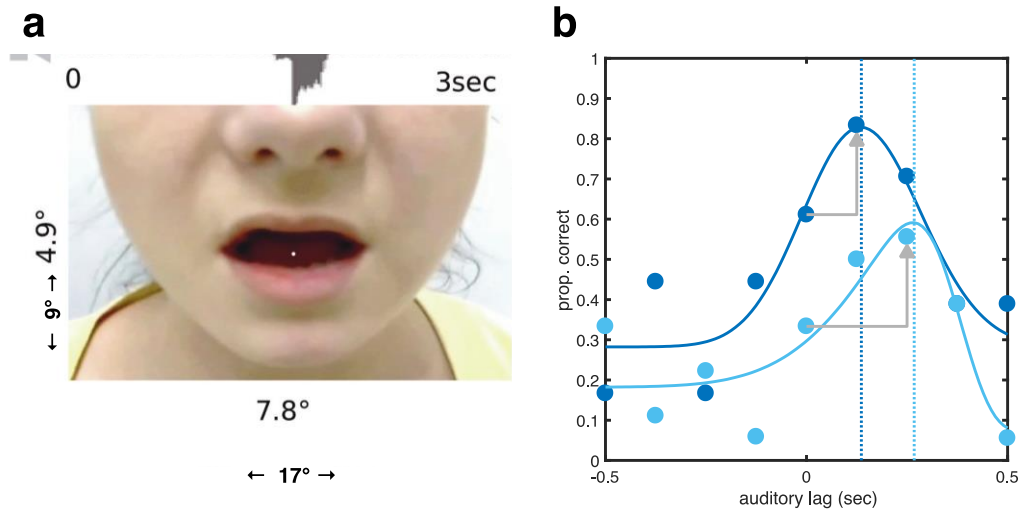


Figure 2

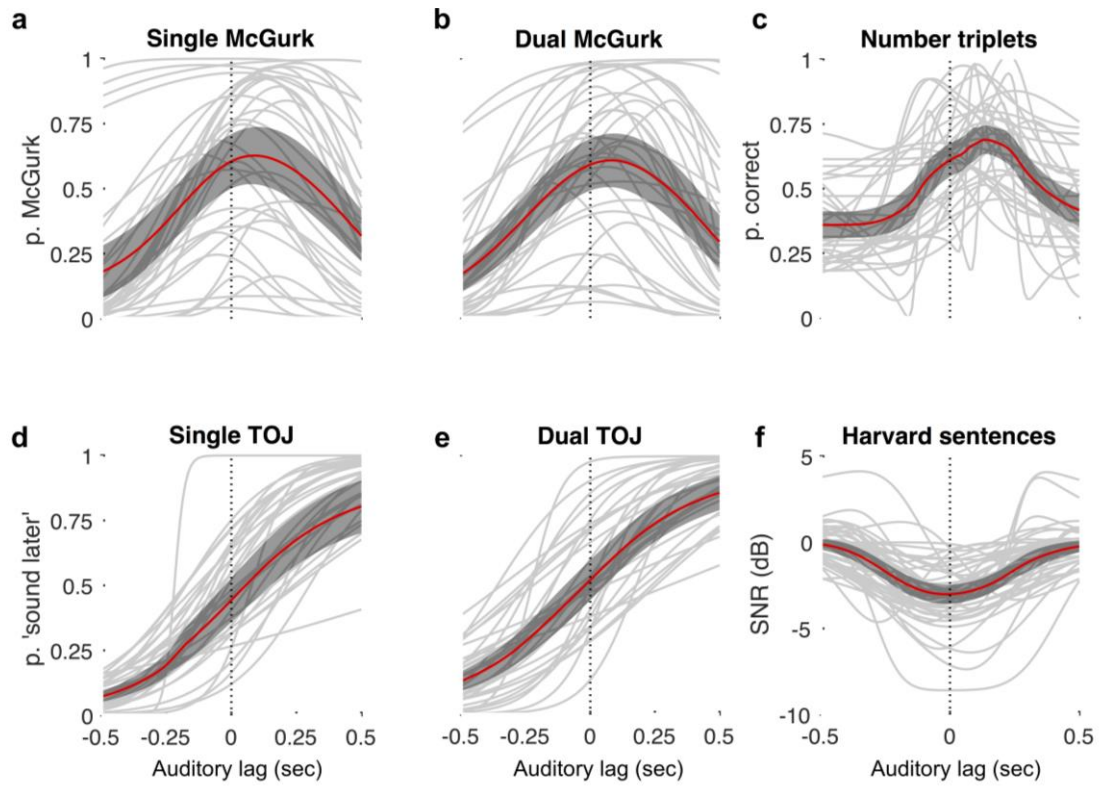


Figure 3

