Title

Seeing objects helps us better hear the sounds they make

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Abstract

It has been established that lip-reading improves the perception of auditory speech stimuli. But does the visual enhancement of auditory sensitivity extend to "objects" other than speech? In other words, does seeing an object help one hear it better? Here we report a series of psychophysical experiments in humans showing that the visual enhancement of auditory sensitivity generalizes to material objects. We further show that the crossmodal enhancement was modulated by the conscious visualization of the stimulus: we can better hear the sounds an object makes when we are conscious of seeing that object. Our work extends an intriguing crossmodal effect, previously circumscribed to speech, to a wider domain of real-world objects. We also connect the phenomenon of consciousness with functional consequences on the ability of one sensory modality to enhance the sensitivity of another.

Introduction

Can seeing an object help us to hear better the sound that object makes? The answer might be yes, given that we can detect speech sounds more sensitively when we watch a speaker's articulatory movements – when we lip read – especially in noisy environments (Grant & Seitz, 2000; Bernstein, Auer, & Takayanagi, 2004). To date, however, visual enhancement of auditory sensitivity has only been demonstrated for linguistic objects, and there are reasons to believe that this crossmodal effect might be narrowly circumscribed. Audiovisual speech is regarded as a special class of stimulus and presumed to be processed in a privileged mode (Tuomainen, Andersen, Tiippana, & Sams, 2005; Vatakis, Ghazanfar, & Spence, 2008). It is not known if this remarkable crossmodal effect respects the hard boundary of linguistic objects or if it generalizes to a wider domain of natural objects.

There is a deep literature on the crossmodal interactions between simple tones and flashes of light. For these elementary audiovisual events, there is ample evidence of both crossmodal facilitation (e.g., Child & Wendt, 1938; Schirillo, 2011) and interference (e.g., Colavita, 1974; Lovelace, Stein, & Wallace 2003; Fassnidge, Cecconi, & Freeman, 2017). By comparison, material objects draw on semantic knowledge and permit much richer spectral and temporal crossmodal interchange than do beeps and flashes.

Here we report a psychophysical investigation into visual enhancement of auditory sensitivity, explicitly targeting non-speech material objects. Under a variety of visual co-stimulation conditions, we estimated auditory detection thresholds with unbiased two-interval forced choice procedures. Set against a constant level of acoustic noise, the power of an auditory signal was adjusted up or down, depending on the subject's performance in preceding trials. Subjects reported which of two intervals of acoustic white noise contained an additive sound signal. Two different sound-producing objects were employed, a musical triangle and a tambourine. Auditory thresholds obtained under different conditions of visual co-presentation were subjected to planned directional comparisons, with statistical significance determined by non-parametric permutation tests.

In a first study, we estimated the auditory detection thresholds of subjects using the transformed up-down procedure (Levitt, 1971). We compared auditory thresholds obtained while subjects viewed a static fixation cross, with thresholds obtained while subjects viewed a silent video of the object. We also tested whether any enhancement provided by the object video was due to a reduction in temporal uncertainty (Tjan, Chao, & Bernstein, 2014), perhaps alerting auditory attention to the signal's onset within the noise interval. To this end we compared the video cue to a visual timing cue, which shifted the color of the fixation cross with the onset and offset of the ostensible sound signal.

In a preregistered second study, we sought to replicate and extend the findings from the first, using the Psi method of Bayesian adaptive estimation of psychometric thresholds (Kontsevich & Tyler, 1999) and repeated testing of subjects (15 hours over five days). We performed a more stringent dissection of the temporal information provided by the object video, generating an abstract visualizer stimulus based on the sound signal's amplitude envelope. This visual timing stimulus provided fine temporal information with a minimum of object-related semantic information (after Maddox, Atilgan, Bizley, & Lee, 2015). Any excess crossmodal enhancement provided by the object video over the visualizer stimulus would therefore not be attributable to a reduction in temporal uncertainty.

In a separate part of the pre-registered study, we tested the dependence of crossmodal enhancement on conscious vision. Did the object videos need to be consciously seen for auditory enhancement to occur? We presented visual stimuli dichoptically to manipulate their conscious visibility. Auditory thresholds were compared when subjects consciously saw the object video with one eye, and when the object video was presented to the same eye but rendered unconscious with continuous flash suppression (CFS, Tsuchiya & Koch, 2005) presented to the other eye. Finally, auditory thresholds were obtained under conditions of binocular rivalry (BR), when both visual objects were presented, one to each eye, but only one object – either congruent or incongruent with the sound – was consciously seen.

Results

1. Study 1.

We recruited 18 subjects to perform a two-interval forced choice (2IFC) task to estimate auditory detection thresholds. We adaptively estimated the threshold signal-to-noise ratio for detection of an auditory signal embedded in noise, under various visual co-stimulation conditions. Noise level, set by each subject, was held constant throughout the trials; signal RMS power was varied to target the 70.7% accuracy level using the transformed up-down procedure with a two-down one-up rule.

We calculated the difference between the relevant pair of thresholds for each subject and then tested whether the group-level differences were significantly different from zero in the predicted direction. Our statistical analysis evaluated the likelihood of obtaining values equal to or more extreme than the ones observed, in an empirical statistical distribution of values obtained under the null hypothesis, in which the visual conditions were permuted.

Object Video vs. Fixation. We found subject-wise improvement in auditory sensitivity (reduced detection thresholds) with co-presentation of object videos, as compared to co-presentation of a static fixation cross (Fig. 1; mean reductions of 2.04 and 2.21

dB SNR for the triangle and the tambourine, respectively; permutation P values = 0.013 and 0.001).

