

Sound alters activity in human V1 in association with illusory visual perception

S. Watkins,^{a,b,*} L. Shams,^c S. Tanaka,^d J.-D. Haynes,^{a,b} and G. Rees^{a,b}

^aWellcome Department of Imaging Neuroscience, Institute of Neurology, University College London, 12 Queen Square, London WC1N 3BG, UK

^bInstitute of Cognitive Neuroscience, University College London, Alexandra House, 17 Queen Square, London WC1N 3AR, UK

^cDepartment of Psychology, University of California, Los Angeles, Los Angeles, CA 90095-1563, USA

^dFaculty of Human Sciences, Jin-Ai University, Takefu, Japan

Received 7 July 2005; revised 4 January 2006; accepted 12 January 2006
Available online 23 March 2006

When a single brief visual flash is accompanied by two auditory beeps, it is frequently perceived incorrectly as two flashes. Here, we used high field functional MRI in humans to examine the neural basis of this multisensory perceptual illusion. We show that activity in retinotopic visual cortex is increased by the presence of concurrent auditory stimulation, irrespective of any illusory perception. However, when concurrent auditory stimulation gave rise to illusory visual perception, activity in V1 was enhanced, despite auditory and visual stimulation being unchanged. These findings confirm that responses in human V1 can be altered by sound and show that they reflect subjective perception rather than the physically present visual stimulus. Moreover, as the right superior temporal sulcus and superior colliculus were also activated by illusory visual perception, together with V1, they provide a potential neural substrate for the generation of this multisensory illusion.

© 2006 Elsevier Inc. All rights reserved.

Introduction

The integration of information from multiple senses is fundamental to our perception of the world. Traditionally, it has been assumed that multisensory integration occurs after sensory signals have undergone extensive processing in unisensory cortical regions. However, recent studies in monkey and humans show multisensory convergence at low-level stages of cortical sensory processing previously thought to be exclusively unisensory (for a review, see Schroeder and Foxe, 2005). For example, both touch and eye position can influence responses in monkey auditory

association cortex and primary auditory cortex, respectively (Fu et al., 2003, 2004; Schroeder et al., 2001). Similarly, primate auditory cortex demonstrates integrated responses to facial and vocal signals of conspecifics (Ghazanfar et al., 2005). These single unit studies are complemented by human event-related potential work demonstrating interactions between auditory and visual (Fort et al., 2002; Giard and Peronnet, 1999; Molholm et al., 2002, 2004) or somatosensory (Foxe et al., 2002; Murray et al., 2005) stimuli at very short latency (46–150 ms). One recent fMRI study has shown evidence of audiovisual integration in BA 17 (Calvert et al., 2001), suggesting that primary visual cortex may respond to non-visual inputs. These demonstrations of early modulation of unisensory cortices by multisensory signals challenge hierarchical approaches to sensory processing (Felleman and Van Essen, 1991; Schroeder and Foxe, 2005), but the function of such multisensory convergence at the anatomically lowest stage of cortical processing remains unclear.

An important but unresolved issue that may provide insight into the function of multisensory convergence concerns how such neural interactions might be reflected in conscious perception. If activity in early sensory cortices corresponds to a particular conscious experience, then modification of that activity by converging multisensory input should be related to changes in conscious experience. Behaviorally, the combination of information from different senses can function to reduce perceptual ambiguity (Sumbly and Pollack, 1954) and enhance stimulus detection (Bolognini et al., 2005; Frassinetti et al., 2002; Stein et al., 1996). Critically, multisensory convergence can also influence the consciously perceived properties of stimuli (McGurk and MacDonald, 1976; Mottonen et al., 2002; Murray et al., 2004, 2005; Shams et al., 2000; Stein et al., 1996). However, there has been relatively little study of how changes in conscious perception associated with multisensory interactions might be reflected in changes in brain activity. Here, we therefore sought to address this issue by measuring brain activity with high field fMRI in human volunteers experiencing an established audiovisual illusion, in which the presence of irrelevant sounds can modify the perception

* Corresponding author. Institute of Cognitive Neuroscience, University College London, 17 Queen Square, London WC1N 3AR, UK. Fax: +44 20 7813 1420.

E-mail address: swatkins@fil.ion.ucl.ac.uk (S. Watkins).

Available online on ScienceDirect (www.sciencedirect.com).

of a simple visual stimulus (Shams et al., 2000). Crucially, this illusion occurs on only a proportion of trials, with veridical perception of the visual stimulus being reported on the non-illusion trials. We could thus compare trials with identical auditory and visual stimulation that nevertheless had very different perceptual outcomes.

Visual-evoked potentials and fields are modified at short latency in association with the illusion (Bhattacharya et al., 2002; Shams et al., 2001, 2005), raising the possibility that audiovisual interactions responsible for illusory perception might occur in retinotopic visual cortices. Such a possibility would be consistent with observations of multisensory interactions in human occipital cortex (Calvert et al., 2001) plus increasing evidence for an association between human V1 activity and unisensory conscious visual experience (Tong, 2003). We therefore employed retinotopic mapping (Serenio et al., 1995) and specifically focused on activity in retinotopically defined V1, in order to better study the localization of any multisensory interactions associated with changes in conscious experience.

Methods

Subjects

Seventeen young adults (8 females, 18–30 years old, right handed) with normal hearing and normal or corrected to normal vision gave written informed consent to participate in the study, which was approved by the local ethics committee. Prior to scanning all subjects took part in a behavioral pilot experiment, following which three subjects were excluded because they did not report the multisensory illusion. Following scanning, two subjects were rejected on the basis of excessive head movement (>5 mm), and one subject was rejected because technical problems with the electrostatic headphones. Eleven subjects (8 females, 18–30 years old, right handed) were therefore included in the analysis reported here.

Stimuli

Visual stimuli were projected from an LCD projector (NEC LT158, refresh rate 60 Hz) onto a circular projection screen at the rear of the scanner. The subjects viewed the screen via a mirror positioned within the head coil. The auditory stimuli were presented binaurally using electrostatic headphones (KOSS, Milwaukee, USA, Model: ESP 950 Medical) custom adapted for use in the scanner. All stimuli were presented using MATLAB (Mathworks Inc.) and COGENT 2000 toolbox (www.vislab.ucl.ac.uk/cogent/index.html). Visual stimuli consisted of an annulus with luminance 420 cd/m² and eccentricity 8.5–10° of visual angle presented for 17 ms. The background was a uniform gray screen of luminance 30 cd/m². Luminance calibration was achieved via a viewing aperture in the MRI control room using a Minolta LS-100 spot photometer. We used an annulus displayed in the peripheral visual field in association with auditory stimulation to maximise illusory perception, which is stronger for stimuli displayed in the periphery (Shams et al., 2002). In addition, the cortical representation of such a peripheral annulus avoids the foveal confluence at the occipital pole (Serenio et al., 1995), where it is extremely difficult to distinguish activity from different early retinotopic visual cortical areas. Our stimulus geometry therefore permitted us

to clearly distinguish activity in V1, V2, and V3 from other cortical areas. The auditory stimuli consisted of a sine wave with frequency of 3.5 kHz, duration of 10 ms (with a ramp time of 1 ms at each end of the sound wave envelope), and volume of 95 dB. The sound intensity (SPL) produced by the headphones was measured while the headphones were a suitable distance away from the scanner using a sound meter (Radioshack 33–2055).

