Our daily activities are guided by an amalgam of sensory inputs from different modalities, most notably vision and hearing. These sensory modalities, although “segregated” in textbooks, function together to specify behaviorally important objects and events. While the question of auditory/visual interactions has a long history in experimental psychology, recent developments in neuroscience now make it feasible to relate audio-visual integration to underlying neural mechanisms. With this as our motive, we have exploited visual motion perception -- whose physiological bases are reasonably well understood -- to study how sound modulates the efficacy of neural signals arising in visual motion pathways.

Our experiments utilized the well-known motion aftereffect (MAE), i.e., the illusory motion of a stationary “test pattern” following prolonged adaptation to visual motion. For adaptation stimuli we employed bivectorial motion displays consisting of two arrays of moving dots superimposed within a circular aperture centered on a video monitor (Figure 1a). One array comprised 50 randomly positioned dots all moving upward within the aperture and the other consisted of a variable number of dots that moved leftward. The number of leftward moving dots (expressed as a percentage of upward dots) varied over blocks of trials from 100 - 0% in 1-octave steps. During a given adaptation period, visual motion was accompanied by: 1) no sound, 2) stationary sound, 3) stereophonic sound moving leftward (“same” as leftward moving adaptation dots), and 4) stereophonic sound moving rightward (“opposite” to the leftward adaptation motion). The compelling impression of sound motion was produced by
reciprocally modulating the intensity of tones broadcast from a pair of stereo speakers located immediately to either side of the video monitor. The speed of the moving sound was adjusted to match the speed of the leftward moving dots; visual and auditory motion appeared to originate from the same spatial location. Six test periods were interleaved with 60-sec adaptation periods, and during each test period observers used a computer mouse to indicate the perceived direction of illusory motion when viewing stationary dots (unaccompanied by sound). During a given block of test/adaptation presentations, the signal strength of the leftward motion and the associated sound condition were constant. At least two minutes expired before a new block of adaptation conditions was tested.

In the absence of sound, perceived direction of the MAE was governed by the visual signal strength of the leftward moving dots, coinciding closely with the vector sum of the MAEs associated with adaptation to upward motion and with adaptation to leftward motion (Figure 1b). This finding is predictable from earlier results. MAE direction was also influenced by the direction of moving sound accompanying visual motion: sound moving leftward (“same”) strengthened the efficacy of the leftward visual motion signal and sound moving rightward (“opposite”) attenuated visual motion’s efficacy. Moving sound paired with completely random motion during adaptation produced no MAE. This pattern of results has been replicated in other naïve observers tested on a subset of these conditions (Figure 1c).

It is unlikely that sound’s influence on vision is attributable to attention. For one thing, observers were not asked actively to attend to sound. For another, attention’s influence on visual motion adaptation is confined to weak motion signals, whereas sound’s ability to modulate visual motion adaptation ranges to strong visual motion signals.

In a second experiment, we relocated the stereo speakers to a position 0.5 m above the video monitor, thereby placing the moving sound at a spatial location different from visual motion. This manoeuvre eliminated sound’s impact on visual adaptation motion: perceived direction of the MAE depended exclusively on vision, even though the sound’s movement was still compellingly experienced.

From the curves in Figure 1b, we estimated sound’s effectiveness by determining the increase (or decrease) in motion signal strength necessary to produce a shift in perceived MAE
direction equivalent to that produced by sound. The effect of sound is approximately equivalent to a 0.3 log-unit change in real motion signal strength. We may, in other words, usefully think of moving sound as effectively adding strength to visual elements moving in the same direction, presumably boosting activity in neurons selective to that direction of visual motion. By the same token, sound moving in a direction opposite to visual motion weakens the strength of that motion signal, presumably attenuating activity in direction-selective neurons activated by that visual motion. Evidently sound modulates responses in direction-selective neurons only when those neurons are activated by some degree of coherent visual motion; adaptation with sound alone, or with sound paired with incoherent motion, produces no deflection in the MAE.

Possible physiological mechanisms for audio-visual registration of motion signals can be identified. It is well established that the parietal pathway includes visual areas, most notably MT, involved in registration of visual motion direction\textsuperscript{8}. Moreover, within multiple areas along the auditory pathways neurons sensitive to auditory motion have been identified\textsuperscript{9,10}. The parabelt region of auditory cortex sends projections to superior temporal sulcus, which contains multiple visual areas including area MST which receives input from MT\textsuperscript{11}. So the neural links between hearing and vision are in place, and our results disclose the utility of audio-visual motion adaptation as a means for studying those neural links.


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Figure Caption

Fig. 1 Sound modulates visual motion signals. A) Schematic of visual adaptation display. Two sets of black dots seen against a white background (16 cd m\(^2\)) appeared superimposed within a 5.5 deg diameter circular aperture. The 50 dots in one set moved smoothly upward at 3 deg/sec, and the variable number of dots in the other set moved leftward. Upon exiting the circular aperture, dots were wrapped around to the opposite side of the aperture. All animations were programmed in MatLab running in conjunction with the Psychophysics Toolbox\(^\text{12}\) and were displayed on a video monitor (75 Hz frame rate) under the control of a PowerPC G3 computer. Located to either side of the monitor was a pair of stereo speakers broadcasting series of tones whose left- and right-speaker intensities were ramped over time to simulate lateral movement that coincided in space and time with the leftward moving dots; maximum intensity was approximately 70 dB\(_{spl}\). During a given adaptation sequence, the number of leftward moving dots and the direction of sound motion were fixed. Each condition began with 60-sec of adaptation followed by brief test periods interspersed with 60-sec periods of readaptation; this sequence continued until the observer made 6 estimates of MAE direction by using the screen cursor to denote the point around the perimeter of a field of stationary dots coinciding with the perceived direction of drift of those dots. B) Average results from three observers, one naive about the purpose of the experiment. Data points denote for each of six leftward motion strength levels (expressed relative to upward) the perceived direction of MAE associated with stationary sound, sound moving leftward (“same”) and sound moving rightward (“opposite”). The small diagonal bar in the symbol box denotes the average standard error of the directional estimates. C) Perceived MAE direction (arithmetic means with ± 1 SE) obtained from two naive observers tested with 25% leftward dots and with stationary sound, sound moving leftward (“same”) and sound moving rightward (“opposite”).
a) strength upward + variable strength leftward

adaptation

b) MAE direction (relative to no sound)

left

up

same

stationary

opposite

c) Strength leftward motion (% re upward)

MAE direction (relative to no sound)