Onset Cue vs. Fixation. We found a mixed pattern of auditory improvement by the co-presentation of a timing cue, as compared to presentation of a fixation cross alone. The timing cue significantly improved detection of the triangle sound (mean reduction of 1.2 dB SNR; $P = 0.04$), but did not significantly improve detection of the tambourine sound.

Object Video vs. Onset Cue. For both objects, co-presentation of the object videos yielded superior auditory sensitivities, compared to the timing cues (mean improvement of 0.86 and 1.63 dB SNR for triangle and tambourine, respectively; P = 0.025 and 0.001).

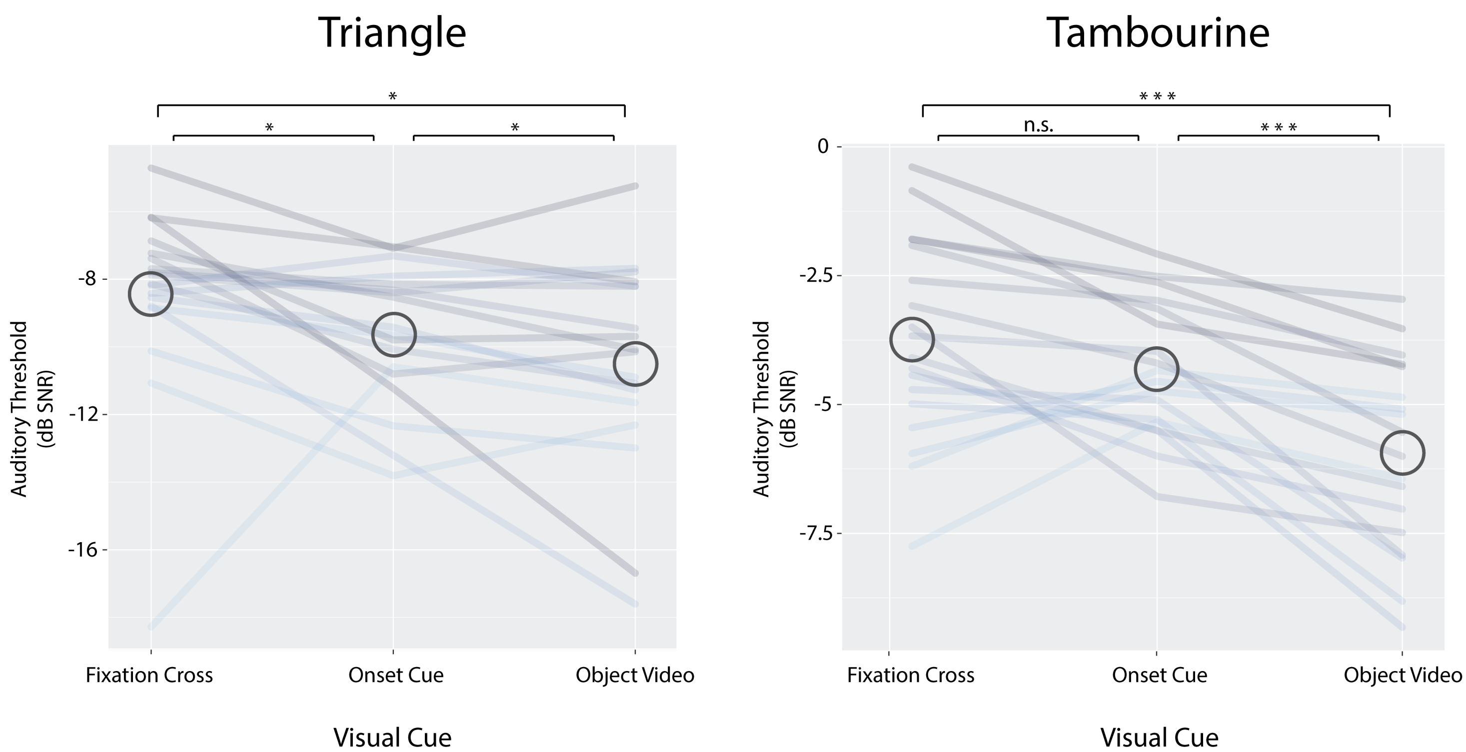

Figure 1. Visual cues reduced the detection thresholds for object sounds presented in noise. Each line joins the thresholds measured under three visual conditions for a particular subject. Lines are colored from gray to blue, sorted in descending order of threshold values in the fixation condition. Circles are centered on the group average threshold, but note that statistical comparisons were performed in a subject-wise manner. Auditory sensitivity was greater when viewing the object video than when viewing a static fixation cross. Object videos also yielded lower auditory thresholds than did a visual onset cue. Asterisks throughout denote the following permutation *P* values: * < 0.05; ** < 0.01; *** < 0.001.

2. Study 2.

In a pre-registered replication of Study 1, we recruited nine subjects for multi-day repeated psychophysical testing, using the Psi method to estimate auditory thresholds. The object stimuli remained the same, but the temporal "visualizer" cue provided much more information about object dynamics, with minimal semantic information. It was created by transforming the amplitude envelope of the object sound into a signal that modulated the diameter of a visually presented circle at 60 Hz, following the strategy of Maddox et al. (2015).

Object Video vs. Fixation. We replicated the main finding from our first study: co-presentation of an object video resulted in higher auditory sensitivity (lower thresholds) than co-presentation of a static fixation cross, for both objects (Fig. 2; mean reductions of 0.81 and 0.65 dB SNR for triangle and tambourine, respectively; *P*s = 0.0001 for both objects).

Visualizer vs. Fixation. Once again, we found a mixed pattern of auditory enhancement by a visual temporal cue. Auditory sensitivity was significantly higher for detection of the triangle sound when accompanied by the visualizer (mean reduction of 0.87 dB SNR; $P = 0.0005$), but not for the tambourine sound.

