

Early- and Late-Onset Blind Individuals Show Supra-Normal Auditory Abilities in Far-Space

Patrice Voss,¹ Maryse Lassonde,¹
Frederic Gougoux,¹ Madeleine Fortin,¹
Jean-Paul Guillemot,^{1,2} and Franco Lepore^{1,*}

¹Centre de Recherche en Neuropsychologie
et Cognition

Université de Montréal
Case Postale 6128
Succursale Centre-Ville
Montréal, Québec, H3C 3J7
Canada

²Université du Québec à Montréal
Département de Kinanthropologie
Case Postale 8888
Succursale Centre-Ville
Montréal, Québec, H3C 3P8
Canada

Summary

Blind individuals manifest remarkable abilities in navigating through space despite their lack of vision. They have previously been shown to perform normally or even supra-normally in tasks involving spatial hearing in near space [1, 2], a region that, however, can be calibrated with sensory-motor feedback. Here we show that blind individuals not only properly map auditory space beyond their peri-personal environment but also demonstrate supra-normal performance when subtle acoustic cues for target location and distance must be used to carry out the task. Moreover, it is generally postulated that such abilities rest in part on cross-modal cortical reorganizations [3–6], particularly in the immature brain, where important synaptogenesis is still possible [7–9]. Nonetheless, we show for the first time that even late-onset blind subjects develop above-normal spatial abilities, suggesting that significant compensation can occur in the adult.

Results and Discussion

Most studies examining auditory localization in blind individuals who showed supra-normal performance have looked, with at least one exception [10], at spatial hearing in near space [1, 2]. However, in this region, auditory representations can be calibrated through sensory-motor feedback such as touching the source of the sound or through the use of a cane, for example. In far space, on the other hand, no such calibration is possible. Does this mean that localization ability breaks down because the space representations cannot be validated? That is precisely the first question we tried to answer in the present study. Also, there is some debate about whether late-onset blind subjects can benefit from compensation. We ourselves tested a large number of these subjects in a monaural localization task [1], a task

in which early-onset blind subjects demonstrated supra-normal performance, and showed that they were indistinguishable from sighted control subjects. Moreover, brain imaging has demonstrated that visual cortex is recruited to carry out tactile tasks, such as Braille reading, only in subjects who became blind before adolescence [8–9], suggesting that the critical period for the functional shift from processing visual stimuli to tactile ones in visual cortex does not extend to adulthood. Yet, in real-life situations, particularly those involving cane-guided locomotion, many late-onset blind subjects can learn to use sound cues. Thus, the second question we investigated was whether there are ecologically significant tasks in which late-onset blind subjects can outperform sighted controls.

Two groups of blind subjects (an early-onset and a late-onset blind group) as well as a control group composed of blindfolded sighted subjects participated in the experiment. We assessed their ability to discriminate differences in sound location by using three tasks: a frontal minimum-audible-angle task (stimulus presented directly in front of the subject; see Figure 1), a peripheral minimum-audible-angle task (stimulus presented 90° from the mid-sagittal plane; see Figure 2), and a minimum-audible-distance task (stimulus presented in front of the subject on the midline; see Figure 3). We carried out the experiments in a large room with background noise to simulate a natural environment. The subject was seated 3 m from a table whose surface was positioned at ear level and on which the speaker lay. The stimuli were two 90 ms noise bursts separated by a 1500 ms silent interval. An experimenter held the speaker at the 0° azimuth position (or 0 cm position in the minimum-audible-distance task) for the first sound and then during the silent interval moved it to the left or right (or to the back in the distance task) or moved it back to the same position. The participant had to indicate whether the second sound came from the same or a different position.

In the first task, we therefore examined whether the subjects were able to properly localize sounds in conditions in which the sources are placed beyond the range that would allow calibration of auditory space by sensory-motor feedback. Performances are plotted in Figure 1. These were analyzed with a repeated-measures ANOVA, and differences between groups failed to reach significance ($F = 0.67$; $p = 0.52$). This result, though at first glance unspectacular, is quite important because it indicates that blind individuals are in fact able to properly calibrate far-auditory space despite their not being able to use either vision or touch to validate their calibration and is in good agreement with previous results in near space [1, 2]. Moreover, the finding that blind subjects were not superior to sighted ones probably reflects the fact that all three groups demonstrated excellent performance, and hence there was a floor effect that prevented any group from outperforming the others (as also found in the previous studies [1, 2]).

