Grouping by feature of cross-modal flankers in temporal ventriloquism

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Signals in one sensory modality can influence perception of another, for example the bias of visual timing by audition: temporal ventriloquism. Strong accounts of temporal ventriloquism hold that the sensory representation of visual signal timing changes to that of the nearby sound. Alternatively, underlying sensory representations do not change. Rather, perceptual grouping processes based on spatial, temporal, and featural information produce best-estimates of global event properties. In support of this interpretation, when feature-based perceptual grouping conflicts with temporal information-based in scenarios that reveal temporal ventriloquism, the effect is abolished. However, previous demonstrations of this disruption used long-range visual apparent-motion stimuli. We investigated whether similar manipulations of feature grouping could also disrupt the classical temporal ventriloquism demonstration, which occurs over a short temporal range. We estimated the precision of participants’ reports of which of two visual bars occurred first. The bars were accompanied by different cross-modal signals that onset synchronously or asynchronously with each bar. Participants’ performance improved with asynchronous presentation relative to synchronous - temporal ventriloquism - however, unlike the long-range apparent motion paradigm, this was unaffected by different combinations of cross-modal feature, suggesting that featural similarity of cross-modal signals may not modulate cross-modal temporal influences in short time scales.

An important task for the brain in everyday situations is to process multisensory signals. For our sensory system to construct a coherent representation of the environment, it needs to infer which of the many sensory signals it receives at any given time come from the same source, and how those signals should be combined1–3. Much of recent research has focused on studying the circumstances under which signals from different modalities are combined. The way in which sequences of sensory signals are combined or segmented into different perceptual groups appears to be influenced by the spatial, temporal, and featural relationships between them. In the spatial domain, the simple example of perceptual grouping is spatial ventriloquism, whereby vision appears to capture the perceived spatial location of an auditory stimulus4–7. A similar phenomenon has been reported in the temporal domain - temporal ventriloquism - wherein the timing of auditory events influences the apparent timing of visual events8–12. In an early demonstration of temporal ventriloquism8, participants were sequentially presented with two lights, above and below fixation, and performed a temporal order judgment (TOJ) reporting which one had lit up first. The lights were paired with brief, spatially uninformative sounds, with the onsets presented synchronously with the lights or at varying degrees of asynchrony, leading or lagging the lights. When the sounds led the onset of the first light and trailed the onset of the second, participants’ performance on the TOJ improved as though the timing of the onset of the lights had been drawn towards the timing of the sounds, and consequently away from one another.

Building on this early demonstration, Freeman and Driver8 provided a further compelling case in support of temporal ventriloquism using a visual apparent motion paradigm. Successive presentation of a visual flash to one side and then the other of a scene can invoke the appearance of directional motion when the visual stimulus-onset asynchrony (vSOA) is shorter in one direction (e.g. left-to-right separated by 333 ms) than the other (right-to-left separated by 666 ms). In their demonstration, Freeman and Driver kept the vSOAs constant (500 ms) such that the visual presentation produced an ambiguous direction of apparent motion. Instead, they varied the SOA of auditory signals that accompanied each visual onset (flankers). The cross-modal flankers could lead the left visual onset and lag the right visual onset, or vice versa. When the flanker lagged the left visual onset and led the right visual onset, participants were more likely to report rightward apparent motion (or vice versa). This occurred despite the fact that the vSOAs were identical on all trials and thus always suggested an ambiguous direction.

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of visual apparent motion. On the basis of these results, a strong account of temporal ventriloquism has been proposed wherein temporal ventriloquism is the result of the sounds changing the timing of the flash at a basic sensory level.

Although much of the focus in cross-modal interactions has been on the influences of these primary sensory dimensions of space and time, there is also evidence that the content or features contained within each signal contribute to the overall multisensory interpretation. For example, it has been shown that the strictness with which participants report synchrony (or asynchrony) between temporally-offset audio and visual signals depends on the type of signal presented (e.g. human face and voice or hammer hitting a peg). More recently, it was demonstrated that participants' performance on an audio-visual TOJ improved when male or female faces were combined with male or female voices compared with when the auditory and visual stimuli were not matched (e.g. a male voice and female face). Moreover, the after-effect induced by audio-visual temporal adaptation is constrained to the content(s) of the adapting stimulus (again, male or female faces and voices).