Procedure

On each experimental trial, subjects were presented with one or two briefly and successively flashed visual stimuli, either alone or accompanied by one or two successively presented auditory beeps. These comprised six different trial types that represented all the possible combinations of flashes and beeps. For clarity, these trial types will subsequently be referred to by consistent abbreviations. For example, ‘F2B1’ refers to trials on which there were two flashes and one beep, while ‘F2’ refers to a trial on which only two flashes were presented with no auditory stimulation. The interval between flashes in the two flash conditions (F2, F2B1, and F2B2) was 56 ms. Pilot behavioral work confirmed that whether beeps and flashes were presented simultaneously or with slight temporal offset (Shams et al., 2002) made little difference to behavioral reports of illusory perception. On trials with two flashes and one beep (F2B1), the auditory beep was presented simultaneously with the first flash. Participants maintained central fixation throughout and indicated whether they perceived one or two flashes, by pressing one of two response keys on a keypad held in their right hand. Each trial lasted 90 ms followed by a 1800-ms response interval. Eye position data were collected on eight participants during the trials to ensure participants maintained fixation. One eighth of all trials were null trials, during which no visual or auditory stimuli were presented. There were thus seven physically different types of trial. The responses of participants were further used to post hoc divide the F1B2 trials into those on which the illusion was perceived (“F1B2-Illusion”), and those on which it was not (“F1B2-no Illusion”). Each participant completed between 4 and 8 runs of 128 trials divided equally between the different trial types. Trials were pseudo-randomly distributed within a run.

fMRI scanning

A 3 T Siemens Allegra system was used to acquire both T2*-weighted echoplanar (EPI) images with blood oxygenation level-dependent contrast (BOLD) and T1-weighted anatomical images. Each EPI image comprised of thirty-two 3-mm axial slices with an in-plane resolution of 3 × 3 mm positioned to cover the whole brain. Data were acquired in five runs for the first seven subjects, each run consisting of 214 volumes and between six and eight runs, for the last four subjects, each run consisting of 137 volumes. The first five volumes of each run were discarded to allow for T1 equilibration effects. Volumes were acquired continuously with a TR of 2.08 s per volume. During scanning, eye position and pupil diameter were continually sampled at 60 Hz using long-range infrared video-oculography (ASL 504LRO Eye Tracking System, Mass). Eye movements were monitored on-line via a video screen for all subjects. Subjects completed a short pilot in the scanner to ensure that they could maintain fixation. The eye tracker was calibrated at the start of each experimental run. Eye position was not recorded in three of the subjects for technical reasons.

Data analysis

Eye tracking data were analyzed with MATLAB (Mathworks Inc., Sherborn, MA). Blinks and periods of signal loss were removed from the data. Mean eye position, expressed as a distance from fixation, was then computed for each trial type and every participant from whom data were available. A repeated measures ANOVA was used to establish whether mean eye position deviated significantly from fixation or between conditions.

Data analysis: fMRI preprocessing

Functional imaging data were analyzed using Statistical Parametric Mapping software (SPM2, Wellcome Department of Imaging Neuroscience, University College London). All image volumes were realigned spatially to the first and temporally corrected for slice acquisition time (using the middle slice as a reference). Resulting image volumes were coregistered to each subject's structural scan. The fMRI data were analyzed using an event-related model. Activated voxels in each experimental condition for each subject were identified using a statistical model containing boxcar waveforms representing each of the experimental conditions, convolved with a canonical hemodynamic response function and mean corrected. Motion parameters defined by the realignment procedure were added to the model as six separate regressors of no interest. Multiple linear regression was then used to generate parameter estimates for each regressor at every voxel

for every subject. Data were scaled to the global mean of the time series and high pass filtered (cut-off: 0.0083 Hz) to remove low-frequency signal drifts.

Retinotopic analyses

To identify the boundaries of primary visual cortex, standard retinotopic mapping procedures were used (Serenio et al., 1995; Teo et al., 1997; Wandell et al., 2000). Flashing checkerboard patterns covering either the horizontal or vertical meridian were alternated with rest periods for 16 epochs of 26 s over a scanning run lasting 165 volumes (see Fig. 1A for details). SPM2 was used to generate activation maps for the horizontal and vertical meridians. Mask volumes for each region of interest (left and right V1, V2d, V2v, V3d, V3v) were obtained by delineating the borders between visual areas using activation patterns from the meridian localizers (see Fig. 1B for representative meridian maps). We followed standard definitions of V1 together with segmentation and cortical flattening in MrGray (Teo et al., 1997; Wandell et al., 2000).

Using the mask volumes for left and right V1, V2, and V3, we identified voxels that showed significant activation ($P < 0.05$ uncorrected) for the comparison of all trials on which visual stimulation was present (i.e., all experimental conditions) compared to null events, employing the regression analysis described above. This comparison identifies voxels activated by the annular visual stimulus in each of the retinotopic areas determined by the

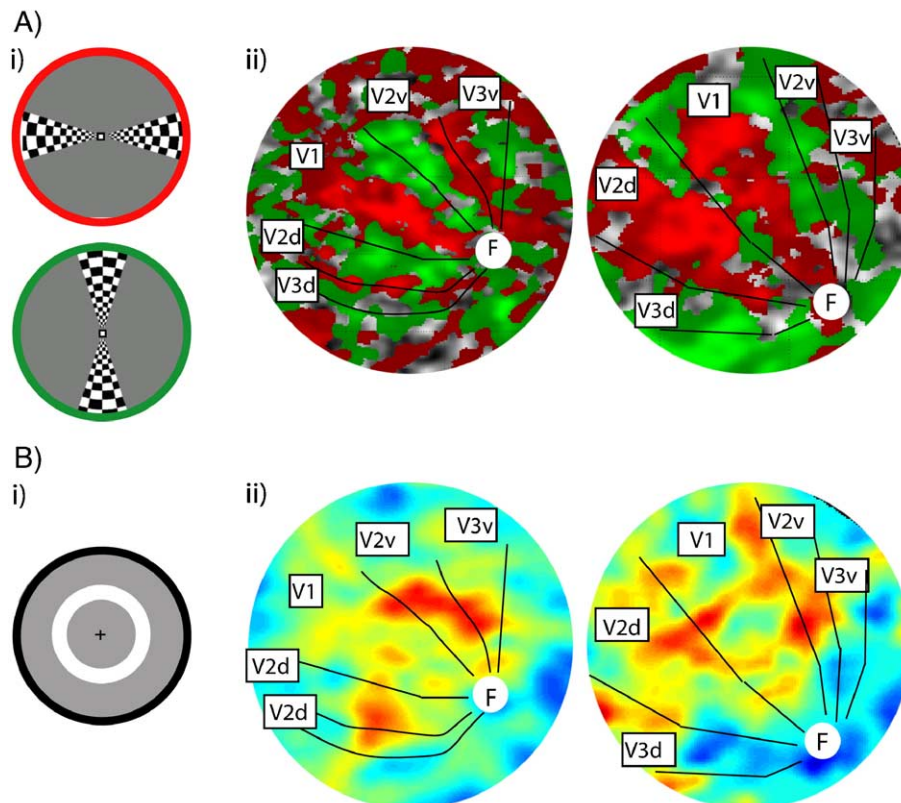


Fig. 1. Stimulus representation in visual cortex. (Ai) Visual stimuli used to map the horizontal and vertical meridians (see Methods) (ii). The outline of individual visual areas V1, V2v, V2d, V3v, and V3d and the fovea (determined by meridian mapping, see Methods) are demonstrated for two representative subjects. (Bi) Visual stimulus used in the main experiment. (ii) The spatial distribution of stimulus-evoked activity (contrast of all visual events (F1B1, F1B2, F2B1, F2B2, F1, and F2) versus null events thresholded at $P < 0.05$ uncorrected) is shown projected onto a flattened representation of visual cortex for two representative subjects (see Methods).