Object Video vs. Visualizer. For the triangle, the object video did not significantly enhance auditory sensitivity in comparison to the visualizer. However, for the tambourine, the object video yielded significantly lower auditory thresholds than did the visualizer (0.36 dB SNR mean reduction; $P = 0.01$).

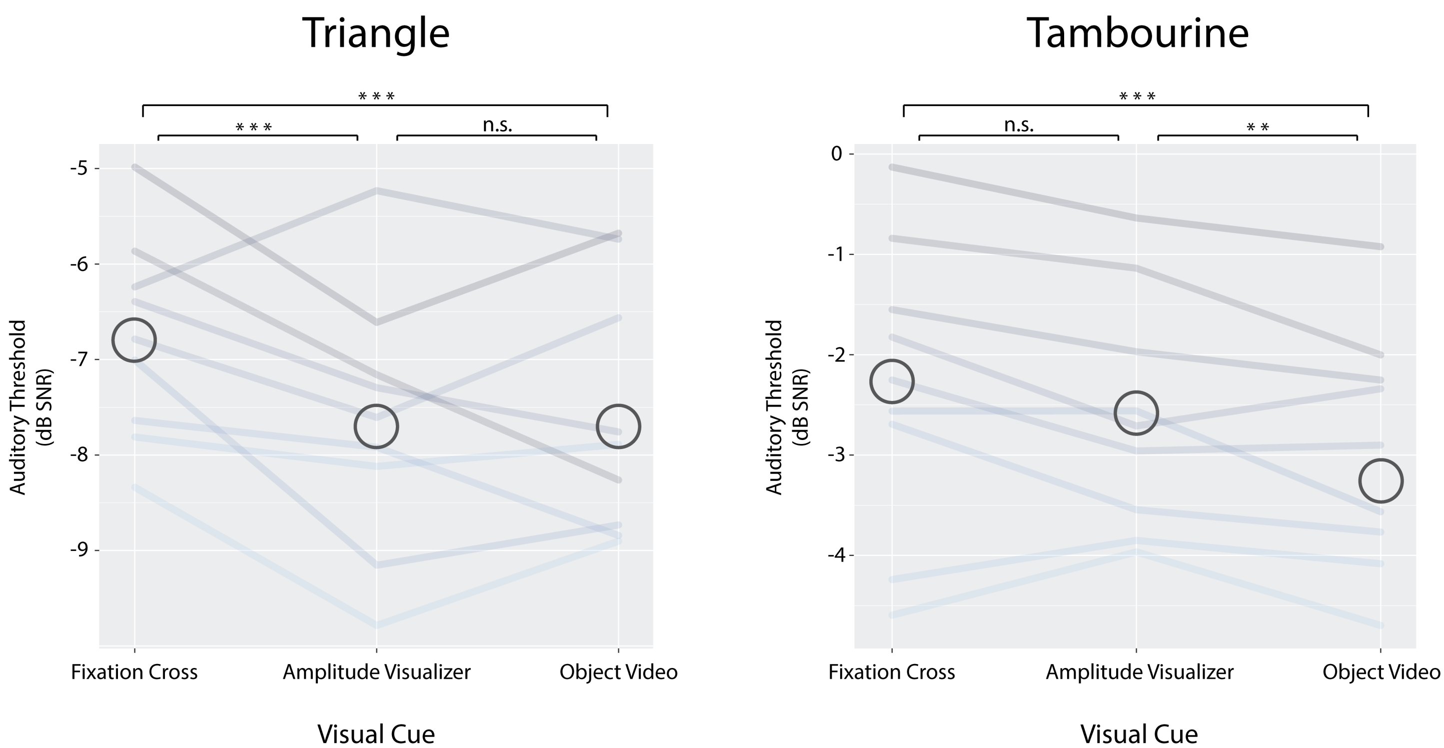

Figure 2. Replication of object-based visual enhancement of auditory detection. A pre-registered follow-up study replicated the reduction in auditory detection thresholds by co-presentation of the corresponding object video, as compared to co-presentation of a fixation cross. For the triangle, a visualizer containing fine temporal information yielded lower auditory thresholds than did the fixation cross. For the tambourine, the object video was a superior cue to the visualizer.

Masking the object video from consciousness with CFS. We manipulated conscious visibility of the objects by dichoptic presentation of different visual stimuli to each eye. CFS was used to mask a normally visible object from consciousness. Auditory detection thresholds for the triangle was not significantly modulated by CFS (Fig. 3, top left). However, auditory thresholds for the tambourine were significantly lower when the object video was presented to one eye and consciously visible, than when the same object video (presented to the same eye) was masked from consciousness by presenting rapidly shifting Mondrian scenes to the other eye (Fig. 3, top right; 0.47 dB SNR mean reduction; $P = 0.003$).

Consciously seeing the congruent object under BR vs. Consciously seeing the incongruent object under BR. Both objects were visually presented, one to each eye, but only one object was rendered consciously visible. We exerted strong control of perceptual dominance during BR by adapting the strategy of unbalanced stimuli in CFS. The "preferred" object video was presented to the subject's dominant eye and at greater contrast, and the "non-preferred" object video to the non-dominant eye at reduced contrast. The preferred object was reported to be in exclusive visual awareness in 98% of BR trials, even with a relatively liberal instruction for reporting seeing the non-preferred object. For both sounds, auditory thresholds were lower when the congruent object was consciously visible than when the incongruent object was consciously visible (Fig. 3, bottom; mean reductions of 0.69 and 0.44 dB SNR for triangle and tambourine, respectively; P = 0.001 and 0.017). This comparison was a follow-on analysis not anticipated in our pre-registration.