Using a visual apparent motion paradigm similar to that described above, a study by Roseboom et al. investigated the role of cross-modal flanker feature on temporal ventriloquism. Participants were presented with visual flashes accompanied by cross-modal flanker signals (either in synchrony or leading/lagging). Successive flankers could be either the same signal (e.g. two audio pure-tone stimuli) or different (e.g. auditory white noise and pure tone). Participants simply had to report the apparent motion direction of the sequence. As in the original demonstration, temporal offset between the flankers and the visual flashes influenced the reported motion direction (Fig. 1A). However, when successive cross-modal flankers differed (e.g. left flash led by audio noise, right flash lagged by pure tone), the influence of flanker timing was greatly reduced (Fig. 1B). Moreover, when successive flankers were the same, but successive flanker pairs differed (e.g. successive flanker stimulus cycles of noise-noise, pure tone-pure tone; Fig. 1C, and the order of this sequence conflicted with the putative influence...
of temporal ventriloquism, noise leads-pure tone lags, pure tone leads-noise lags), the ‘temporal ventriloquism’
effect was completely abolished. Finally, in presentations that contained no difference between visual flash and
flanker timing (synchronous presentation of cross-modal pairs), and thus remained temporally ambiguous, but
the similarity of successive flanker pairings was manipulated (e.g. pure tone-pure tone, noise-noise; Fig. 1D),
biases in reported visual apparent motion direction qualitatively similar to those purportedly resulting from
‘temporal ventriloquism’ were found. Similar results were also reported when the flanker signals differed across
modality such that, for example, a tactile signal led the left visual flash while an auditory signal lagged the right.

That manipulations of cross-modal flanker signals that changed nothing about timing could severely disrupt
and even abolish the apparent temporal ventriloquism, and that similar effects could be produced in the absence
of any temporal difference, suggests that a strong interpretation of temporal ventriloquism is unlikely – at least for
long range visual apparent motion displays such as used in the two studies described above. Moreover, that simi-
lar results were found when the flankers differed but came from the same sensory modality as when they differed
across modalities, implies a higher-level, supra-modal influence of perceptual grouping based on feature, rather
than a lower-level, within-modality process.

While the results of these experiments clearly demonstrate the importance of perceptual grouping based on
featural similarity in determining cross-modal signal combinations, as noted, the experiments in Freeman and
Driver and Roseboom et al. both used long-range apparent motion stimuli (long spatial and temporal inter-
vals). It remains unclear whether a similar influence of grouping by feature would affect temporal ventriloquism
occurring on a much shorter time-scale. Indeed, previous research suggests important differences between
short and long-range visual apparent motion processing mechanisms. Thus, in this study, we examine whether
differences in cross-modal flanker feature similarity can also disrupt temporal ventriloquism on a short tempo-
ral scale. To do so, we use a paradigm similar to the classic temporal ventriloquism demonstration provided by
Morein-Zamir et al. While the original study always used the same auditory tone for both cross-modal flankers,
here we use the same combinations of cross-modal flanker stimuli as used in Roseboom et al., including com-
binations of audio noise, pure tone audio, and tactile stimuli. By using combinations of flanker stimuli that differ
both within (audio noise and pure tone) and across modality (audio and tactile), we can investigate whether, as
for the case of long-range visual apparent motion, the role of perceptual grouping within the flanker sequence is
similar, regardless of whether the differences are defined by sensory modality or by features within a modality.

Consistent with the proposals in Roseboom et al., that both temporal and featural cues contribute to the
segmentation of the stimulus sequence, we predict that presentations containing featurally different cross-modal
flankers will drive perceptual grouping of events in the temporal ventriloquism display, enhancing perceptual
segmentation by comparison with presentations containing identical flankers that rely on temporal informa-
tion only. Therefore, as depicted in Fig. 2, we expect conditions in which the cross-modal flankers are presented