It is well established that the right hemisphere is more

*Correspondence: franco.lepore@umontreal.ca

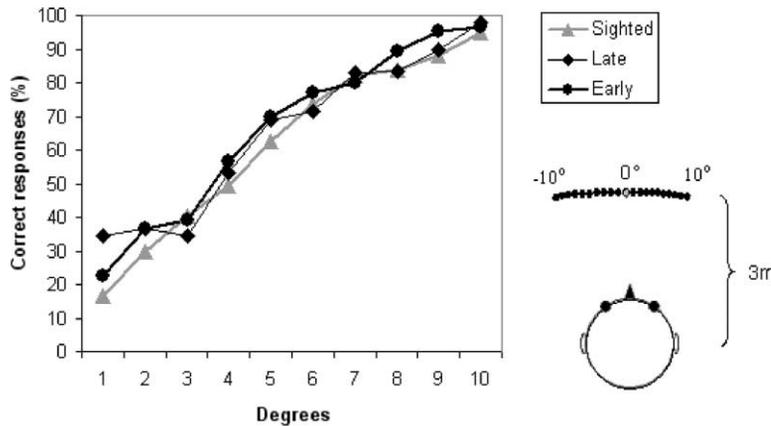


Figure 1. Performance of the Three Groups on the Minimum-Audible-Angle Discrimination in the Frontal Position

Results show that the groups are indistinguishable from each other. On the right side of the figure is illustrated the experimental setup. Correct responses on catch trials (not included in the figure) were as follows: sighted (87%), late (83%), and early (89%).

specialized in the analysis of space and that although auditory pathways project to both hemispheres, contralateral projections predominate [11]. Although unrelated to the principal objectives of this study, we examined whether performance was similar when the stimuli were presented in the left and right hemifields. We carried out repeated-measures ANOVA and showed that performance was better when stimulus changes occurred in the left hemifield, and this was true in all three groups (sighted: $F = 23.914$, $p < 0.001$; early: $F = 23.174$, $p < 0.001$; late: $F = 5.439$, $p = 0.033$). Laterality effects in space perception were thereby confirmed.

The second task was also a minimum-audible-angle task, but with stimuli presented in peripheral space straddling the inter-aural plane. To control for laterality effects, we presented the stimulus for half of the subjects in the left hemifield and for the other half in their right hemifield. The performances are illustrated in Figure 2. All the groups needed far larger angles before they noticed differences in sound source positions than they had in the first task, a result that is in agreement with

previous behavioral studies showing a relation between minimal angle and eccentricity [1, 12, 13]. The ANOVA showed that significant differences were present between the groups ($F = 4.45$; $p = 0.02$). A post-hoc Tukey test indicated that the early-onset blind group performed significantly better than the sighted group ($p = 0.006$). Furthermore, differences in performances depended on the hemifield (frontal versus rear) in which the second sound was presented, and a significant group \times position \times hemifield interaction ($F = 2.11$; $p = 0.023$) was found. This triple interaction reflects the fact that in the frontal hemifield, the early-onset blind subjects showed a tendency to be better than the other two groups ($F = 2.734$; $p = 0.081$). In the rear hemifield, instead, both groups of blind individuals outperformed the sighted group ($F = 4.647$; $p = 0.017$), as revealed by post-hoc Tukey tests between early-onset and sighted subjects ($p = 0.032$) and between late-onset and sighted subjects ($p = 0.053$). These results suggest that in the frontal hemifield, the three groups of subjects were not statistically different from each other, as was the case