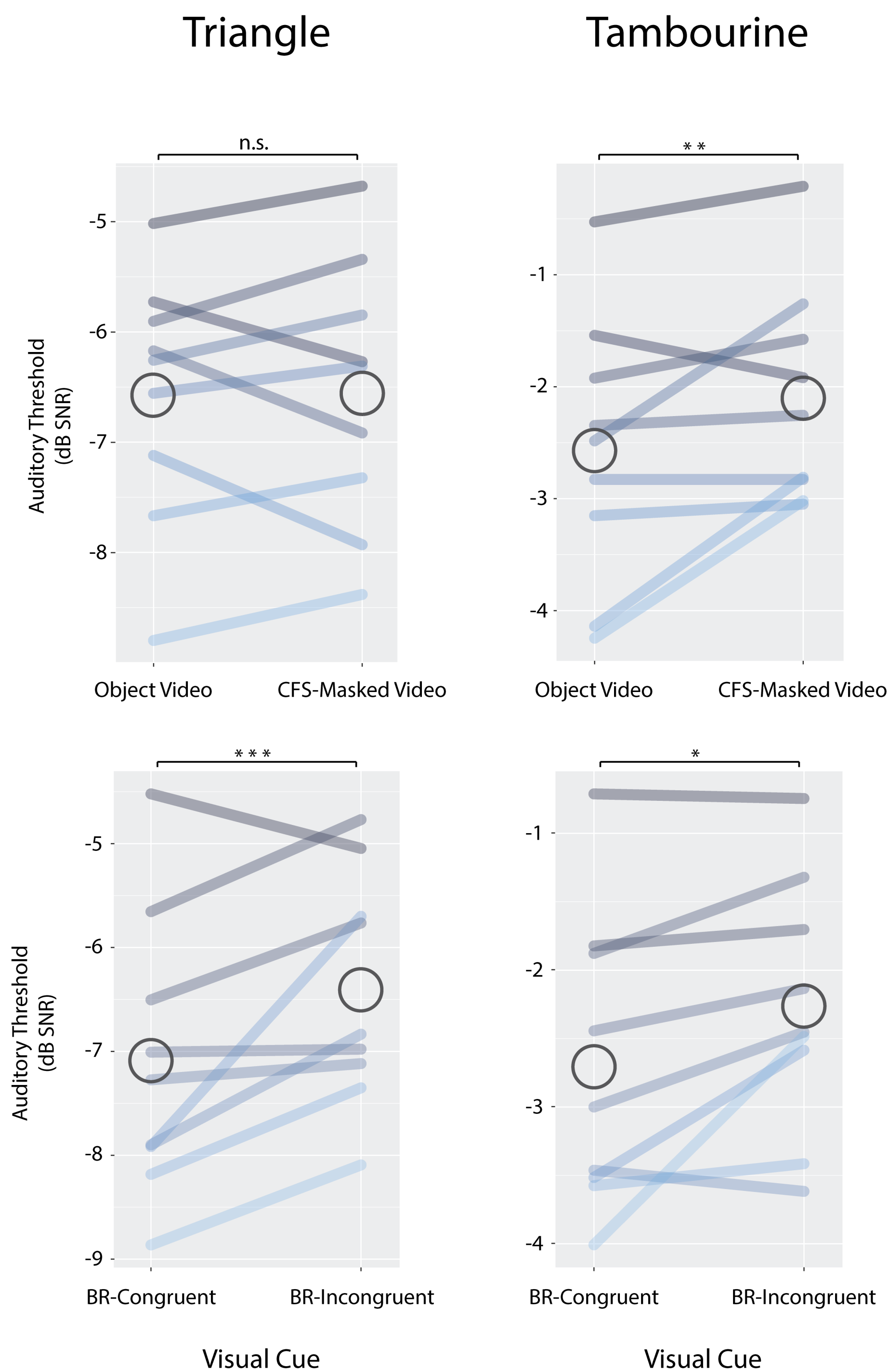

Figure 3. Visual enhancement of auditory sensitivity was modulated by visual consciousness. *Above*, for the tambourine sound only, masking the visually presented object from consciousness raised the auditory threshold, as compared to consciously viewing the object without CFS. *Below*, both objects were visually presented, one to each eye, to induce binocular rivalry (BR). Auditory thresholds were lower when BR cues resulted in visual experience of the congruent object, rather than of the incongruent object.

Discussion

Our results demonstrate the equivalent of lip-reading for non-linguistic objects. Seeing an object helps us better hear the sound that the object makes. The observed magnitudes of visual enhancement for hearing object sounds (0.65 - 2.21 dB SNR) were comparable to those previously reported for improvement in hearing speech sounds (0.8-2.2 dB SNR; Grant & Seitz, 2000). This improvement was not fully accounted for by the coarse or fine temporal information provided by abstract visual cues. Visual cues were more effective when they were consciously experienced than when they were presented to the eyes but not "seen". When both object videos were presented, one to each eye, subjects were more sensitive to hearing an object's sound when they consciously saw the congruent object.

Hearing better, not quicker

Our findings of auditory threshold reduction demonstrate the enhancement of hearing itself, and not the enhanced performance of a behavior informed by hearing. An example of behavioral enhancement is a reduction in reaction times with multimodal stimulation. Co-presentation of an object's sound and image reduced reaction times for object recognition compared to presentation in one modality alone, or presentation of incongruent objects across the modalities (Giard & Peronnet, 1999; Molholm, Ritter, Javitt, & Foxe, 2004; Suied, Bonneel, & Viaud-Delmon, 2009). But speeded reaction times do not necessarily reflect increased sensitivity. One may be more quick to report recognition of an object due to the summation of multimodal information, rather than the enhancement of one modality by the other.