independent meridian mapping procedure. Informal examination of these activations superimposed on flattened representations of occipital cortex confirmed our expectation that they represented voxels activated by our annular visual stimulus (see Fig. 1B for two representative participants). Having thus independently identified the stimulus representation in V1–V3, the final analytic step was to extract and average regression parameters resulting from the analysis of the main experimental time-series (described above). This procedure reliably yielded estimates of percentage signal change for each condition averaged across voxels in V1, V2, and V3 that responded to the visual stimulus for every participant. The percentage signal change was divided by the average cortical response to visual stimulation (i.e., $(F1 + F2) / 2$) in each subject to produce a normalized percentage signal change for each condition. The statistical significance of any differences in activation between audiovisual and visual trial types was subsequently assessed by entering the normalized percentage signal change for each participant in each of the conditions (F1, F2, F1B1, F2B1, F1B2 no-Illusion, F2B2) into a two-way within subjects ANOVA using a conventional significance level of $P < 0.05$ (two tailed). The factors were flash number (1 or 2) and bleep number (0, 1, or 2). The statistical significance of any differences in activation between the F1B2 Illusion condition and the F1B2-no-Illusion condition was assessed by entering the normalized percentage signal change for each subject in each condition into a two tailed t test using a significance level of $P < 0.05$ (two tailed). Finally, we calculated an image of the voxels in V1 that did not show a significant response to the visual stimulus. We then used this image to repeat the above procedure to examine the response to each condition in the non-stimulus responsive area of V1. Corrections for multiple comparisons were made for brain regions where we had no a priori hypotheses. In retinotopic visual cortex, we made no correction, as we independently defined the anatomical borders and specific anatomical location activated by the stimuli using orthogonal contrasts, and had specific hypotheses regarding the level of activation in different conditions based on prior work with this paradigm.

Whole brain analysis

To complement the retinotopic analyses, we also conducted an unbiased examination of regions outside retinotopic cortex using a random effects whole-brain analysis. We did not further examine regions within occipital cortex for this analysis, as it is well established that there is very significant variability in retinotopic areas across individuals (Dougherty et al., 2003). This variability is independent of gyral and sulcal anatomy, it is not taken into account by the spatial normalization required for this group analysis. The realigned and slice time corrected images from each participant were spatially normalized to a standard EPI template volume based on the MNI reference brain in the space of Talairach and Tournoux (1988). The normalized image volumes were then smoothed with an isotropic 9-mm FWHM Gaussian kernel. These data were analyzed using an event-related random effects model, the first stage of which was identical to the regression model described above for the retinotopic analyses, except now applied to spatially normalized images. Activated voxels in each experimental condition for each participant were identified using a statistical model containing boxcar waveforms representing each of the eight experimental conditions, convolved with a canonical hemodynamic response function and mean corrected. Motion parameters

defined by the realignment procedure were added to the model as six separate regressors of no interest. Multiple linear regression was then used to generate parameter estimates for each regressor at every voxel for every participant. Data were scaled to the global mean of the time series and high pass filtered (cut-off: 0.0083 Hz) to remove low-frequency signal drifts. The resulting parameter estimates for each regressor at each voxel were then entered into a second level analysis where each participant served as a random effect in a repeated measures ANOVA. Appropriate corrections were made for non-sphericity and correlated repeated measures (Friston et al., 2002). The main effects and interactions between conditions were then specified by appropriately weighted linear contrasts and determined on a voxel-by-voxel basis. For these whole brain analyses, a statistical threshold of $P < 0.05$ for multiple comparisons was used, except for the superior colliculus where a sphere of diameter 4 mm centered on the anatomical location of the superior colliculus (as defined by previous studies (Calvert et al., 2001)) was used to apply a small volume correction ($P < 0.05$, corrected).

Results

Behavioral

Analysis of behavioral responses during scanning confirmed (see Fig. 2C for a full description of behavioral responses in every condition) that participants were able to accurately report the number of flashes when there was no associated auditory stimulus (i.e., F1 and F2 trial types), when the numbers of flashes and bleeps were identical (i.e., F1B1 and F2B2 trial types; accuracy, 93%, SE across participants, 3%) or when two flashes were presented with one bleep (F2B1 accuracy, 88%; SE across participants, 4%). However, on a large proportion of trials when one flash was accompanied by two bleeps (F1B2 trials), participants reported an illusory perception of two flashes (“F1B2-Illusion”; 32% of all F1B2 trials, SE across participants, 5%). On the remainder of F1B2 trials, participants reported veridical perception of one flash (“F1B2-no Illusion”). Signal detection theory analysis indicated a change in sensitivity (d') between visual stimuli presented alone and visual stimuli presented with concurrent auditory stimuli. Sensitivity d' was defined as $d' = z(\text{hits}) - z(\text{false alarms})$, where z is the inverse cumulative normal. For this analysis, double flashes were treated as the target and a correct identification of that stimulus was counted as a ‘hit’, while the correct identification of a single flash was counted as a ‘correct rejection’. ‘False alarm’, therefore, corresponded to single flash trials on which participants reported seeing two flashes. On average, the presence of two bleeps ($d' = 2.67$, $SD = 0.47$) decreased sensitivity by 15% compared with the visual-alone conditions ($d' = 2.28$, $SD = 0.60$; $t(10) = 2.74$, $P = 0.02$). The presence of concurrent auditory bleeps was not associated with any significant change in absolute criterion bias ($|\beta| = 1.46$, $SD = 2.2$) compared to the visual alone condition ($|\beta| = 0.27$, $SD = 0.2$; $t(10) = 1.71$, $P = 0.12$). Had the illusion been the result of a change in criterion bias, the sensitivity should stay constant; yet we identified significant changes in d' due to the introduction of concurrent auditory stimuli, suggesting changes in the perceptual processing of the stimulus. This replicates previous findings with this multisensory illusion (Shams et al., 2002) and confirms that illusory multisensory perception can be robustly demonstrated even in the noisy environment of the fMRI scanner.