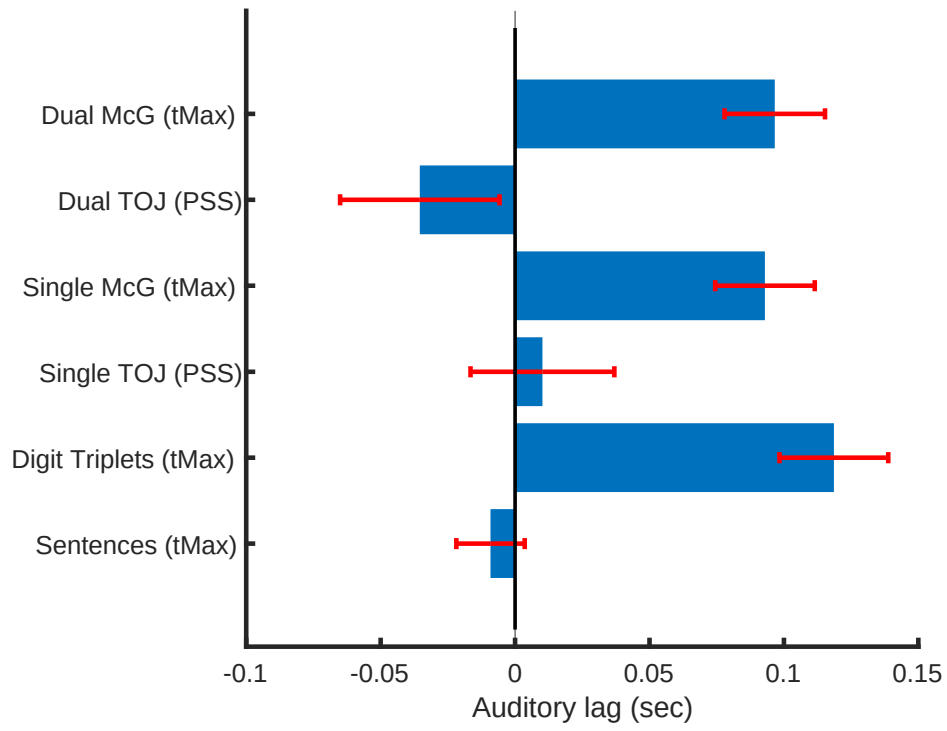


Figure 4

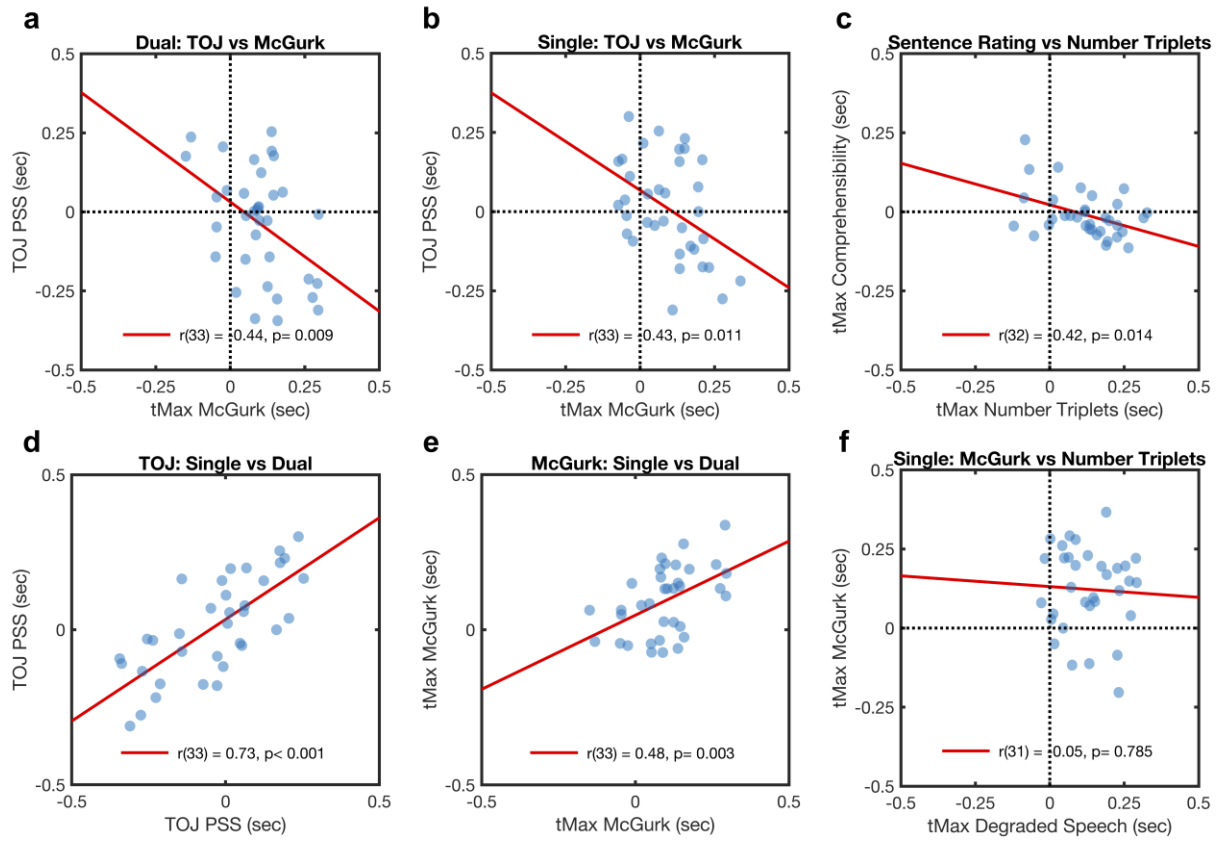


Figure 5