**Figure 2.** Experimental manipulations of timing and cross-modal flanker similarity in a temporal
ventriloquism paradigm based on Morein-Zamir et al. (A) Identical flankers presented synchronously with
the onset of visual events. (B) When cross-modal flankers are presented synchronously but differ in modality
(or feature within modality), TOJ performance is consistent with the perceived timing of the visual onsets
being further apart. (C) When the flankers are identical and presented asynchronously to the visual onsets,
TOJ performance is similarly improved (temporal ventriloquism). (D) When flankers differ and are presented
asynchronously, TOJ performance is improved consistent with the timing of the visual onsets being even further
apart.
asynchronously with the visual stimuli to demonstrate improved precision - performance consistent with the visual event timing being drawn in the direction of the cross-modal event timing (temporal ventriloquism; Fig. 2C and 2D versus 2A and 2B). We additionally expect that performance will be enhanced in conditions in which the flanker stimuli differ by comparison to when they are the same, regardless of whether a temporal difference is also present (Fig. 2B versus 2A, and 2D versus 2C). Note that although in Fig. 2 we depict the predicted improvement in precision as a shift in timing of the visual flash, consistent with the simple mechanistic suggestion for temporal ventriloquism, this is not what we believe is happening. This depiction is used as a visual convenience to communicate equivalence in performance to a condition with greater temporal separation between visual events, indicating the greater ease with which a TOJ can be made. Finally, based on the results obtained by Roseboom et al. when the flanker sequences differed either across modality, or within, we do not expect differences in visual TOJ precision between within and across modality flanker pair conditions.

Methods

Participants. 20 participants (19 naïve) completed the experiment. All participants reported normal or corrected-to-normal vision and hearing. Naïve participants received ¥1000 per hour for taking part. Informed consent was obtained from all participants, and the research was approved by the ethics committee at Nippon Telegraph and Telephone Corporation. The experiments were carried out in accordance with the guidelines laid out in the Helsinki Declaration.

Apparatus. The apparatus and basic stimuli were similar to those in Roseboom et al.19. Visual stimuli were generated with a VSG 2/3 from Cambridge Research Systems (CRS) and presented on a 21 inch Sony Trinitron GDM-F520 monitor, with resolution of 800 × 600 pixels (refresh rate 100 Hz) at a viewing distance of ~105 cm. Auditory and tactile stimuli were generated using a TDT RM1 mobile processor (Tucker-Davis Technologies). Auditory stimuli were presented via a centrally-positioned loudspeaker at ~60 cm distance. Auditory stimulus presentation timing was controlled using a digital line from a VSG Break-out box (CRS) connected to the VSG, which triggered the RM1. Tactile stimuli were delivered via a vibration generator (EMIC Corporation) from ~50 cm distance. Participants rested their right arm on an armrest and their finger was rested on the vibration generator.

Stimuli. The visual stimuli in all conditions were white bars (CIE 1931 x = 0.297, y = 0.321, luminance 123 cd/m²; size 0.25 × 1.55 dva). The bars were positioned against a black background with a white central fixation dot, with a distance of 3.35 dva to the left and right of fixation, and 2 dva above fixation. Throughout the experiment, participants were presented with continuous broadband auditory noise from the loudspeaker at ~80 db SPL. Auditory stimuli were composed of a 10 ms pulse, containing 1 ms cosine onset and offset ramps of either a transient amplitude increase in the broadband noise (Noise stimulus, ~85 db SPL) or a 1500 sine-wave carrier (Pure tone stimulus). To mask the noise produced by the tactile stimulator, participants wore Sennheiser HDA200 headphones for passive noise cancelling. Tactile stimuli consisted of a 10 ms pulse, containing 1 ms cosine onset and offset ramps, of a 20 Hz sine-wave carrier. A depiction of a single trial is provided in Fig. 3.

Figure 3. A depiction of a single experimental trial. In this trial, the cross-modal flankers are both pure tone audio, and are asynchronous with respect to the bars, which have a vSOA of 120 ms. In this trial the participant would be expected to report that the left bar appeared first.
Task and procedure. The visual inter-stimulus onset asynchrony (vSOA) varied between the following values: \(-120\) ms, \(-80\) ms, \(-50\) ms, \(-40\) ms, \(-30\) ms, \(-10\) ms, then \(10\) ms up to \(120\) ms in the same increments. Negative number indicates that the left visual stimulus appeared first. Cross-modal flankers could be presented either synchronously (50% of trials) or asynchronously (50% of trials) with the visual stimuli. When presented asynchronously, they led the onset of the first visual stimulus and lagged the onset of the second visual stimulus by \(100\) ms. Visual stimuli remained on the screen after their onsets until a response was recorded (see Fig. 3).