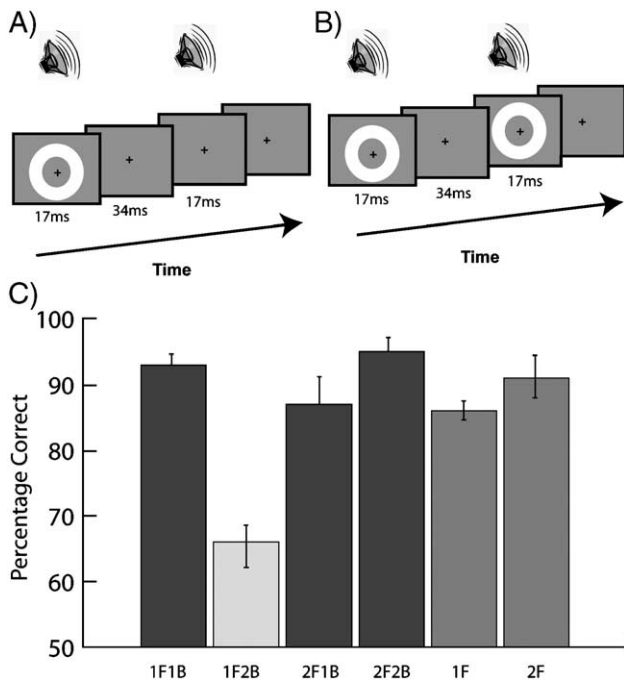


Fig. 2. Stimulus configuration. Visual stimuli consisted of an annulus presented in the peripheral visual field. The auditory stimuli consisted of a sine wave with frequency of 3.5 kHz, duration of 10 ms, and volume of 95 dB. Subjects were presented with one or two briefly and successively flashed visual stimuli, either alone or accompanied by one or two successively presented auditory bleeps. (A) A single visual flash presented with two auditory bleeps (F1B2). (B) Two visual flashes presented with two auditory bleeps (F2B2). On trials with two flashes and two bleeps (F2B2), the bleeps were presented simultaneously with the flashes. (C) Behavioral results. Participants responded with a button press on each trial to indicate whether they saw one or two flashes. Percentage correct responses averaged across all the participants ($n = 11$) are shown for the six different conditions: F1B1 (one flash with one bleep), F1B2 (one flash with two bleeps), F2B1 (two flashes and one bleep), F2B2 (two flashes and two bleeps), F1 (one flash presented alone with no auditory stimulation), and F2 (two flashes presented alone with no auditory stimulation). The error bars represent standard errors of the mean. Note, the low probability of correct responses in the F1B2 condition indicates that on the remaining trials (35%), the participants reported the illusory perception of two flashes.

Eye position data

Participants were requested to maintain fixation at the centre of the display. During scanning, eye position was monitored on-line in all participants to ensure participants successfully maintained fixation throughout the experiment sessions. For technical reasons, eye data were only recorded in eight participants. A repeated measures ANOVA showed no statistical difference in mean eye position from fixation or between conditions for the eight participants in whom eye tracking data were available ($F(7,49) = 0.485$, $P = 0.841$).

Functional MRI

Retinotopic analyses

We first conducted a two-way within subjects ANOVA on the data with correct responses from each visual area. As our stimulus was circularly symmetric and auditory stimuli presented binaurally, we combined measurements across hemispheres to produce a

single averaged measure for V1, V2, and V3. The factors were flash number (1 or 2) and bleep number (0, 1 or 2, hereafter referred to as 'B0', 'B1' or 'B2' respectively). We found a significant main effect of flash number (V1: [$F(1,10) = 11.8$, $P = 0.006$]; V2: [$F(1,10) = 9.4$, $P = 0.01$]; V3: [$F(1,10) = 26$, $P = 0.0004$]) since responses were larger following two flashes than one. The main effect of bleep number was also significant (V1: [$F(2,20) = 10.7$, $P = 0.006$]; V2: [$F(2,20) = 6.9$, $P = 0.008$]; V3: [$F(2,20) = 6.7$, $P = 0.01$]). This was due to an increased response in retinotopic cortex when a visual event is accompanied by a sound compared to a visual event alone regardless of the number of bleeps (Fig. 3A and Table 1), (B1–B0, [$t(10) = 3.2$; $P = 0.009$], B2–B1, [$t(10) = 1.25$; $P = 0.2$] and B2–B0, [$t(10) = 5.1$; $P = 0.001$]). Importantly, there was no interaction of flash number with bleep number (V1: [$F(2,20) = 0.04$, $P = 0.9$]; V2: [$F(2,20) = 0.64$, $P = 0.5$]; V3: [$F(2,20) = 0.1$, $P = 0.8$]). Thus, early retinotopic visual areas generally showed enhanced activation when a visual stimulus was accompanied by sound, consistent with previous work implicating these structures in multisensory processing (Calvert et al., 2001).

These findings provide some preliminary evidence regarding multisensory auditory–visual interactions in retinotopic visual cortex. However, our primary goal was to identify correlates of changes in *conscious perception* associated with multisensory interactions. On F1B2 trials, a significant proportion evoked the illusion of two flashes (F1B2-Illusion), while on the remainder, only one flash was perceived (F1B2-no Illusion). We therefore next compared activity in retinotopic visual areas that was evoked on F1B2-Illusion trials with F1B2-no Illusion trials. Note that because we compared physically identical trials with exactly the same visual and auditory stimulation, any differences in brain activity associated with this comparison *cannot* reflect differences in visual or auditory stimulation. We found that activity in V1 was significantly higher for F1B2-Illusion trials on which the illusion was perceived compared to F1B2-no Illusion when the illusion was not perceived ($[t(10) = 2.25$, $P = 0.047$], two tailed) (see Fig. 4 for full details). The activity in V1 in the F1B2-Illusion condition was not significantly different to the F2B2 condition [$t(10) = 0.209$; $P = 0.84$]. This enhanced cortical response to the illusory perception was specific to the retinotopic locations of V1 responding to the visual annulus, as there was no significant effect of the illusion in the regions of V1 that did not respond to the visual annulus [$t(10) = 0.54$, $P = 0.61$]. Thus, illusory visual perception induced by sound is associated with significantly greater activation of stimulus-responsive retinotopic regions of the first visual cortical area, V1. The effect of the auditory–visual illusion on V1 activity was highly consistent across participants, with ten of our eleven participants showing an increase in activity for F1B2-Illusion versus F1B2-no Illusion trials (Fig. 5B). To visually assess the time course of the event-related activations, we plotted peristimulus time histograms for the two principal comparisons of interest (F1B2-Illusion and F1B2-no Illusion) averaged across subjects (Fig. 5A). There was no correlation between the magnitude of the cortical response on F1B2-Illusion trials and the proportion of trials on which each participant experienced the illusion (correlation coefficient = -0.148 ; $r^2 = 0.022$, $P > 0.1$).

Whole brain analyses

To complement the retinotopic analyses, we also performed whole-brain analyses of activity for each of the main comparisons

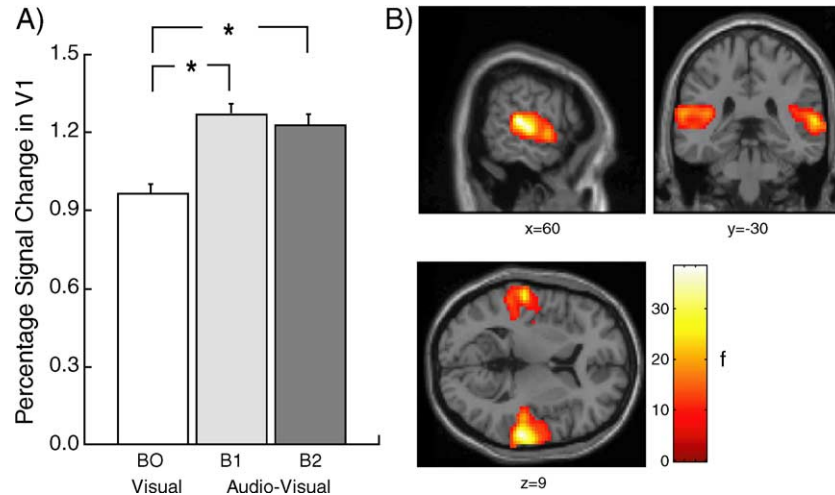


Fig. 3. Cortical areas activated by visual stimuli accompanied by auditory stimuli compared to visual stimuli alone. (A) Signal change in V1 for visual stimuli alone (B0: $(F1 + F2) / 2$) compared with visual stimuli accompanied by sounds (B1: $(F1B1 + F2B1) / 2$ and B2: $(F1B2\text{-no Illusion} + F2B2) / 2$) collapsed across the number of visual flashes. Data shown are averaged across the eleven subjects (see Methods for further details) with error bars representing the standard error of the mean, and the symbol ‘**’ indicating statistical significance ($P < 0.05$). (B) Shown in the figure are some of the cortical loci where event-related activity was significantly greater during audiovisual trials compared to visual trials alone (main effect of auditory stimulation; $P < 0.05$, corrected for multiple comparisons; see also Results). The left hemisphere is presented on the left. The color of the activation represents the f value, as indicated by the scale bar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