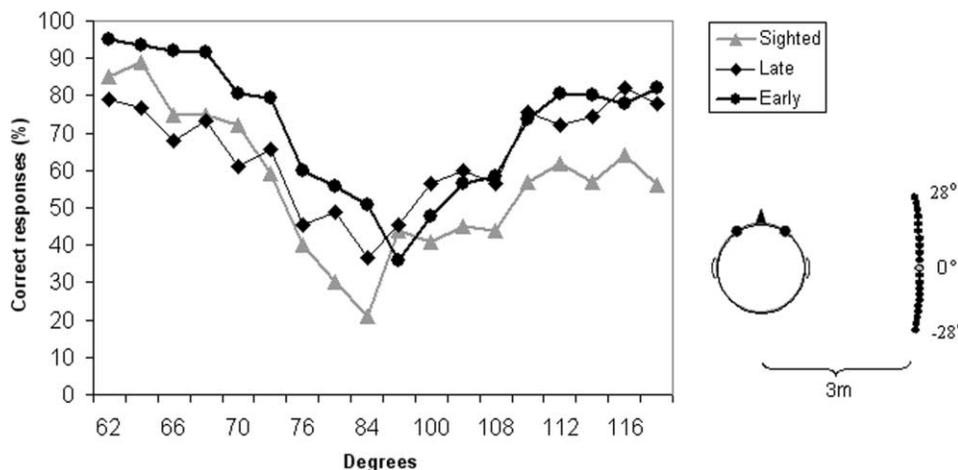


Figure 2. Performance of the Three Groups on the Minimum-Audible-Angle Discrimination in Peripheral Space

Results show that the early-onset blind group discriminates the sound sources more accurately than the other two groups, who are indistinguishable from each other when the sound is presented in front of the inter-aural plane. When the sound is presented behind the inter-aural plane, however, the early- and late-onset groups perform similarly and better than the sighted controls. On the right side of the figure is illustrated the experimental setup. The degree values (62°–116°) refer to the degree separation between the position of the speaker and the mid-sagittal plane. Correct responses on catch trials (not included in the figure) were as follows: sighted (82%), late (71%), and early (91%).

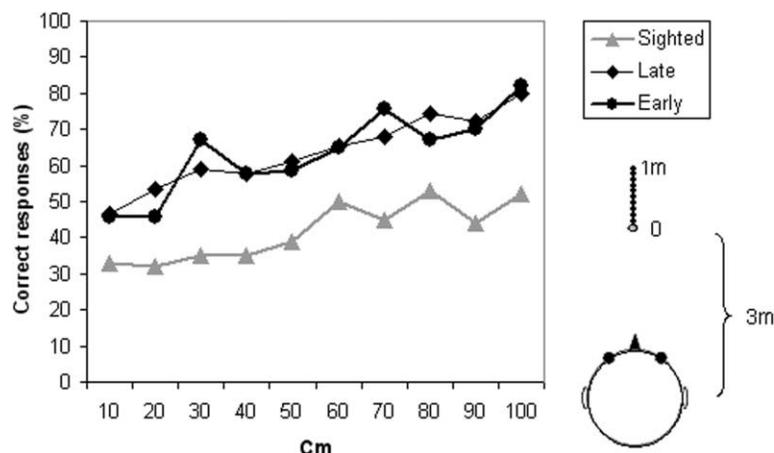


Figure 3. Performance of the Three Groups on the Minimum-Audible-Distance Discrimination

Results show that the early- and late-onset groups perform similarly and better than the sighted control group, the latter group of subjects performing at chance level even at the maximum distance of 1 m. On the right side of the figure is illustrated the experimental setup. Correct responses on catch trials (not included in the figure) were as follows: sighted (79%), late (80%), and early (81%).

in the first experiment (although the early blind are close to showing a superior performance), whereas in the rear hemifield both groups of blind subjects outperformed sighted subjects. Moreover, we found no significant relation between the subjects' ages at the onset of blindness ($r = -0.281$; $p = 0.195$) or the duration of blindness ($r = 0.207$; $p = 0.344$) with the overall performances obtained in this task.

The third task consisted of a minimum-audible-distance task, and the results are plotted in Figure 3. Overall group differences were significant ($F = 7.86$; $p = 0.002$). Post-hoc analyses revealed that the early-onset ($p = 0.007$) and the late-onset ($p = 0.003$) blind subjects did not differ from each other, and both performed better than the sighted controls, whose performance was at chance level even for the maximum distance (1 m) used herein. This suggests that late-onset blind individuals can show supra-normal performance, despite the fact that blindness occurred after the critical period for large-scale reorganization. It is thus possible that they developed these spatial-hearing abilities because these are vital in their everyday lives. When having to cross a street, for example, benefiting from well-calibrated spatial hearing becomes essential for their safety, and hence large functional resources are engaged in the task.