Crossmodal improvements in reaction time and accuracy have also been observed when identifying objects specifically by their sounds (Schneider et al. 2008; Masakura et al. 2016). This type of crossmodal enhancement is not symmetrical: vision enhances auditory identification moreso than audition enhances visual identification (Yuval-Greenberg & Deouell 2009). The effect may be long-lasting, as prior study of visual objects primes later identification of their sounds (Greene et al. 2001). However, this pattern of results can be explained by a visually-mediated shift of an auditory criterion. A person might be quicker to report hearing a dog's bark when primed beforehand with a picture of a dog, not necessarily because the bark sounds any louder, but because they are more inclined to ascribe barking to the same sound. In the object identification setting it is not yet known if vision can enhance auditory sensitivity, rather than reaction times or accuracies.

We show, in the 2IFC object detection setting, a basic, sensory-level improvement of hearing by seeing. Our experimental dissection of temporal information from the visual cue reveals the effect is at least partially mediated by semantic knowledge. The mixed results from the two objects seem to show an object- or event-dependence of the effect. There can be many routes to detection; some objects may rely more on timing information (e.g. the triangle) and others on crossmodal semantic information (e.g. the tambourine). Different objects have different levels of emphasis on their semantic content. Language objects are especially well-characterized by their crossmodal semantics (though they are perhaps "not that special" after all, see Vroomen & Stekelenberg 2011). At the other end, the minimal audiovisual events of beeps and flashes may rely more on the "structural" aspects of temporal and spatial coincidence. These synthetic stimuli, however, do not have the benefit of semantic associations acquired over long exposure in real-world conditions.

Speculation on a neural mechanism

A possible neural substrate for the observed crossmodal enhancement may have been identified by a previous study from our group, which found that patterns of activity in early auditory cortices were associated with the identification of the objects presented in silent videos (Meyer et al., 2010). These activity patterns may support the observed gain in low-level auditory sensitivity. The object specificity of this gain argues for a top-down coordination of modality-invariant object representations compatible with the framework of audiovisual convergence-divergence zones (Damasio, 1989a, 1989b). We have previously detected evidence of audiovisual CDZs roughly midway on the cortical surface between the early auditory and early visual cortices, in the temporoparietal cortices (Man, Kaplan, Damasio, & Meyer, 2012). The findings from our study would expand the role of CDZs, to not only bind disparate fragments of sensory knowledge, but to actively promote binding by enhancing the ability to detect those fragments. This would be in line with the global neuronal workspace theory of consciousness (Dehaene & Naccache, 2001). The specific contents of consciousness of one modality – vision in our case – were broadcast widely and deeply through the brain to achieve integrated multisensory experiences of the objects of daily life.

Imagery or Attention?

An object-based visual cue provides rich temporal and semantic information that can automatically draw auditory attention (Molholm, Martinez, Shpaner, & Foxe, 2007), and/or evoke a precisely specified auditory image. The question arises if one or the other mechanism is responsible for crossmodal enhancement. In the intramodal case, auditory imagery has been shown to enhance auditory sensitivity in a stimulus-selective manner (Farah & Smith, 1983). Imagery of a stimulus may directly improve detection by priming the sensory representations of that stimulus, or else it might indirectly recruit attention to specific frequency components of the stimulus. A later study showed that auditory imagery can also interfere with auditory detection in a selective manner (Okada & Matsuoka, 1992), arguing that imagery, rather than attention, may be the operative mechanism. The experience of imagery may become a distraction from detection, whereas (imagery-driven) recruitment of attention would not be expected to impair detection.

Earlier studies of auditory imagery have shown a Perky effect, where internal imagery is mistaken for an external stimulus (Perky, 1910). If subjects can hear an imagined sound in their mind's ear vividly enough to mistake it for a presented sound (as indeed our subjects often did, spontaneously reporting hearing signals in both intervals even though they were strictly presented in only one interval), then imagery may change the nature of the behavioral task. The addition of subjectively experienced imagery may transform a 2IFC signal detection task into a subjective intensity discrimination task. The two intervals to be discriminated would be one containing auditory imagery + noise and the other containing auditory imagery + external signal + noise. Crossmodal facilitation may therefore occur by visually triggered auditory imagery converting a detection task into a relatively easier discrimination task. It is especially appealing to posit a subjective auditory component because of its demonstrated relation to the subjective nature of the visual cue.

Crossmodal sensitivity enhancement mediated by crossmodal imagery may be considered a case of crossmodal perceptual completion (Spence & Deroy, 2013). Whichever object was consciously seen would have been the one consciously heard in the mind's ear. Indeed, there is evidence that simply imagining the sight of an object can affect auditory perception of the object (Berger & Ehrsson 2013).

Vision alters auditory experience, and vice versa

In considering the possibility that visually-cued auditory imagery can amplify the subjective intensity of sounds, we can point to other examples of visual alterations of auditory experience. The McGurk effect (McGurk & MacDonald, 1976) is a powerful demonstration of this effect for linguistic objects. Later studies with material objects found that clapping was reported as sounding louder when also seeing it (Rosenblum & Fowler, 1991); seeing violin strings plucked or bowed affected the identification of their perceived sounds (Saldaña & Rosenblum, 1993); and watching short or long playing gestures influenced the reported duration of a marimba note (Schutz & Lipscomb, 2007).

The link we find between visual consciousness and auditory perception brings us to a fascinating parallel literature in the other direction, of crossmodal influences on visual consciousness (reviewed by Deroy et al. [2014]). Sounds and touches have been found to induce a bias in favor of the congruent visual experience under binocular rivalry (Kang & Blake 2005; van Ee et al. 2009; Conrad et al. 2010; Chen et al 2011; Lunghi et al. 2014), CFS (Alsius & Munhall 2013; Cox & Hong 2016), backward masking (Chen & Spence 2010), bistability (Hsiao et al. 2012), and motion induced blindness (Chang et al. 2015). Changes of visual consciousness have been proposed to be mediated by crossmodal attention (Alais et al. 2010) or, closer to our view, imagery (Pearson et al. 2008). Finally, a study by Chen and Spence (2011) found the inverse of our main result: sounds enhanced visual sensitivity for detecting congruent objects, but only when the sound preceded the visual signal by enough time (~350 ms) to allow for activation of semantic representations.

