Pharmacology Biochemistry & Behavior, Vol. 19, pp. 813–820, 1983.

Rotational Behavior Following Cholinergic Stimulation of the Superior Colliculus in Rats[1]

DOUGLAS A. WELDON, LAWRENCE C. CALABRESE[2] AND KATHRYN J. NICKLAUS[3]

Department of Psychology, Hamilton College, Clinton, NY 13323

Received 25 March 1982

WELDON, D. A., L. C. CALABRESE AND K. J. NICKLAUS. *Rotational behavior following cholinergic stimulation of the superior colliculus in rats.* PHARMACOL BIOCHEM BEHAV **19**(5) 813–820, 1983.—Rats which received microinjections of carbachol into the superior colliculus exhibited pronounced dose-dependent rotational behavior contralateral to the site of injection (Experiment 1). Wet dog shakes were also observed in some animals. Similar injections in the midbrain reticular formation produced immobility with slight contralateral flexion of the neck. Convulsions were observed in some rats after injections into either anatomical location. In Experiment 2, circling induced by carbachol in the superior colliculus was blocked by prior injection of either the muscarinic receptor antagonist scopolamine or the nicotinic receptor antagonist mecamylamine, suggesting that both nicotinic and muscarinic receptors are involved in the effect. In Experiment 3 contralateral rotational behavior was induced by intracollicular microinjections of the combination of acetylcholine chloride and physostigmine. The results suggest that collicular mediation of contralateral rotational behavior, and perhaps orientation, might involve cholinergic receptors.

Acetylcholine Carbachol Circling behavior Orientation Reticular formation Rotational behavior Superior colliculus

WHEN rats orient to stimuli in their environment, they engage in eye, head and body movements. Current research indicates that the superior colliculus (SC) plays a role in such orientations. The rodent SC has a spatiotopic organization of the environment, and neurons there respond to visual, auditory, and somesthetic stimuli [4, 14, 54, 58]. Unilateral electrical stimulation elicits contralateral movements of the eyes [30], and unilateral lesions of the SC produce ipsiversive turning of the entire body [5, 8, 26, 53]. In addition, animals with bilateral SC lesions are deficient in orientation to food or distracting stimuli [13, 17, 31, 33, 51]. Taken together, these studies suggest that responses of SC neurons to novel environmental stimuli eventually lead to behaviors directing the animal towards those stimuli.

The neurochemistry of the SC is still relatively unexplored, but several neurotransmitters are known to exist there. Microiontophoretically applied acetylcholine, dopamine, norepinephrine, and serotonin affect the neural activity of cat SC cells [55]. In rats, glutamate is suspected to have a role in corticotectal neurotransmission [28]. Gamma aminobutyric acid (GABA) is found in the superficial layers of the SC [24,36] and recent work has provided evidence for a role of this neurotransmitter in orientation and posture. For example, injection of the GABA receptor antagonist picrotoxin in the SC induces contralateral circling behavior [21,25], and in animals with unilateral 6-hydroxydopamine lesions of the substantia nigra, apomorphine-induced rotational behavior is attenuated in animals with SC lesions. The striato-nigrotectal system, which uses GABA as a neurotransmitter [10,62], has been proposed to be involved in these effects [21,25].

Acetylcholine might also be an important neurotransmitter in SC mediated behavior, since both muscarinic and nicotinic receptors have been identified in the SC [12,15]. The cholinergic terminals in the SC probably do not originate in the retina [3], but some could project from the nucleus cuneiformis [19]. The research reported here was designed to study the role of SC cholinergic receptors in orientation by measuring rotational behavior after collicular microinjections of cholinergic agonists and antagonists.

EXPERIMENT 1

Experiment 1 investigated chemical stimulation of the SC with a cholinomimetic to determine whether circling behavior was (1) dose-dependent and (2) anatomically specific. To examine these questions, various doses of carbachol were injected into either the SC or the midbrain reticular formation (MRF).