The evaluation of relative distances along the midline rests on a number of possible sources of information: spectral content and sound level [14] as well as the ratio of direct to reverberant energy [15]. Similarly, when localizing sound position in peripheral regions, especially when they straddle the inter-aural plane, binaural cues benefit significantly from spectral and head shadow cues [16]. The present results suggest that blind individuals probably utilize many of these subtle cues more effectively. In support of this explanation, we recently demonstrated that, in a monaural localization task, modifying spectral cues perturbed their ability to correctly localize sound sources [17]. Blind subjects also outperform sighted subjects at discriminating other subtle acoustic information, such as pitch [18]. If they process auditory information more effectively, however, it is still not resolved through which mechanism(s) this is achieved. On the one hand, it could be due to increased learning in the utilization of subtle cues, as has been suggested for both unilaterally deaf [19] and normally

hearing subjects [20]. On the other hand, cross-modal reorganization of deafferented structures is a possibility (auditory: [4, 8, 18–20]; tactile: [7, 21, 22]). The intramodal expansion of tonotopic representations in auditory cortex may also play a role [23]. Another hypothesis might be that blind humans make better use of audio-motor feedback [24]. It is quite likely that a relative combination of all these mechanisms permits blind individuals to develop superior hearing capacities.

As regards the early- versus late-onset controversy, a number of recent studies have demonstrated that restructuring might in fact occur in the mature brain. Event-related potentials have indicated that posterior brain areas are activated during sound-change detection in both early- and late-onset blind subjects [7]. PET imaging revealed activation of visual cortex during Braille reading and auditory word processing in both early- and late-onset blind subjects [25], although the patterns were somewhat different. A recent fMRI study has shown that sighted adults deprived of vision for a period of 5 days displayed activation of visual cortex in response to tactile stimulation [26]. Perhaps this recruitment of visual cortex by auditory stimulation is achieved through awakening of dormant horizontal connections between these cortices; such projections have recently been demonstrated in normal adult primates [27].

In summary, compared with sighted subjects, blind subjects manifest normal or supra-normal abilities to discriminate the relative positions of two sounds presented in far-auditory space as well as to determine the relative distance between them. These results are important in that they show that blind individuals not only establish accurate auditory spatial representations beyond peri-personal space but also manifest superior discriminative abilities with respect to sighted individuals in tasks that require the analysis of subtle cues to discrimination, in particular spectral cues and possibly level cues. Furthermore, these supra-normal spatial auditory abilities appear to develop even in late-onset blind individuals. This may be due to the fact that these skills are so critical for the individuals' ability to navigate through their environment while carrying out even the most basic of spatial tasks and, more importantly, life-threatening ones that they invest significant neural and cognitive resources to develop strategies to cope with their handicap.

Experimental Procedures

Participants

Two groups of blind subjects and one of sighted individuals participated in the experiment. The sighted control group was composed of ten blindfolded subjects who ranged in age from 18 to 24 and had a mean age of 21.2 years. The blind subjects consisted of two groups: an early-onset blind group composed of 14 individuals who ranged in age from 21 to 54 with a mean of 39.3 years and who had lost their vision before they reached 11 years of age, with a mean duration of blindness of 36.6 years, and a late-onset blind group of nine individuals who ranged in age from 23 to 55 with a mean of 41.6 years and who had lost their sight after the age of 16 years, with a mean duration of blindness of 20.2 years. In all cases, blindness was attributable to peripheral damage, and there were no additional neurological problems. Audiometric thresholds were assessed for all participants and indicated normal and comparable hearing in both ears.

Materials and Stimuli

The experiment was held in a large room (L: 40 m; W: 13 m; H: 3 m), in which the natural background noise level was approximately 38 dB-A at stimulus position. The stimuli were broadband noise bursts (0.6–12 kHz) that lasted 90 ms (10 ms rise/fall time) and were delivered through a small speaker (Projects Unlimited: series FS-30S) with an Accusonic amplifier (20 watts). The sound source was calibrated to 70 dB-A prior to each testing session. A superimposed background broadband noise was also presented and calibrated at 60 dB-A; this had the dual purpose of simulating a more natural environment and of masking any noise that the experimenter could have made while moving the speaker. It was produced by a Coulbourn generator and was delivered through two small speakers (Projects Unlimited: series FS-30S) positioned on either side at 2.8 m from stimulus position and directed toward the subject. Head movements were controlled with a small laser pointer that was attached to the subject's head and pointed to a white screen situated behind the subject. Stimuli were presented when the pointer indicated frontal fixation. Because the stimulus was of short duration, no head or eye movements, which could have been used to localize the sounds, were possible during stimulus presentation. Moreover, any movement preceding stimulus presentation aborted the trial.