There were five types of cross-modal flanker: audio noise only, tactile only, audio noise-tactile, audio pure tone only, and noise-pure tone. Experimental conditions are listed in Table 1. In audio noise only, all cross-modal events were broadband auditory noise. In pure-tone only, all cross-modal events were the pure tone stimuli. In the tactile only, all cross-modal events were tactile stimuli. In the audio-tactile, one visual stimulus was paired with audio noise and the other with a tactile stimulus. In the audio noise-pure tone condition, one visual stimulus was paired with the pure tone stimulus while the other was paired with audio noise. In these combination cross-modal flanker conditions, half of the trials were led by one cross-modal flanker type and followed by the other (e.g. in the audio noise-tactile condition, half the trials had the audio noise signal paired with the first visual stimulus, followed by the tactile signal paired with the second visual stimulus, and the order was reversed for the remaining 50% of trials).

In total, participants completed 48 trials for each combination of cross-modal flanker condition, synchrony and vSOA, i.e., 1,152 trials for each cross-modal flanker condition and 5,760 trials in total per participant. Each trial session was comprised of 288 trials (144 trials with synchronous flankers and 144 with asynchronous flankers), with trials completed in a pseudo-random order and taking approximately 10 minutes to complete. Participants completed 20 experimental sessions in a pseudo-random order across two days. In all conditions, the participants’ task was only to report on which side the visual stimulus appeared first, left or right.

Data availability statement. The data (in.csv format) and R code used for data analysis are available as supplement.

Results

Just-noticeable differences. We took the proportion of ‘right first’ responses for each participant in each condition and fitted a logistic function using the ‘quickpsy’ package for R\(^{21}\). An example of the fitted logistic function to the data from a single participant is shown in Fig. 4 below. From this we calculated the just-noticeable differences (JNDs) and points of subjective equality (PSEs) for each participant, in each condition. JNDs were
Differences in PSE between conditions may indicate differences in the influence of different flanker signals based on perceptual latency, and thus may be masking possible differences in JND above. Consequently, the same statistical analyses were applied to PSEs (see Fig. 6) as for the JNDS above, to test if there was a difference in PSE between when the flanker events were the same and when they differed. A Bayesian RM-ANOVA was conducted on the PSE data. The model with main effects of condition and synchrony, but no interaction, had the most evidence ($BF_{10} = 24,058.16 \pm 2.75\%$). A frequentist RM-ANOVA conducted on all PSE data showed, in agreement with the Bayesian test, a main effect of condition ($F(4, 171) = 9.37, p < 0.001$) and a main effect of synchrony ($F(1, 171) = 6.23, p = 0.013$). PSEs were $\pm 0.18$ ms in the synchronous conditions, compared to $2.57$ ms in the asynchronous conditions, showing a slight bias for participants to report the left visual stimulus as having occurred first when asynchronous flankers were present ($BF_{10} = 5.99 \pm 0\%$). The mean PSEs for the 5 conditions (averaged across synchrony) were as follows: $-3.6$ ms in audio-noise-only, $3.53$ ms in audio-tactile, $1.55$ ms in pure tone-audio-noise, $-1.35$ ms in pure tone-only, and $5.86$ ms in the tactile-only condition.

Identical tests were carried out on the directional PSE data (split by order of cross-modal flankers, as in the directional JNDS). Mean PSEs for the four conditions were: audio-tactile: $0.97$ ms, tactile-audio: $6.11$ ms, noise-pure tone: $-1.4$ ms, and pure tone-noise: $4.52$ ms. A Bayesian RM-ANOVA showed that the model with a main effect of condition only had the most evidence ($BF_{10} = 240.73 \pm 1.87\%$). Follow-up Bayesian t-tests showed that these differences occurred between the two cross-modal flanker conditions, i.e., there were differences between the noise-pure tone condition and the audio-tactile condition ($BF_{10} = 72.48 \pm 0\%$), between pure tone-noise and tactile-audio ($BF_{10} = 10.88 \pm 0\%$), and between noise-pure tone and tactile-audio...
There were no systematic differences between the two directions of either of the conditions (e.g. noise-pure tone vs. pure tone-noise). These results suggest that any potential influence of different perceptual latencies for different flanker signals did not affect our interpretation of the role of featural and temporal flanker grouping in this case.