outlined above (see Methods). We initially conducted a two-factor ANOVA. The factors were flash number (1 or 2) and bleep number (0, 1 or 2). As expected, we found a significant main effect of flash number in the left and right occipital cortex (though as this is group data we have no information on which retinotopic area or areas this might represent). The main effect of bleep number was also significant (see Table 1 for a complete listing of these loci and their stereotactic locations, plus Fig. 3B). This was due to an increased cortical response when a visual event is accompanied by a sound compared to a visual event alone regardless of the number of bleeps [B1–B0, $t_{\max} = 7.41$; $P < 0.0001$, B2–B1, $t_{\max} = 4.83$; $P = 0.1$ and B2–B0, $t_{\max} = 8.68$; $P < 0.0001$]. There was no significant interaction between the number of flashes and the number of bleeps ($t < 3.86$, $P > 0.7$). Activation of similar loci has been associated with audiovisual integration (Calvert et al., 2001).

Finally, unrestricted whole-brain analysis of illusory multisensory perception (i.e., F1B2-Illusion versus F1B2-no Illusion) additionally revealed significant activation in the right superior temporal sulcus (ascending posterior segment of the STS, abutting

the supramarginal gyrus; co-ordinates $[54, -54, 30]$ $t = 6.83$; $P = 0.02$ corrected, number of voxels in the cluster = 88) and the superior colliculus (coordinates $[2, -30, 0]$, $t = 3.12$; $P = 0.03$ corrected for anatomically specified small volume examined; see Methods). These activated loci are shown in Figs. 4B and C. There were no cortical areas that showed a significant response to F1B2-no Illusion > F1B2 Illusion.

In summary, the presence of auditory stimuli enhanced visual responses in V1, V2, and V3 (Fig. 3 and Table 1). In contrast, the more restricted comparison of those multisensory F1B2 trials that either evoked the illusion (“F1B2-Illusion”) or did not (“F1B2-no Illusion”) revealed enhanced activity in primary visual cortex, the superior temporal sulcus, and superior colliculus (Fig. 4).

Discussion

Irrespective of perception, we found that concurrent auditory stimulation enhanced activity in human V1, V2, and V3. Our

Table 1

Coordinates and f values for event-related activation associated with the main effect of auditory stimulation ($P < 0.05_{\text{FDRcorrected}}$)

Location	Coordinates $[x, y, z]$	BA	Number of voxels in cluster	f value	P value
Rt primary and secondary auditory cortex extending to superior temporal sulcus	63, -30, 9	22/41/42	846	38.40	.0001
Lt primary and secondary auditory cortex extending to superior temporal sulcus	-57, -24, 3	22/41/42	645	30.50	.0001
Lt middle frontal gyrus	-36, -3, 36	6	6	10.56	.010
Rt insular	45, 9, 9	–	1	9.24	.021
Lt Cerebellum	-24, -69, -24	–	4	8.32	.035
Lt insular	-36, -15, 6	–	1	8.27	.036
Anterior cingulate	-15, 30, 30	23	3	8.02	.042
Rt occipital cortex	6, -84, 30	18	1	7.80	.048

Only the most significant peaks within each area of activation are reported in the table.

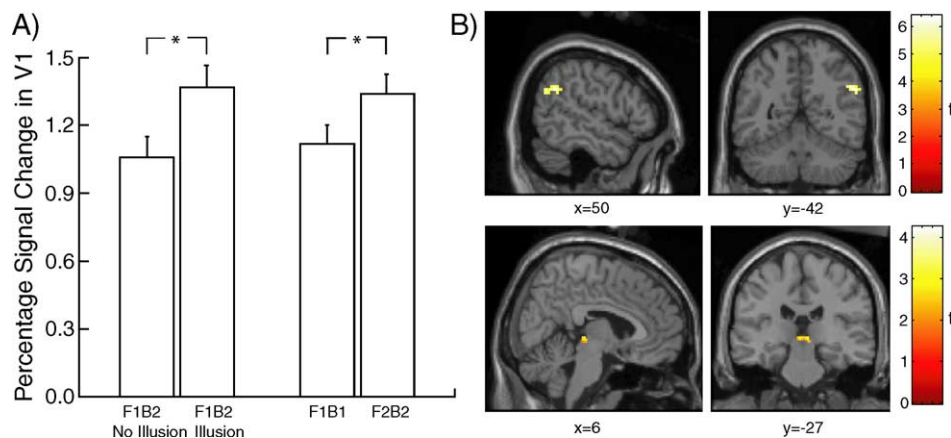


Fig. 4. Cortical areas activated by multisensory illusory perception. (A) Signal change in primary visual cortex associated with illusory multisensory perception. The mean percentage signal change in retinotopically defined V1 (see Methods) is shown for the condition F1B2-no Illusion (one flash with two beeps when subjects reported correctly the perception of one flash), F1B2-Illusion (one flash with two beeps when subjects reported the illusory perception of two flashes), F1B1, and F2B2. Data shown are averaged across the eleven subjects (see Methods for further details) with error bars representing the standard error of the mean, and the symbol ‘*’ indicating statistical significance ($P < 0.05$). (B) Shown in the figure are cortical loci outside retinotopic cortex where event-related activity was also significantly greater during F1B2-Illusion trials compared to F1B2-no Illusion trials ($P < 0.05$, corrected for multiple comparisons; see also Results). Activated cortical loci in the right superior temporal sulcus (ascending posterior segment) projected onto a sagittal and coronal slice of a canonical T1 template image in the stereotaxic space of Talairach and Tournoux (1988). (C) Activated cortical loci in the superior colliculus projected onto a sagittal and coronal slice of the canonical T1 template image. The left hemisphere is presented on the left. The color of the activation represents the t value, as indicated by the scale bar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

findings are broadly consistent with previous observations that behavioral or physiological responses to visual stimulation can be modified by sound (Bermant and Welch, 1976; Kitagawa and Ichihara, 2002; Morrell, 1972; Reisberg, 1978; Sekuler et al., 1997). In humans, several functional imaging studies have demonstrated that multisensory interactions can occur in extrastriate regions of visual cortex previously held to be unisensory (Amedi et al., 2001; Calvert and Thesen, 2004; Calvert et al., 1997; Lloyd et al., 2003; Macaluso et al., 2000) and even in Brodmann area 17 of occipital cortex (Calvert et al., 2001). None of these earlier human studies used retinotopic mapping to functionally identify early retinotopic visual cortex. Our study therefore extends this important earlier work by explicitly quantifying multisensory effects in retinotopically defined early visual cortex and confirms that multisensory convergence can occur at the first cortical stages of human visual processing.