Procedure

Three tests allowed assessment of the ability of the subjects to discriminate differences in sound location: a frontal minimum-audible-angle task (see Figure 1), a peripheral minimum-audible-angle task (see Figure 2), and a minimum-audible-distance task (see Figure 3). The subject was seated 3 m from a table whose surface was positioned at ear level. The procedure was similar for the two minimum-angle tasks. A perimeter arc having a 3 m radius was drawn on the table. Marks were drawn on this perimeter arc so that speaker positions could be identified. They were spaced in 1.0° increments, from -10° to 10° for the frontal task and from -28° to 28° for the peripheral minimum-audible-angle task. In order to counterbalance possible subtle laterality effects, in the peripheral minimum-angle task the stimuli were presented in the left hemifield for half the subjects and the right hemifield for the other half (with the exception of the late-onset group, for which five subjects had the stimuli presented in the right hemifield and four in the left). As for the minimum-audible-distance task, the table was marked in 10 cm increments from 0 to 100 cm (0 being exactly 3 m in front of the subject on the mid-sagittal plane and 100 cm being situated beyond this point, that is, at 4 m from the subject).

The stimuli were two 90 ms noise bursts separated by a 1500 ms silent interval. An experimenter held the speaker at the 0° azimuth position (or 0 cm position in the minimum-audible-distance task) for the first sound and then during the silent interval moved it to the left or right (or to the back in the distance task) or put it back in the same position (catch trials). The speaker was positioned on the marked template facing the subject. Stimulus position changes followed a pseudo-random order. Each of the two minimum-audible-angle tasks comprised 220 trials (200 "different" trials and 20 "same"

trials), whereas the minimum-audible-distance task was composed of 110 trials (100 "different" trials and 10 "same" trials). The participant indicated whether the second sound came from the same position as the first sound or a different one.

Acknowledgments

We thank the Institut Nazareth et Louis-Braille (INLB) for assistance in recruiting blind participants. This study was supported by grants from the Canadian Institutes of Health Research as well as the Canada Research Chairs to M.L. and F.L.. Additionally, P.V. was funded in part by the Réseau Provincial en Adaptation-Réadaptation du Fonds de Recherche en Santé du Québec (FRSQ), and F.G. received graduate scholarships from the Natural Sciences and Engineering Research Council of Canada and from FRSQ.