A traditional RM-ANOVA on the directional PSE data showed different results; there was a main effect of condition ($F(3, 133) = 8.08, p = 0.0001$) but also a synchrony × condition interaction ($F(3, 133) = 3.76, p = 0.012$). Follow-up multiple comparisons (FDR-corrected) showed significant differences between PSEs in audio-tactile asynchronous and tactile-audio asynchronous conditions ($t(133) = 3.5, p < 0.001$), between audio noise-pure tone asynchronous and pure tone-audio noise asynchronous ($t(133) = 4.22, p < 0.001$), among other significant differences between conditions and a difference between synchronous and asynchronous PSE in the noise-pure tone condition ($t(133) = 2.59, p = 0.037$).

**Discussion and Conclusions**

Based on previous results, we expected that presentation of cross-modal flankers that differ by feature would enhance segmentation of the stimulus sequence and improve participants' performance for determining which visual stimulus occurred first. This enhancement would be revealed by improved precision on visual TOJ for conditions in which cross-modal flankers differed, by comparison with when they were identical and thus provided only temporal cues to segmentation. However, we found that manipulations of flanker feature similarity both between (audition-tactile) and within (audio noise-pure tone) modalities did not affect participants' ability
to discriminate which of two visual stimuli occurred first. Similarly, there was no difference in directional PSEs between the different directions of each pair of cross-modal flankers, indicating that any potential differences in perceptual latency between different signals did not affect the presence of temporal ventriloquism. Only a difference in timing of cross-modal flankers relative to the visual stimuli (synchronous or asynchronous) produced a reliable difference in performance. Therefore, it appears that perceptual grouping based on feature similarity of cross-modal flankers does not influence the perception of visual sequences within the classic temporal ventriloquism paradigm. This would suggest that the additional feature information was not used by our participants in this setup and paradigm. These findings are inconsistent with results previously reported by Roseboom et al. for another case that claimed to demonstrate temporal ventriloquism using long-range visual apparent motion. The results of that study showed that the apparent temporal capture ascribed to temporal ventriloquism was modulated by differences in the flanker feature and thus was likely not consistent with strong accounts of temporal ventriloquism in which the sound changes the timing of the visual stimulus at a sensory level.

In looking for a possible explanation for the difference in results between these experiments, the clearest difference in experimental design is the temporal scale. In the previous study, a long-range visual apparent motion stimulus was used. This stimulus had a single cycle period of approximately 1 second and repeated multiple times. By comparison, in this study, all stimuli were presented within a maximum of 320 ms in a single-shot presentation, with the key visual task occurring in only 120 ms or less. Previous results indicate that temporal ventriloquism-like effects can be found for both short and long temporal scales, though it is also known that long-range and short-range apparent motion, defined by the difference in spatial and temporal extent, differ in the way that they are processed. This leaves the possibility that only the higher-level processing involved in long-range visual apparent motion is susceptible to the influence of grouping by cross-modal feature.

However, an explanation based on temporal scale alone is inconsistent with previous results. In a series of experiments examining the cross-modal double-flash illusion (DFI), it was demonstrated that manipulations of

![Figure 6](image-url)
feature similarity in the cross-modal flankers interfered with the basic cross-modal effect (a bias of visual number by auditory number). Previous studies had demonstrated that temporal and spatial proximity of the multisensory signals were key parameters in determining the strength of the illusion. This was disputed in another study, where the authors reported that when the two flankers differed in either modality (audio-tactile) or feature within modality (audio noise – pure tone), the DFI was abolished, suggesting that – consistent with results from temporal ventriloquism using long-range visual apparent motion – similarity of flankers by feature is important in determining whether the cross-modal signals come from a common source. The DFI occurs within a short temporal interval, with all stimuli being presented within approximately 100 ms. Consequently, it must be possible for featural information to contribute to cross-modal processing of stimuli presented within a short (100 ms) period. This apparent contradiction may be resolvable if estimating number (the task in DFI paradigms) is, in general, a more complex process than determining which of two visual events occurred first. Consistent with this idea, it has been shown that besides being susceptible to the influence of cross-modal feature information, the DFI is modulated by attention. In general, perception of numerosity has also been shown to operate largely supramodally and adaptation of numerosity operates on perceived rather than physical number, features generally indicative of higher-level processing. However, it is thought that several distinct processes underlie numerosity, including processes for smaller (like in the DFI) and larger numbers, and so this is by no means a clear conclusion to draw. In any case, clearly a short stimulus presentation period does not necessarily exclude the possible influence of cross-modal featural information on visual perception.