Importantly, we further examined how neural interactions associated with multisensory processing might be reflected in conscious perception. Participants were asked to report their perception of the visual stimulus on a trial-by-trial basis, which allowed us to confirm illusory perception of two flashes on a proportion of the F1B2 trials (F1B2-Illusion), as previously reported (Shams et al., 2000). Critically, we found that brain activity evoked in human V1 on illusion trials (F1B2-Illusion) was significantly greater than on physically identical trials where no illusion was reported (F1B2-no Illusion). Indeed, the cortical activity evoked on F1B2-Illusion trials was not reliably different from F2B2 trials (see Fig. 4). This effect was robust across participants (Fig. 5B) and also associated with enhanced activity in the superior colliculus and superior temporal gyrus (Fig. 4). This enhancement of activity in association with illusory perception did not reflect differences in eye position or eye movements on different trials. Nor did it reflect a general alerting effect caused by changes in auditory stimulation, as both visual and auditory stimulation were identical on illusion and no-illusion trials. Nor

was it explained by any bias for our participants to respond incorrectly to the number of beeps (signal detection analysis revealed a significant change in sensitivity when visual events were accompanied by two beeps with no significant change in absolute criterion bias). Instead, we conclude that activity in primary visual cortex corresponded better to participants’ subjective reports of their visual experience on F1B2 trials, rather than with the physical stimulation (which remained unchanged). That V1 activity can be more closely related to conscious visual experience rather than physical stimulation is increasingly recognized in unisensory studies. For example, activity evoked in human V1 by a visual stimulus briefly presented at the contrast detection threshold is higher on trials when participants successfully detect it than when they fail to do so (Ress and Heeger, 2003). Moreover, when participants falsely perceive the presence of a low-contrast stimulus on trials when the stimulus was physically absent (false alarms), V1 activity is similar to that on trials where participants correctly report the physical presence of a stimulus (Ress and Heeger, 2003). This suggests that for visual stimulation alone, V1 activity can more closely correspond to the contents of consciousness than to visual stimulation. The present findings show that such an association of V1 activity with conscious perception extends to suprathreshold visual stimuli under normal viewing conditions and to changes in visual perception brought about by multisensory stimulation.

The temporal resolution of fMRI is relatively low, so this study does not provide useful information about the timing of the multisensory effects on visual perception that we observed. Rather, it provides precise localization of these effects to the anatomically lowest stage of cortical processing. Such findings are consistent with the work reviewed earlier suggesting that for sensory modalities such as audition, multisensory influences also extend to the earliest stages of cortical processing (see Introduction and Schroeder and Foxe, 2005). Event-related potential recordings in human show that multisensory integration can occur very early in

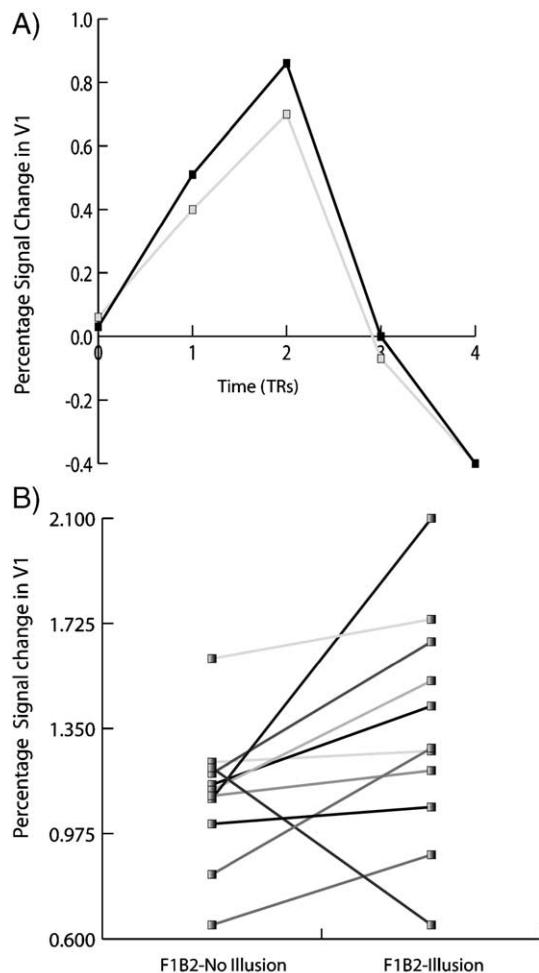


Fig. 5. (A) Time courses for the V1 cortical responses in the F1B2-Illusion (black line) and F1B2-no Illusion (grey line) condition. Percentage signal change in V1 is plotted against time from stimulus onset (units of TR = 2.08 s) for both conditions averaged across subjects. The time courses were calculated for each of the subjects by using a statistical model containing a boxcar waveform representing each of the experimental conditions, convolved with a series of FIR (finite impulse response) functions. Motion parameters defined by the realignment procedure were added to the model as six separate regressors of no interest. Multiple linear regression was then used to generate parameter estimates for each regressor at each time point for every subject. The data used in this model were extracted from the area of V1 that responded to the visual stimulus. This was calculated by masking V1 (determined by retinotopic mapping (see Methods)) with the cortical area that showed a significant response ($P < 0.05$ uncorrected) to the contrast of all visual events (F1B1, F1B2, F2B1, F2B2, F1 and F2) >null. (B) Signal change in V1 for the conditions F1B2-Illusion and F1B2-no Illusion for every subject.

visual processing. For example, a change in a simple visual stimulus that is accompanied by a change in pitch of a concurrent tone can lead to modification of the ERP at very short latencies (Giard and Peronnet, 1999), and auditory clicks can modify the evoked potential to pattern stimulation in visual cortex (Arden et al., 2003). Similarly, a surprisingly early right parieto-occipital interaction between auditory and visual stimulation is seen in the ERP waveform during a simple reaction time task (Molholm et al., 2002). For the particular multisensory illusion reported here, visual-evoked potentials and fields associated with the illusory

perception are modified at a short latency (Bhattacharya et al., 2002; Shams et al., 2001, 2005) consistent with generators in early visual cortex. Our new findings extend this earlier work by demonstrating that non-visual stimuli can affect early visual processing in human primary visual cortex.

Our physiological data do not precisely define how these effects arise, particularly regarding the association of V1 activation with illusory visual perception in the illusion studied here. Primary visual cortex receives projections from at least twelve areas described as belonging to the visual cortex (Felleman and Van Essen, 1991). Recently, slightly weaker more distant projections have been described from areas in the ventral (Distler et al., 1993) and dorsal visual pathways and from the lateral intraparietal area (Boussaoud et al., 1990; Rockland and Van Hoesen, 1994). Several recent papers have used retrograde tracer injections to demonstrate projections from primary auditory cortex, auditory association areas, and the superior temporal polysensory area (STP) to the area of primary visual cortex representing the peripheral visual field (Clavagnier et al., 2004; Falchier et al., 2002; Rockland and Ojima, 2003). These connections have a laminar signature and a termination pattern consistent with feedback or lateral type connections (Rockland and Ojima, 2003). The function of these projections to V1 has been the subject of much debate, but they may serve to enhance perceptual capabilities; for example, the addition of an auditory signal to a visual signal leads to improved detection compared to a visual signal alone (Bolognini et al., 2005; Frassinetti et al., 2002; Gondan et al., 2005; Miller, 1982; Molholm et al., 2002; Schroger and Widmann, 1998). Thus, it is possible that these connections mediate the increased activity in V1 that we observed. Intriguingly, we found a greater cortical response for F1B2 Illusion > F1B2 no-Illusion only in the stimulus responsive area of primary visual cortex. This implies that an auditory stimulus is only effective at exciting primary visual cortex when preceded by a visual stimulus. This finding is consistent with the temporal properties of the illusion (Shams et al., 2000).