Received: March 18, 2004

Revised: August 10, 2004

Accepted: August 10, 2004

Published: October 5, 2004

References

1. Lessard, N., Paré, M., Lepore, F., and Lassonde, M. (1998). Early-blind human subjects localize sound sources better than sighted subjects. *Nature* 395, 278–280.
2. Röder, B., Teder-Sälejärvi, W., Sterr, A., Rösler, F., Hillyard, S.A., and Neville, H.J. (1999). Improved auditory spatial tuning in blind humans. *Nature* 400, 162–166.
3. Leclerc, C., Saint-Amour, D., Lavoie, M.E., Lassonde, M., and Lepore, F. (2000). Brain functional reorganization in early blind humans revealed by auditory event-related potentials. *NeuroReport* 11, 545–550.
4. Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M.P., Dold, G., and Hallett, M. (1996). Activation of the primary visual cortex by Braille reading in blind subjects. *Nature* 380, 526–528.
5. Weeks, R., Horwitz, B., Aziz-Sultan, A., Tian, B., Wessinger, C.M., Cohen, L.G., Hallett, M., and Rauschecker, J.P. (2000). A Positron emission tomographic study of auditory localization in the congenitally blind. *J. Neurosci.* 20, 2664–2672.
6. Kujala, T., Alho, K., Paavilainen, P., Summala, H., and Naatanen, R. (1992). Neural plasticity in processing of sound location by the early blind: an event-related potential study. *Electroencephal. Clin. Neurophysiol.* 84, 469–472.
7. Kujala, T., Alho, K., Huotilainen, M., Ilmoniemi, R.J., Lehtokoki, A., Leinonen, A., Rinne, T., Salonen, O., Snikkonen, J., Standertskjöld-Nordenstam, C.G., et al. (1997). Electrophysiological evidence for cross-modal plasticity in humans with early- and late-onset blindness. *Psychophysiology* 34, 213–216.
8. Sadato, N., Okada, T., Honda, M., and Yonekura, Y. (2002). Critical period for cross-modal plasticity in blind humans: a functional MRI study. *Neuroimage* 16, 389–400.
9. Cohen, L.G., Weeks, R.A., Sadato, N., Celnik, P., Ishii, K., and Hallett, M. (1999). Period of susceptibility for cross-modal plasticity in the blind. *Ann. Neurol.* 45, 451–460.
10. Ashmead, D.H., Wall, R.S., Ebinger, K.A., Eaton, S.B., Snook-Hill, M.M., and Yang, X. (1998). Spatial hearing in children with visual disabilities. *Perception* 27, 105–122.
11. Grön, G., Wunderlich, A.P., Spitzer, M., Tomczak, R., and Riepe, M.W. (2000). Brain activation during human navigation: gender-different neural networks as substrate for performance. *Nat. Neurosci.* 3, 404–408.
12. Middlebrooks, J.C., and Green, D.M. (1991). Sound localization by human listeners. *Annu. Rev. Psychol.* 42, 135–159.
13. Poirier, P., Miljourns, S., Lassonde, M., and Lepore, F. (1993). Sound localization in acallosal human listeners. *Brain* 116, 53–69.
14. Little, A.D., Mershon, D.H., and Cox, P.H. (1992). Spectral content as a cue to perceived auditory distance. *Perception* 21, 405–416.
15. Bronkhorst, A.W., and Houtgast, T. (1999). Auditory distance perception in rooms. *Nature* 397, 517–520.

16. Van Wanrooij, M.M., and Van Opstal, A.J. (2004). Contribution of head shadow and pinna cues to chronic monaural sound localization. *J. Neurosci.* *24*, 4163–4171.
17. Doucet, M.E., Gagné, J.P., Leclerc, C., Lassonde, M., Guillemot, J.P., and Lepore, F. (2004). Blind subjects process auditory spectral cues more efficiently than sighted people. *Exp. Brain Res.*, in press.
18. Gougoux, F., Lepore, F., Lassonde, M., Voss, P., Zatorre, R.J., and Belin, P. (2004). Pitch discrimination in the early blind. *Nature* *430*, 309.
19. Slattery, W.H., and Middlebrooks, J.C. (1994). Monaural sound localization: acute versus chronic unilateral impairment. *Hear. Res.* *75*, 38–46.
20. Butler, R.A. (1987). An analysis of the monaural displacement of sound in space. *Percept. Psychophys.* *41*, 745–750.
21. Kujala, T., Alho, K., Kekoni, J., Hämäläinen, M.S., Reinikainen, K., Salonen, O., Standertskjöld-Nordenstam, C.G., and Näätämen, R. (1995). Auditory and somatosensory event-related brain potentials in early blind humans. *Exp. Brain Res.* *104*, 519–526.
22. Cohen, L.G., Celnick, P., Pascual-Leone, A., Corwell, B., Faiz, L., Dambrosia, J., Honda, M., Sadato, N., Gerloff, C., Catala, M.D., et al. (1997). Functional relevance of cross-modal plasticity in blind humans. *Nature* *389*, 180–183.
23. Elbert, T., Sterr, A., Rockstroh, B., Pantev, C., Müller, M.M., and Taub, E. (2002). Expansion of the tonotopic area in the auditory cortex of the blind. *J. Neurosci.* *22*, 3439–3445.
24. Lewald, J. (2002). Opposing effects of head position on sound localization in blind and sighted human subjects. *Eur. J. Neurosci.* *15*, 1219–1224.
25. Buechel, C., Price, C., Frackowiak, R.S., and Friston, K. (1998). Different activation patterns in the visual cortex of late and congenitally blind subjects. *Brain* *121*, 409–419.
26. Pascual-Leone, A., and Hamilton, R. (2001). The metamodal organization of the brain. *Prog. Brain Res.* *134*, 427–445.
27. Falchier, A., Clavagnier, S., Barone, P., and Kennedy, H. (2002). Anatomical evidence of multimodal integration in primate striate cortex. *J. Neurosci.* *22*, 5749–5759.