Another aspect that may differ between short-range apparent motion, and the DFI and long-range apparent motion is the degree of ambiguity in the visual display. It is possible that the short-range, sequential visual order judgment we used was relatively easy for our participants and could be resolved based on temporal cues alone. If temporal ventriloquism follows simple Bayesian inference in spatial, temporal, and featural dimensions, the influence of feature may be minimal because the information coming from spatial and temporal dimensions is sufficiently precise to make the temporal order judgment with negligible contribution from the additional information. By comparison, the long range visual apparent motion stimuli described in the previous studies were deliberately temporally ambiguous, as the cycle periods were physically matched to produce ambiguous apparent motion (e.g. Freeman and Driver kept their VSOs identical and only varied auditory signal timing). Considering the DFI, it has been shown that the primary determinant of the magnitude of the DFI is participants’ initial visual precision – the less ambiguous the number of visual flashes, the less influence of the cross-modal information. Indeed, using the typical visual stimuli to find a DFI, even in the visual stimulus only condition participants often demonstrate a high error rate, incorrectly reporting if there had been one or two flashes. If a Bayesian inference process is determining the perceived temporal order of events utilising temporal, spatial, and featural information, the way to demonstrate an influence of cross-modal featural information on the classic temporal ventriloquism paradigm would simply be to make the task harder. Decreasing the precision with which the sequential visual temporal order judgement is made, for example by embedding the visual onsets within visual noise, should increase the influence of cross-modal featural information relative to the basic spatial and temporal contributions, increasing the difference in performance between different flanker combination conditions. If such an experiment still found no evidence of the influence of cross-modal featural information in determining visual processing, this might indicate, somewhat consistent with the conclusions drawn by and, that temporal ventriloquism, at least on short time scales, occurs within relatively low-level sensory processing (e.g. area MT) and relies only on the primary, modality redundant sensory dimensions of space and time. Such studies are necessary to resolve this long-standing issue of precisely what information is available at what processing level when combining information from different sensory modalities.