When participants experienced illusory visual perception, enhanced activity was not only identified in V1 but also in the superior colliculus and the right superior temporal sulcus (STS), which may also play a role. In particular, the STS may be the human homologue of macaque area STP and has been consistently associated with integration between visual and auditory stimulation (Beauchamp, 2005; Beauchamp et al., 2004; Calvert et al., 2000; Olson et al., 2002), particularly in speech recognition (Pekkola et al., 2005; Rajj et al., 2000; Saito et al., 2005; Sekiyama et al., 2003; von Kriegstein et al., 2005). A recent study also showed that the STS is involved in cross-modal associative learning (Tanabe et al., 2005). Similarly the superior colliculus is known to play an important role in multisensory integration. Many studies in animals demonstrate the presence of multisensory neurons in the superior colliculus (Meredith and Stein, 1983; Meredith et al., 1987; Stein et al., 1975; Wallace et al., 1996, 1998). Consistent with this, in humans, there is an enhanced superior colliculus response to a multisensory signal compared to a unisensory signal (Calvert et al., 2001). Future studies should therefore attempt to elucidate the possible functional role of each structure in the illusion studied here.

Conclusion

Taken together, we found that responses of retinotopic visual areas V1–V3 to visual stimulation are significantly enhanced by

concurrent auditory stimulation. Specifically, when this auditory stimulation gave rise to an illusory change in perceptual experience, this was associated with specific enhancement of in primary visual cortex, superior colliculus and right superior temporal sulcus.

Acknowledgments

This work was supported by the Wellcome Trust. We thank Toshio Inui and Shinsuke Shimojo for their support.

References

- Amedi, A., Malach, R., Hendler, T., Peled, S., Zohary, E., 2001. Visuo-haptic object-related activation in the ventral visual pathway. *Nat. Neurosci.* 4, 324–330.
- Arden, G.B., Wolf, J.E., Messiter, C., 2003. Electrical activity in visual cortex associated with combined auditory and visual stimulation in temporal sequences known to be associated with a visual illusion. *Vision Res.* 43, 2469–2478.
- Beauchamp, M.S., 2005. See me, hear me, touch me: multisensory integration in lateral occipital-temporal cortex. *Curr. Opin. Neurobiol.* 15, 145–153.
- Beauchamp, M.S., Argall, B.D., Bodurka, J., Duyn, J.H., Martin, A., 2004. Unraveling multisensory integration: patchy organization within human STS multisensory cortex. *Nat. Neurosci.* 7, 1190–1192.
- Bermant, R.L., Welch, R.B., 1976. Effect of degree of separation of visual–auditory stimulus and eye position upon spatial interaction of vision and audition. *Percept. Mot. Skills* 42, 487–493.
- Bhattacharya, J., Shams, L., Shimojo, S., 2002. Sound-induced illusory flash perception: role of gamma band responses. *NeuroReport* 13, 1727–1730.
- Bolognini, N., Frassinetti, F., Serino, A., Ladavas, E., 2005. “Acoustical vision” of below threshold stimuli: interaction among spatially converging audiovisual inputs. *Exp. Brain Res.* 160, 273–282.
- Boussaoud, D., Ungerleider, L.G., Desimone, R., 1990. Pathways for motion analysis: cortical connections of the medial superior temporal and fundus of the superior temporal visual areas in the macaque. *J. Comp. Neurol.* 296, 462–495.
- Calvert, G.A., Thesen, T., 2004. Multisensory integration: methodological approaches and emerging principles in the human brain. *J. Physiol. (Paris)* 98, 191–205.
- Calvert, G.A., Bullmore, E.T., Brammer, M.J., Campbell, R., Williams, S.C., McGuire, P.K., Woodruff, P.W., Iversen, S.D., David, A.S., 1997. Activation of auditory cortex during silent lipreading. *Science* 276, 593–596.
- Calvert, G.A., Campbell, R., Brammer, M.J., 2000. Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Curr. Biol.* 10, 649–657.
- Calvert, G.A., Hansen, P.C., Iversen, S.D., Brammer, M.J., 2001. Detection of audio-visual integration sites in humans by application of electrophysiological criteria to the BOLD effect. *NeuroImage* 14, 427–438.
- Clavagnier, S., Falchier, A., Kennedy, H., 2004. Long-distance feedback projections to area V1: implications for multisensory integration, spatial awareness, and visual consciousness. *Cogn. Affect. Behav. Neurosci.* 4, 117–126.
- Distler, C., Boussaoud, D., Desimone, R., Ungerleider, L.G., 1993. Cortical connections of inferior temporal area TEO in macaque monkeys. *J. Comp. Neurol.* 334, 125–150.
- Dougherty, R.F., Koch, V.M., Brewer, A.A., Fischer, B., Modersitzki, J., Wandell, B.A., 2003. Visual field representations and locations of visual areas V1/2/3 in human visual cortex. *J. Vis.* 3, 586–598.
- Falchier, A., Clavagnier, S., Barone, P., Kennedy, H., 2002. Anatomical evidence of multimodal integration in primate striate cortex. *J. Neurosci.* 22, 5749–5759.
- Felleman, D.J., Van Essen, D.C., 1991. Distributed hierarchical processing in the primate cerebral cortex. *Cereb. Cortex* 1, 1–47.
- Fort, A., Delpuech, C., Pernier, J., Giard, M.H., 2002. Early auditory–visual interactions in human cortex during nonredundant target identification. *Brain Res. Cogn. Brain Res.* 14, 20–30.
- Foxe, J.J., Wylie, G.R., Martinez, A., Schroeder, C.E., Javitt, D.C., Guilfoyle, D., Ritter, W., Murray, M.M., 2002. Auditory-somatosensory multisensory processing in auditory association cortex: an fMRI study. *J. Neurophysiol.* 88, 540–543.
- Frassinetti, F., Pavani, F., Ladavas, E., 2002. Acoustical vision of neglected stimuli: interaction among spatially converging audiovisual inputs in neglect patients. *J. Cogn. Neurosci.* 14, 62–69.
- Friston, K.J., Penny, W., Phillips, C., Kiebel, S., Hinton, G., Ashburner, J., 2002. Classical and Bayesian inference in neuroimaging: theory. *NeuroImage* 16, 465–483.
- Fu, K.M., Johnston, T.A., Shah, A.S., Arnold, L., Smiley, J., Hackett, T.A., Garraghty, P.E., Schroeder, C.E., 2003. Auditory cortical neurons respond to somatosensory stimulation. *J. Neurosci.* 23, 7510–7515.
- Fu, K.M., Shah, A.S., O’Connell, M.N., McGinnis, T., Eckholdt, H., Lakatos, P., Smiley, J., Schroeder, C.E., 2004. Timing and laminar profile of eye-position effects on auditory responses in primate auditory cortex. *J. Neurophysiol.* 92, 3522–3531.
- Ghazanfar, A.A., Maier, J.X., Hoffman, K.L., Logothetis, N.K., 2005. Multisensory integration of dynamic faces and voices in rhesus monkey auditory cortex. *J. Neurosci.* 25, 5004–5012.
- Giard, M.H., Peronnet, F., 1999. Auditory–visual integration during multimodal object recognition in humans: a behavioral and electrophysiological study. *J. Cogn. Neurosci.* 11, 473–490.
- Gondan, M., Niederhaus, B., Rosler, F., Roder, B., 2005. Multisensory processing in the redundant-target effect: a behavioral and event-related potential study. *Percept. Psychophys.* 67, 713–726.
- Kitagawa, N., Ichihara, S., 2002. Hearing visual motion in depth. *Nature* 416, 172–174.
- Lloyd, D.M., Shore, D.I., Spence, C., Calvert, G.A., 2003. Multisensory representation of limb position in human premotor cortex. *Nat. Neurosci.* 6, 17–18.
- Macaluso, E., Frith, C.D., Driver, J., 2000. Modulation of human visual cortex by crossmodal spatial attention. *Science* 289, 1206–1208.
- McGurk, H., MacDonald, J., 1976. Hearing lips and seeing voices. *Nature* 264, 746–748.
- Meredith, M.A., Stein, B.E., 1983. Interactions among converging sensory inputs in the superior colliculus. *Science* 221, 389–391.
- Meredith, M.A., Nemitz, J.W., Stein, B.E., 1987. Determinants of multisensory integration in superior colliculus neurons: I. Temporal factors. *J. Neurosci.* 7, 3215–3229.
- Miller, J., 1982. Divided attention: evidence for coactivation with redundant signals. *Cogn. Psychol.* 14, 247–279.
- Molholm, S., Ritter, W., Murray, M.M., Javitt, D.C., Schroeder, C.E., Foxe, J.J., 2002. Multisensory auditory–visual interactions during early sensory processing in humans: a high-density electrical mapping study. *Brain Res. Cogn. Brain Res.* 14, 115–128.
- Molholm, S., Ritter, W., Javitt, D.C., Foxe, J.J., 2004. Multisensory visual–auditory object recognition in humans: a high-density electrical mapping study. *Cereb. Cortex* 14, 452–465.
- Morrell, F., 1972. Visual system’s view of acoustic space. *Nature* 238, 44–46.
- Mottron, R., Krause, C.M., Tiippana, K., Sams, M., 2002. Processing of changes in visual speech in the human auditory cortex. *Brain Res. Cogn. Brain Res.* 13, 417–425.
- Murray, M.M., Michel, C.M., Grave, d.P., Ortigue, S., Brunet, D., Gonzalez, A.S., Schneider, A., 2004. Rapid discrimination of visual and multisensory memories revealed by electrical neuroimaging. *NeuroImage* 21, 125–135.
- Murray, M.M., Molholm, S., Michel, C.M., Heslenfeld, D.J., Ritter, W., Javitt, D.C., Schroeder, C.E., Foxe, J.J., 2005. Grabbing your ear: rapid