Is consciousness necessary for crossmodal enhancement?

We found enhancement of auditory sensitivity when a congruent object, rather than an incongruent object, was in visual consciousness. However, this does not imply that visual consciousness is required for visual-to-auditory enhancement. Unconscious vision – of a picture masked by CFS – is still capable of driving object-based visual attention (Chou & Yeh, 2012). On the other hand, if auditory enhancement is mediated not by attention but by auditory imagery, we would predict that the visual cue must be consciously experienced to evoke the (consciously experienced) auditory imagery.

Reaction times to auditory stimuli can be enhanced with invisible visual cues. In the language domain, identification of an auditory spoken word was speeded by CFS-masked visual speech of the congruent word (Plass, Guzman-Martinez, Ortega, Grabowecky, & Suzuki, 2014). There is even evidence for congruency priming of audiovisual letters and numbers when subjects are unaware of both sight and sound (Faivre, Mudrik, Schwartz, & Koch, 2014). However, we have come across no evidence that invisible visual cues may enhance auditory sensitivity, rather than auditory reaction times. On balance, we believe that the crossmodal enhancement observed in our study is probably mediated by conscious imagery.

Methods

1. Study 1

1.1. Participants

We recruited 18 subjects from the community of the Universidade Federal do Rio Grande do Sul in Porto Alegre, Brazil. Subjects were adults with self-reported normal hearing and normal or corrected-to-normal vision. In the case of corrected vision, the use of contact lenses was preferred over glasses, with a maximum prescription of +/- 3 diopters. Exclusion criteria were a prior diagnosis of psychiatric disorder or use of psychiatric drugs. Subjects received no monetary compensation for their participation, following local regulations. Approval for research involving human subjects was obtained from the Brazilian Ministry of Health's Ethics Commission (Comissão Nacional de Ética em Pesquisa, CONEP) and the Institutional Review Board of the University of Southern California.

1.2. Stimuli

Two sound-producing objects were used, a musical triangle and a tambourine. Audio-visual recordings of the objects generating sounds were made with a digital camera (Olympus E-P2). The majority of the frame was occupied by the objects, with limited view of the hands manipulating them. A set of sound stimuli and silent video stimuli were extracted from the recordings, and all were truncated to two seconds.

The two non-object visual stimuli were a static fixation cross and an onset cue. The onset cue consisted of a fixation cross that shifted its color from white to red and back to white, in synchrony with the onset and offset of the auditory signal.

All stimuli were presented in a light- and sound-attenuated testing chamber. Videos were displayed on a 14” Dell monitor (60 Hz refresh rate), at a viewing distance of 40 cm. Sounds were played over Sennheiser HD-202 headphones driven by a Macbook laptop. Stimulus presentation was precisely controlled with Psychtoolbox (Version 3.0.10) [Brainard 1997] in Matlab (R2015b). Subjects were familiarized with the object audiovisual stimuli by viewing them on a loop for one minute. Prior to the familiarization phase subjects individually adjusted absolute volume levels to one that they would be comfortable with over long-duration testing.

We used a two-interval forced choice (2IFC) task. Each trial contained two intervals of sound, one containing only Gaussian white noise, the other containing the same noise sample with an additive acoustic signal. Noise duration was four seconds and signal duration was two seconds; signal onset was randomly placed between one and two seconds after noise onset. The stereo signal was averaged across L/R channels and converted to two channels of mono signal. To reduce the temporal cueing by sudden sound onset/offset (auditory attack and release), the auditory signal was linearly faded in and out over 500 ms each.

1.3. Procedure

For each 2IFC trial the subjects indicated which interval contained the auditory signal. We adaptively estimated the threshold signal-to-noise ratio for detection of an auditory signal embedded in noise. Noise level, set by each subject, was held constant throughout the trials; signal RMS power was varied to target the 70.7% accuracy level using the transformed up-down procedure of Levitt (1971) with a two-down one-up rule. The initial trial was presented at 0 dB SNR, with step sizes diminishing on the following schedule: 3 dB for reversals 1-2, 1 dB for reversals 3-5, 0.5 dB for reversals 6-8, 0.25 dB for reversals 9-10, and 0.1 dB for reversals 11-13. Threshold was calculated as the mean of the final 10 reversals.

The order of presentation of objects was counterbalanced across subjects. For each object, thresholds were measured for the fixation cross condition, then the onset cue condition, and finally the object video condition.

1.4. Statistical analysis

We hypothesized that measured auditory thresholds would be different when subjects viewed certain visual stimuli as compared with certain other visual stimuli. Specifically, we tested the following directional hypotheses:

1. Object video thresholds would be lower than fixation thresholds.
2. Object video thresholds would be lower than onset cue thresholds.
3. Onset cue thresholds would be lower than fixation thresholds.

We calculated the difference between the relevant pair of thresholds and then tested whether it was significantly different from zero in the predicted direction. Our statistical analysis evaluated the likelihood of obtaining values equal to or more extreme than the ones observed, in an empirical statistical distribution of values obtained under the null hypothesis. We generated the null distribution by permuting the experimental data. Under the null, there is no systematic difference in auditory threshold between the two visual conditions being compared. Therefore, the thresholds may be randomly reassigned among visual conditions without affecting the overall distribution of differences. We then calculated the grand average difference between visual conditions over all subjects. This procedure was repeated 10,000 times to generate an empirical null distribution of mean difference values. The p-value was calculated as the proportion of values equal to or greater than that observed in the unpermuted data.