References
1. Wozny, D. R., Beierholm, U. R. & Shams, L. Human tridimensional perception follows optimal statistical inference. *Journal of Vision* 8, 24 (2008).
2. Roach, N. W., Heron, J. & McGraw, P. V. Resolving multisensory conflict: a strategy for balancing the costs and benefits of audio-visual integration. *Proceedings of the Royal Society of London B: Biological Sciences* 273, 2139–2168 (2006).
3. Shams, L. & Beierholm, U. R. Causal inference in perception. *Trends in cognitive sciences* 14, 425–432 (2010).
4. Howard, I. P. & Templeton, W. B. Human spatial orientation. Oxford, England: John Wiley & sons (1966).
5. Jack, C. E. & Thurlow, W. R. Effects of degree of visual association and angle of displacement on the ventriloquism effect. *Perceptual and motor skills* 37, 967–979 (1973).
6. Slutzky, D. A. & Recanzone, G. H. Temporal and spatial dependency of the ventriloquism effect. *Neuroreport* 12, 7–10 (2001).
7. Alais, D. & Burr, D. The ventriloquist effect results from near-optimal bimodal integration. *Current biology* 14, 257–262 (2004).
8. Freeman, E. & Driver, J. Direction of visual apparent motion driven solely by timing of a static sound. *Current biology* 18, 1262–1266 (2008).
9. Morein-Zamir, S., Soto-Faraco, S. & Kingstone, A. Auditory capture of vision: examining temporal ventriloquism. *Cognitive Brain Research* 17, 154–163 (2003).
10. Vroomen, J. & de Gelder, B. Temporal ventriloquism: source modulates the flash-lag effect. *Journal of Experimental Psychology: Human Perception and Performance* 30, 513 (2004).
11. Bertelson, P. & Aschersleben, G. Temporal ventriloquism: crossmodal interaction on the time dimension: 1. evidence from auditory–visual temporal order judgment. *International Journal of Psychophysiology* 50, 147–155 (2003).
12. Fendrich, R. & Corellis, P. M. The temporal cross-capture of audition and vision. *Perception & Psychophysics* 63, 719–725 (2001).
13. Kafalgou, H. & Stoner, G. R. Auditory modulation of visual apparent motion with short spatial and temporal intervals. *Journal of vision* 10, 31 (2010).
14. Kafalgou, H. & Stoner, G. R. Static sound timing alters sensitivity to low-level visual motion. *Journal of vision* 12, 2 (2012).
15. Dixon, N. F. & Spitz, L. The detection of auditory visual desynchrony. *Perception* 9, 719–721 (1980).
16. Vatakis, A. & Spence, C. Crossmodal binding: Evaluating the “unity assumption” using audiovisual speech stimuli. *Perception & Psychophysics* 69, 744–756 (2007).
17. Roseboom, W., Kawabe, T. & Nishida, S. Y. Audio-visual temporal recalibration can be constrained by content cues regardless of spatial overlap. *Frontiers in psychology* 4, 189 (2013).
45. Ernst, M. O. & Banks, M. S. Humans integrate visual and haptic information in a statistically optimal fashion.
44. Battaglia, P. W., Jacobs, R. A. & Aslin, R. N. Bayesian integration of visual and auditory signals for spatial localization.
43. Zimmermann, E. & Fink, G. R. Numerosity perception after size adaptation.
42. Anobile, G., Cicchini, G. M. & Burr, D. C. Separate mechanisms for perception of numerosity and density.
41. Fornaciai, M., Cicchini, G. M. & Burr, D. C. Adaptation to number operates on perceived rather than physical numerosity.
37. Kamke, M. R., Vieth, H. E., Cottrell, D. & Mattingley, J. B. Parietal disruption alters audiovisual binding in the sound-induced flash illusion.
36. Mishra, J., Martínez, A. & Hillyard, S. A. Effect of attention on early cortical processes associated with the sound-induced extra flash illusion.
35. Bizley, J. K., Shinn-Cunningham, B. G. & Lee, A. K. Nothing is irrelevant in a noisy world: sensory illusions reveal obligatory within-modality and across-modality integration.
34. Shams, L., Kamitani, Y. & Shimojo, S. Visual illusion induced by sound.
33. Roseboom, W., Kawabe, T. & Nishida, S. Y. The cross-modal double flash illusion depends on featural similarity between cross-modal inducers. Scientific reports 3, 3437 (2013).
32. Chong, E., Hong, S. W. & Shin, W. Color updating on the apparent motion path. Journal of vision 14, 8 (2014).
31. Claeys, K. G., Lindsey, D. T., De Schutter, E. & Orban, G. A. A higher order motion region in human inferior parietal lobule: evidence from fMRI. Neuron 40, 631–642 (2003).
29. Zhuo, Y. et al. Contributions of the visual ventral pathway to long-range apparent motion. Science 299, 417–420 (2003).
28. Grossberg, S. & Rudd, M. E. Cortical dynamics of visual motion perception: short-range and long-range apparent motion. Psychological review 99, 78–121 (1992).
27. Braddick, O. A short-range process in apparent motion. Vision research 14, 519–527 (1974).
24. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
23. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
22. Morey, R. D., Rouder, J. N., Jamil, T., & Morey, M. R. D. Package 'BayesFactor'. http://cran.r-project.org/web/packages/BayesFactor/BayesFactor.pdf (2015).
21. Linares, D. & López-Moliner, J. quickpsy: An R Package to Fit Psychometric Functions for Multiple Groups. The R Journal 8, 122–131 (2016).
20. Cavanagh, P. & Mather, G. Motion: The long and short of it. Spatial vision 4, 103–129 (1989).
19. Roseboom, W., Kawabe, T. & Nishida, S. Y. Direction of visual apparent motion driven by perceptual organization of cross-modal signals. Journal of vision 13, 6 (2013).
18. Rouder, J. N., Morey, R. D., Lee, J. M., Wagenmakers, E. J., & Morey, M. R. D. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
17. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
16. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
15. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
14. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
13. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
12. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
11. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
10. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
9. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
8. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
7. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
6. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
5. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
4. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
3. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
2. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).
1. Rouder, J. N., Morey, R. D., Speckman, P. L. & Province, J. M. Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology 56, 356–374 (2012).

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Author Contributions

W.R. and S.N. conceived of the study, W.R. collected data, M.K. analysed data, M.K., S.N., W.R. wrote the paper.

Additional Information

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