Multisensory Integration in the Superior Colliculus of the Alert Cat

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Wallace, Mark T., M. Alex Meredith, and Barry E. Stein. Multisensory integration in the superior colliculus of the alert cat. J. Neurophysiol. 80: 1006–1010, 1998. The modality convergence patterns, sensory response properties, and principles governing multisensory integration in the superior colliculus (SC) of the alert cat were found to have fundamental similarities to those in anesthetized animals. Of particular interest was the observation that, in a manner indistinguishable from the anesthetized animal, combinations of two different sensory stimuli significantly enhanced the responses of SC neurons above those evoked by either unimodal stimulus. These observations are consistent with the speculation that there is a functional link among multisensory integration in individual SC neurons and cross-modality attentive and orientation behaviors.

INTRODUCTION

Superior colliculus (SC) neurons have the remarkable ability to respond to more than a single sensory input and to synthesize the information derived from different sensory channels. As a result, combinations of visual, auditory, and somatosensory stimuli can dramatically enhance SC responses above those evoked by individual modality-specific stimuli. Ultimately, these multisensory interactions are believed to significantly enhance SC-mediated attentive and orientation behaviors (Freens et al. 1995; Hughes et al. 1994; Stein et al. 1989).

Multisensory interactions in SC neurons were shown to vary in sign (enhancement vs. depression) and magnitude, depending on a variety of spatial and temporal factors, as well as on the effectiveness of modality-specific stimuli (Stein and Meredith 1993). Although multisensory enhancement is defined as a significant increase in the number of impulses evoked by combined-modality (CM) stimuli over that evoked by the most effective unimodal response (see Meredith and Stein 1983) the absolute magnitude of this enhanced response was shown to vary substantially. Generally, the multisensory response is inversely related to the magnitude of the response to the unimodal stimuli that are combined. Consequently, combinations of the least effective stimuli (those that are difficult to perceive or identify) can have the most profound consequences at the single neuron and the overt behavioral level (see Stein and Meredith 1993). Perhaps most impressive is that under these circumstances multisensory stimuli can evoke responses that exceed the sum of the responses to the individual stimuli (Meredith and Stein 1986). However, these physiological results were obtained in anesthetized preparations, and anesthesia can profoundly alter the responses of neurons to sensory stimuli. Indeed, in some instances SC responses can be evoked that are specific to a given anesthetic condition (Nelson et al. 1989), and in other instances anesthetics can degrade or eliminate brain stem sensory responses (Kuwada et al. 1989). Furthermore, anesthetics can significantly affect cortical activity (Dougherty et al. 1997; Duncan et al. 1982), and the integrative properties of SC neurons were shown to critically depend on cortical inputs (Wallace and Stein 1994). The current experiments were initiated to determine whether the sensory convergence patterns, response properties, and multisensory integration capabilities believed to characterize the SC and help mediate overt behaviors are apparent in the alert, untrained animal. An abstract of these results was published previously (Meredith et al. 1993).

METHODS

Procedures were conducted in accordance with the Guide for Care and Use of Laboratory Animals (National Institutes of Health publication No. 86-23). Data were gathered from three animals. A recording well/head support device and scleral search coils for monitoring eye position were implanted chronically (Judge et al. 1980; Meredith and Stein 1986). Animals accommodated to the restraint apparatus that supported the body and fixed the head at the center of a magnetic field coil system. An opaque screen with 2.5° square windows was placed 50 cm from the eyes (Fig. 1). Food presented in the windows encouraged fixation (Munoz and Guitton 1985), and all quantitative tests were conducted when the animal’s eyes and ears were fixated directly ahead (i.e., “primary” position). On occasion, tests were conducted at different fixation locations and qualitative observations were made.

Recording and stimulation procedures were detailed previously (Meredith and Stein 1986). Briefly, once a neuron’s modality profile and modality-specific response properties were assessed and its receptive field(s) mapped, electronically controlled visual (galvanometer-driven bars of light projected onto a translucent screen) and auditory ( broadband noise bursts delivered from hoop-mounted speakers) stimuli were presented in an interleaved manner individually and in combination. Visual stimuli were typically of luminance 53 cd/m 2 on a background of 2.7 cd/m 2 and could be moved through an amplitude range of 1–90° of visual angle and through a range of speeds from 3 to 500°/s. Auditory stimuli ranged in intensity from 50 to 85 dB SPL on a background of 45 dB. These stimuli had no relevance for the animal because they were not used as fixation or saccade targets.

Multisensory interactions were defined as significant (P < 0.05, t-test) changes in neuronal response evoked by CM stimuli as compared with that elicited by the most effective modality-specific stimulus (Meredith and Stein 1983). Interactive magnitudes were determined with the use of the formula CM = SMmax/SMmax × 100 (SMmax is the response to the most effective modality-specific stimulus). Only responses that occurred during fixation and were time locked to the onset of a stimulus were considered. Because of the difficulties inherent with the delivery of somatosensory stimuli in the search-coil apparatus and/or through the...
FIG. 1. Comparisons between superior colliculus (SC) neurons in the alert (left) and anesthetized (right) preparations. The proportions of unimodal and multisensory neurons (top) and response latencies (middle) are similar in both preparations. Also, despite the observation that neurons in both preparations exhibited wide variability in the size of their receptive fields, they were both characterized by a close cross-modality spatial register (bottom). Often this register was strikingly similar, as shown in these 4 examples. In receptive field plots each concentric circle represents 10°. In the convention for representing auditory space, the caudal half of space is depicted by a hemisphere that was split and folded forward. S, superior; I, inferior; N, nasal; T, temporal. Anesthetized data from Wallace et al. 1993.
FIG. 2. Spatially coincident multisensory stimuli-evoked enhanced responses. Top: receptive fields (shading) and stimulus locations (icons). A: auditory stimulus (square wave A) presented while the eyes were fixated (E_v, vertical eye position; E_h, horizontal eye position) evoked few responses, as shown in the rasters, histogram, and oscillograph (single trial). B: visual stimulus (ramp V) was more effective on most trials. However, the stimulus combination (C) evoked a significantly more vigorous response than to either of the unimodal stimuli and exceeded the sum of the unimodal responses, as shown in the summary bar graph (D). ** P < 0.01.