This procedure permits group-level inference without relying on assumptions of the shape of the distribution of sensory thresholds, or of equal variance of thresholds among subjects. We omit summary statistics of variation that rely on assumptions of the underlying distribution (such as standard deviation or standard error of the mean), in favor of plots of individual-level data that illustrate the total observed variation.

2. Study 2

We pre-registered this study with the Open Science Foundation, specifying all testing procedures, subject enrollment, planned comparisons, and analytical methods, prior to any human observation of the data [https://osf.io/8fyb2/?view_only=af07470991914b74954f11cf9e29c540]. The study stimuli, presentation scripts, and data may be freely accessed at the OSF project page.

2.1. Participants

Subjects were recruited in the same manner as above. Our sample size (n=9) was informed by a prospective power analysis based on the effect sizes observed in Experiment 1, with Cohen's d = 0.57 and 1.13, considered medium and large effects. Based on the larger effect size, and setting alpha = 0.05 and power = 0.8, we calculated a required N of 7. Experiment 2 intended to partially mitigate the large variance observed in the earlier study by performing five repetitions of the thresholding procedure on each subject. This resulted in approximately 15 hours of psychophysical testing over five separate days for each subject. Taking into account the time constraints of subjects and study personnel, we recruited a total of ten subjects, which included one of the authors (GM). One of the subjects failed to complete the study, resulting in an effective enrollment of nine.

2.2. Stimuli

Study 2 contained two phases, the first presenting visual stimuli on a 15” Samsung monitor driven by a MacBook Air and the second presenting visual stimuli dichoptically with a head-mounted display.

In the first phase, the same object stimuli were used as above, though presented with a shorter signal duration of one second embedded within a two-second noise interval, with a signal onset randomly chosen between 0.5s and 1s after noise onset. The signal was linearly faded in and out over 200ms each.

A visualizer cue was created by transforming the amplitude envelope of the object sound into a signal that modulated the diameter of a visually presented circle, following the strategy of Maddox et al. (2015). The original auditory signal was passed through a zero-lag, 5th order, 60 Hz lowpass Butterworth filter, using the Matlab functions *butter* and *filtfilt*.

For dichoptic visual stimulus presentation, we used a head-mounted display consisting of a smartphone (Motorola G4, 5.5" screen size) placed in a TT-VR003 3D VR Headset (TaoTronics). The left and right halves of the screen were exclusively displayed to the left and right eyes. The smartphone screen was controlled as a short latency external display with the TwomonUSB Android App (Easy&Light Software). Object videos were converted to grayscale for dichoptic presentation.

A CFS stimulus was created by rapidly translating and overlaying rectangles of random colors and sizes at approximately 10 Hz (code modified from http://martin-hebart.de/webpages/code/stimuli.html). A CFS stimulus of 120s duration was pre-generated, from which 2s segments were randomly extracted at presentation time.

Adapting the strategy of presenting dichoptically unbalanced stimuli in CFS, we exerted strong control of perceptual dominance during BR by presenting one object video to the subject's dominant eye and at greater contrast, and the other object video to the non-dominant eye at reduced contrast. The "dominant" object video was either congruent or incongruent with the presented sound.

A set of low-contrast videos was created by reducing the luminance contrast to 5%. The following types of dichoptic visual stimuli were created, in the format [Screen Left; Screen Right]:

- Monocular object presentation: [low-contrast object video; blank] and [blank; low-contrast object video]
- CFS-masked objects: [low-contrast object video; CFS] and [CFS; low-contrast object video]
- BR with congruent object dominant: [high-contrast congruent object; low-contrast incongruent object] and [low-contrast incongruent object; high-contrast congruent object]
- BR with incongruent object dominant: [low-contrast congruent object; high-contrast incongruent object] and [high-contrast incongruent object; low-contrast congruent object]

2.3. Procedure

On the first day, subjects became familiarized with the audiovisual stimuli by viewing them on a loop for one minute. For the purposes of biasing visibility under BR, the subject's dominant eye was determined using a hole-in-card test (Handa et al., 2004). The subject's outstretched hands were used to form an aperture sighting a distant object, and the hands were slowly brought inwards to reveal their dominant eye. A second test was administered by viewing the distant object through an aperture as before. Each eye was closed in succession, noting which eye's closing caused displacement of the sighted object. This was taken to be confirmation of the eye's dominance. An initial coarse auditory threshold was determined for each of the auditory stimuli. Subjects performed the 2IFC task with a one-down one-up rule and constant step size of 1 dB, for 6 reversals. This provided an initial estimate of the threshold to serve as the Bayesian prior for the main thresholding procedure using the Psi method (Kontsevich & Tyler, 1999), implemented in the Palamedes Toolbox (Prins & Kingdom, 2009). Due to a software bug omitting the final (45th) trial from approximately 10% of experimental sessions, we excluded the 45th trial from all sessions. Thresholds were taken after 44 trials.

On each day of testing, auditory thresholds were estimated for both objects under each of the following visual conditions: static fixation cross; congruent object video; amplitude envelope visualizer; and CFS. Following a brief rest, auditory thresholds were determined with the following visual stimuli, dichoptically presented: congruent object in non-dominant eye only; incongruent object in non-dominant eye only; CFS in dominant eye and congruent stimulus in non-dominant eye; BR with congruent object dominant; and BR with incongruent object dominant. In CFS and BR conditions, subjects additionally reported their visual experience after each trial by responding whether they had seen the masked/non-dominant stimulus in that trial. Subjects were aware that two objects were presented in BR conditions, and were instructed to set a liberal criterion for reporting seeing the lower contrast object, specifically, if any of its features could be clearly seen and if visibility of the higher contrast object was at all impaired.

On the final day, subjects rated the two object stimuli for their auditory and visual vividness. They also completed the Adapted Betts QMI Vividness of Imagery Scale's auditory and visual subscales (Sheehan, 1967).