- auditory-somatosensory multisensory interactions in low-level sensory cortices are not constrained by stimulus alignment. *Cereb. Cortex* 15, 963–974.
- Olson, I.R., Gatenby, J.C., Gore, J.C., 2002. A comparison of bound and unbound audio-visual information processing in the human cerebral cortex. *Brain Res. Cogn Brain Res.* 14, 129–138.
- Pekkola, J., Ojanen, V., Autti, T., Jaaskelainen, I.P., Mottonen, R., Tarkiainen, A., Sams, M., 2005. Primary auditory cortex activation by visual speech: an fMRI study at 3 T. *NeuroReport* 16, 125–128.
- Raij, T., Uutela, K., Hari, R., 2000. Audiovisual integration of letters in the human brain. *Neuron* 28, 617–625.
- Reisberg, D., 1978. Looking where you listen: visual cues and auditory attention. *Acta Psychol. (Amst)* 42, 331–341.
- Ress, D., Heeger, D.J., 2003. Neuronal correlates of perception in early visual cortex. *Nat. Neurosci.* 6, 414–420.
- Rockland, K.S., Ojima, H., 2003. Multisensory convergence in calcarine visual areas in macaque monkey. *Int. J. Psychophysiol.* 50, 19–26.
- Rockland, K.S., Van Hoesen, G.W., 1994. Direct temporal–occipital feedback connections to striate cortex (V1) in the macaque monkey. *Cereb. Cortex* 4, 300–313.
- Saito, D.N., Yoshimura, K., Kochiyama, T., Okada, T., Honda, M., Sadato, N., 2005. Cross-modal binding and activated attentional networks during audio-visual speech integration: a functional MRI study. *Cereb. Cortex*.
- Schroeder, C.E., Foxe, J., 2005. Multisensory contributions to low-level, ‘unisensory’ processing. *Curr. Opin. Neurobiol.* 15, 454–458.
- Schroeder, C.E., Lindsley, R.W., Specht, C., Marcovici, A., Smiley, J.F., Javitt, D.C., 2001. Somatosensory input to auditory association cortex in the macaque monkey. *J. Neurophysiol.* 85, 1322–1327.
- Schroger, E., Widmann, A., 1998. Speeded responses to audiovisual signal changes result from bimodal integration. *Psychophysiology* 35, 755–759.
- Sekiyama, K., Kanno, I., Miura, S., Sugita, Y., 2003. Auditory–visual speech perception examined by fMRI and PET. *Neurosci. Res.* 47, 277–287.
- Sekuler, R., Sekuler, A.B., Lau, R., 1997. Sound alters visual motion perception. *Nature* 385, 308.
- Sereno, M.I., Dale, A.M., Reppas, J.B., Kwong, K.K., Belliveau, J.W., Brady, T.J., Rosen, B.R., Tootell, R.B., 1995. Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. *Science* 268, 889–893.
- Shams, L., Kamitani, Y., Shimojo, S., 2000. Illusions. What you see is what you hear. *Nature* 408, 788.
- Shams, L., Kamitani, Y., Thompson, S., Shimojo, S., 2001. Sound alters visual evoked potentials in humans. *NeuroReport* 12, 3849–3852.
- Shams, L., Kamitani, Y., Shimojo, S., 2002. Visual illusion induced by sound. *Brain Res. Cogn Brain Res.* 14, 147–152.
- Shams, L., Ma, W.J., Beierholm, U., 2005. Sound-induced flash illusion as an optimal percept. *NeuroReport* 16, 1923–1927.
- Stein, B.E., Magalhaes-Castro, B., Kruger, L., 1975. Superior colliculus: visuotopic–somatotopic overlap. *Science* 189, 224–226.
- Stein, B.E., London, N., Wilkinson, L., Price, D., 1996. Enhancement of perceived visual intensity by auditory stimuli: a psychophysical analysis. *J. Cogn. Neurosci.* 8, 497–506.
- Sumbly, W.E., Pollack, I., 1954. Visual contribution to speech intelligibility in noise. *J. Acoust. Soc. Am.* 26, 212–215.
- Talairach Tournoux, 1988. *Co-Planar Stereotaxic Atlas of the Human Brain*. Theime, Stuttgart, Germany.
- Tanabe, H.C., Honda, M., Sadato, N., 2005. Functionally segregated neural substrates for arbitrary audiovisual paired-association learning. *J. Neurosci.* 25 (27), 6409–6418.
- Teo, P.C., Sapiro, G., Wandell, B.A., 1997. Creating connected representations of cortical gray matter for functional MRI visualization. *IEEE Trans. Med. Imaging* 16, 852–863.
- Tong, F., 2003. Primary visual cortex and visual awareness. *Nat. Rev., Neurosci.* 4, 219–229.
- von Kriegstein, K., Kleinschmidt, A., Sterzer, P., Giraud, A.L., 2005. Interaction of face and voice areas during speaker recognition. *J. Cogn. Neurosci.* 17, 367–376.
- Wallace, M.T., Wilkinson, L.K., Stein, B.E., 1996. Representation and integration of multiple sensory inputs in primate superior colliculus. *J. Neurophysiol.* 76, 1246–1266.
- Wallace, M.T., Meredith, M.A., Stein, B.E., 1998. Multisensory integration in the superior colliculus of the alert cat. *J. Neurophysiol.* 80, 1006–1010.
- Wandell, B.A., Chial, S., Backus, B.T., 2000. Visualization and measurement of the cortical surface. *J. Cogn. Neurosci.* 12, 739–752.