restraining bag, all quantitative tests of multisensory integration involved visual–auditory stimuli. Nonetheless, qualitative observations on somatosensory-responsive neurons were made with the use of taps and strokes from camel hair brushes.

To assess the topography of the SC electrolytic lesions were made in selected electrode penetrations in the final few recording sessions. At the end of the terminal recording session the animal was killed and the tissue was reconstructed as described previously (Wallace et al. 1993).

RESULTS

Seventy-five neurons were examined in the multisensory layers (below stratum opticum) of the SC. Sensory-responsive neurons abounded and in addition to unimodal neurons (56%), multisensory neurons showing different sensory convergence patterns were well represented (44%; Fig. 1). The visual, auditory, and somatosensory representations appeared to be topographic (Stein and Meredith 1993).

The most vigorous visual responses were evoked by moving stimuli. Manipulating the physical parameters of the visual stimulus (e.g., size, direction of movement, and velocity) invariably altered the magnitude of the visual response. Similarly, auditory responses were readily evoked by a host of different stimuli, the most effective of which contained multiple frequencies. All somatosensory neurons exhibited rapidly adapting responses to maintained stimuli and responded to gentle distortion of the hairs or skin (Stein et al. 1976). However, many of these neurons showed a rapid decline in response vigor when identical stimuli were presented repeatedly, even at long (>20 s) interstimulus intervals.

Multisensory neurons had well-defined receptive fields that exhibited cross-modality overlap (Figs. 1 and 2). When stimuli from two different modalities were presented within their respective receptive fields (thus in close spatial proximity), the neuron’s activity was substantially enhanced (Fig. 2). When they were not, response enhancement failed to be produced (Fig. 3). By definition, response enhancement occurs whenever the combined stimulus response significantly exceeds the best modality-specific response (Meredith and Stein 1983). However, in the example shown in Fig. 2, the visual and auditory stimulus combination not only evoked a response that was significantly (P > 0.01) greater than the most effective modality-specific stimulus, but one that was far greater than that predicted by summing the two modality-specific responses (superadditive). This change in the magnitude of an interaction largely depended on the effectiveness of the stimuli that were combined. In all examples tested, the largest response enhancements were obtained by combining the most weakly effective (i.e., those eliciting the fewest impulses) modality-specific stimuli (Fig. 3).

DISCUSSION

The distributions, latencies, and response properties of unimodal and multisensory neurons in the deep layers of the
SC of the alert cat proved to be quite similar to those described in anesthetized animals (for review see Stein and Meredith 1993). Similarly, the integration of cross-modality inputs appeared to abide by the same neural principles. Thus in both preparations the different receptive fields of multisensory neurons were in good spatial register and response enhancements were obtained only when stimuli were spatially coincident (see also Frens and van Opstal 1995; King and Palmer 1985; Peck 1987; Populin and Yin 1997; Wallace et al. 1993; Wallace and Stein 1997).

Although response enhancement to multisensory stimuli was characteristic of the population of neurons studied, the magnitude of the enhanced response varied substantially across the neurons studied from responses that were close to or below a summation of the unimodal responses to multisensory responses that substantially exceeded their sum. This variability appeared to be caused in part by the level of stimulus effectiveness. Modality-specific stimuli that were poorly effective tended to evoke superadditive responses when combined, whereas stimuli that were of higher effectiveness evoked substantially lower levels of enhancement (additive or subadditive). These results parallel those seen in the anesthetized animal, where this principle was referred to as “inverse effectiveness” (Meredith and Stein 1986).

Despite these similarities, differences in the alert and anesthetized preparations were also apparent. In the alert animal some neurons showed strongly habituating responses that exceeded the speed and magnitude of those previously observed in anesthetized animals to the same stimuli (Meredith and Stein 1986; Stein et al. 1976; Wallace et al. 1993). These physiological changes likely reflect shifts of attention and raise the possibility that if these neutral stimuli were associated with specific consequences then responses could have been altered in a variety of ways (see Guitton and Munoz 1991). Indeed, when an animal shifts attention as reflected by a shift in fixation there are profound changes in
sensory responses and receptive field organization (Hartline et al. 1995; Jay and Sparks 1987; Peck 1987), highlighting the dynamic nature of sensory encoding in the alert preparation. Nevertheless, the current results are consistent with the physiological results of studies with anesthetized preparations. They are also consistent with the speculation that previously noted physiological—behavioral parallels (Frens and van Opstal 1995; Hughes et al. 1994; Stein et al. 1989) reflect a functional link between multisensory integration in SC neurons and attentive and orientation behaviors. Similar observations of multisensory enhancements recently made with the use of event-related potentials in monkeys and humans suggest the existence of similar functional links between multisensory processes at the level of the cortical neuron and cross-modality perception (Giard and Peronnet 1997; Lindsley et al. 1997; Sams and Imada 1997).

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