2.4 Statistical Analysis

We performed permutation testing as above. With five repeated days of testing, each day's thresholds were entered into comparisons and permuted, but comparisons were never permuted across days. As a worked example, one of our hypotheses predicted that an auditory threshold measured while watching the object video will be lower than the threshold measured while watching a fixation cross. Our null hypothesis stated that there will be no systematic difference in thresholds across visual conditions. These two thresholds were repeatedly measured on five separate days. For each day, we randomly flipped the thresholds - the auditory thresholds for viewing a fixation cross and for viewing the object were switched with a 50% probability. The difference between each pair of thresholds was calculated and the grand average difference across all days and all subjects was calculated. We repeated this procedure 10,000 times, accumulating values for the grand average difference when assignment of visual condition was not respected. If the unpermuted value was greater than the 95th percentile of the null distribution, we declared the observed difference in auditory thresholds to be significantly greater than chance. The exact P value was equal to the proportion of the distribution greater than or equal to the unpermuted value.

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Author Contributions

KM conceived and designed the study with input from GM and JTK. GM collected behavioral data. KM and GM performed data analysis. KM drafted the manuscript with supervision from AD. All authors discussed the findings and provided input on the manuscript.

Supplementary Results

We first report the results of all planned comparisons stated in our pre-registration. They are presented as specific hypotheses and results grouped under general questions.

Question 1. Does seeing an object improve auditory perception for that object?

Hypothesis 1. Watching an object producing a sound, as compared to watching a static fixation cross, will result in a lower auditory detection threshold for that sound.

Result 1. Comparing the object video condition to the static fixation cross condition, we observe reductions in thresholds of 0.811 dB ($P < 0.0001$) for the triangle sound and 0.649 ($P < 0.0001$) for the tambourine sound.

H2. Watching an incongruent object (producing a sound different from the one heard), as compared to watching a congruent object, will result in a higher auditory detection threshold.

R2. This hypothesis was tested on thresholds from the dichoptic stimulation phase. Monocularly presented objects in low contrast did not show a significant congruency effect on auditory thresholds (reductions of 0.2 dB and 0.29 dB SNR for triangle and tambourine; *P*s = 0.19 and 0.09).

Q2. Does the visual cue need to depict the object, or will some other abstract visual-temporal signal suffice?

H3. Watching an abstract temporal cue (a circle varying in size according to the amplitude envelope of the auditory stimulus), as compared to watching a static fixation cross, will result in a lower auditory detection threshold.

R3. For the triangle, the abstract cue resulted in a significantly lower threshold than did the fixation cross (0.869 dB; $P = 0.0005$). The tambourine's observed reduction, 0.294 dB, was not significant ($P = 0.07$).

H4. Nevertheless, the abstract cue will not be as effective as the object cue at enhancing auditory perception; auditory thresholds for the former will be higher than for the latter.

R4. This hypothesis was not supported for the triangle, which showed a slight increase in threshold (0.06 dB; $P = 0.589$). However, the tambourine showed a significant reduction in threshold when comparing the object to the visualizer (0.355 dB; $P = 0.01$).

Q3. Is visual consciousness required for visual enhancement of auditory perception?

H5. Visual presentation of a congruent object in one eye, rendered unconscious by continuous flash suppression (CFS) presented to the other eye, will abolish the enhancement effect of H1. Viewing an object under CFS, as compared to viewing the object alone, will result in higher auditory thresholds.

R5. This hypothesis was supported for the tambourine sound (0.474 dB reduction; $P = 0.003$) but was not significant for the triangle sound (0.025 dB reduction; $P = 0.453$).

H6. Visual presentation of a congruent object in one eye, rendered unconscious by binocular rivalry (BR) via presentation of a higher contrast incongruent object to the other eye, will abolish the enhancement effect of H1. Despite presentation of the congruent object to one eye, BR with the incongruent object dominating visual consciousness will result in higher auditory thresholds compared to viewing the congruent object alone.

R6. This hypothesis was not supported, as the differences for both sounds were not significant (triangle, 0.174 dB, $P = 0.247$; tambourine, 0.303 dB, $P = 0.053$).

H7. Visual presentation of an incongruent stimulus in one eye, rendered unconscious by the presentation of a higher contrast congruent object in the other eye, will preserve the enhancement effect of H1. Despite presentation of the incongruent object to one eye, BR with the congruent object dominating visual consciousness will result in an auditory threshold no different from viewing the congruent object alone.

R7. This hypothesis was supported for both objects, with no significant differences detected between the conditions (triangle $P = 0.981$, tambourine $P = 0.755$).

Q4. Do individual differences in vividness of imagery correlate with the strength of crossmodal enhancement?

H8. There will be a positive correlation between vividness of auditory imagery and the crossmodal enhancement of auditory thresholds, across subjects. There will be no correlation between vividness of visual imagery and crossmodal enhancement.

R8. The first hypothesis was not supported, with no significant subject-wise correlation between auditory imagery scores and magnitude of enhancement, calculated as the difference between object video thresholds and fixation cross thresholds. The second hypothesis was supported, insofar as no significant relationship was found.

In a follow-on analysis, we addressed the question posed by Spence & Deroy (2014)[1] on crossmodal imagery: would visually-triggered auditory imagery be correlated to one's intrinsic auditory imagery? We correlated subjects' scores on the auditory subscale of the imagery questionnaire with their reports of the vividness of the auditory imagery triggered by the visual stimuli. There was no significant relationship.

[1] Spence, C., & Deroy, O. (2013). Crossmodal Mental Imagery. In Multisensory Imagery (pp. 157–183). New York, NY: Springer New York. http://doi.org/10.1007/978-1-4614-5879-1_9