[1]This research was completed while the first author was supported by a Margaret Bundy Scott Faculty Fellowship from Hamilton College.
[2]Present address: State University of New York, Upstate Medical Center, 766 Irving Avenue, Syracuse, NY 13210.
[3]Present address: Center for Neural Sciences, Brown University, Providence, RI 02912.

METHOD

Animals

The 15 female and 8 male Long-Evans rats were bred at the Hamilton College vivarium and weighed 220–400 g at the beginning of the experiment. The animals were maintained in standard rat cages with food and water available ad lib in a 12:12 light/dark environment with lights on at 0600 hr.

Surgery

Each animal was anesthetized with sodium pentobarbital (40 mg/kg) and its head was shaved and placed into a stereotaxic instrument with the nosebar set 5.0 mm above the interaural position. After a midline incision was made through the scalp, four holes were drilled in the skull and three stainless steel anchor screws were inserted. A 23 ga stainless steel guide cannula (Plastic Products No. 313) was then inserted into the SC, and it was attached with cranioplastic cement. Eleven rats received cannula implants into the SC at the coordinates AP 0.8, L 1.5, DV 1.4 and the remaining 12 rats received cannulas into the MRF at the coordinates AP 0.8, L 1.5, DV −1.5 with respect to interaural zero [39]. The wound was sprinkled with sulfathiazole powder and interrupted silk sutures were applied. A dummy cannula was then inserted into the guide cannula to prevent blockage.

Procedure

After a 7 day recovery period, testing for rotational behavior following intracranial injections began. While each animal was hand held, injections were made via a 27 ga stainless steel internal cannula connected by polyethylene tubing to a Hamilton 10 μl syringe. On each of three consecutive days, each animal received a 0.5 μl injection of 1 μg carbachol (Sigma Chemical Co.), 3 μg carbachol, or vehicle alone (isotonic saline) over a 30 sec period. The drug was dissolved in the vehicle before each day's testing. Immediately following each rat's injection, the dummy cannula was reinserted, the animal was placed on a circular platform 30.5 cm in diameter situated 45.7 cm above a table top, and the number of 360° rotations were counted during a 5 min period.

Histology

After completion of the behavioral testing, each animal was deeply anesthetized with sodium pentobarbital and was intracardially perfused with saline followed by a 10% formalin-saline solution. The brain was then removed, 40-μm sections were taken and stained, and microscopic analysis was made to identify cannula placement locations.

RESULTS AND DISCUSSION

Administration of 1 μg carbachol produced convulsions in 2 SC rats and 1 MRF rat, and administration of the 3 μg dose produced convulsions in 2 rats in each of the cannula placement groups. The drug produced immobility in 9 MRF animals, in which they showed a postural distortion with neck flexion contralateral to the injection side; no such immobility was observed in SC rats (Fisher Exact Probability Test: $p<0.005$). Wet dog shakes following carbachol injections were produced in 7 of the SC rats but in none of the MRF rats (Fisher Exact Probability Test: $p<0.005$).

Rotations were recorded in terms of contralateral and ipsilateral 360° turns with respect to the side of the intracranial injection. The data were analyzed using 2×3 analyses of variance with cannula location (SC or MRF) and carbachol dosage (0, 1.0, and 3.0 μg) as factors. Animals in which convulsions produced any period of inactivity were excluded from the analyses, leaving 8 SC and 9 MRF animals. Carbachol microinjections produced a significant increase in contralateral rotations when injected into the SC, but not when injected into the MRF (dosage × location interaction: $F(2,30)=9.13$, $p<0.001$, see Fig. 1A). Ipsilateral rotations declined as a function of dosage for both groups (dose main effect: $F(2,30)=8.96$, $p<0.001$, see Fig. 1B).

Histological verification showed most cannula placements to be located in the appropriate brain locations (see Fig. 2). Within the MRF group, two placements were near the substantia nigra and one was near the brachium conjunctivum. One SC animal had a cannula on the border of the SC and the inferior colliculus. Another animal had a cannula located in the cortex immediately above the SC; this animal had a convulsion with carbachol administration, but circling behavior was not observed. Within each of the cannula placement groups, no relationships were found between specific cannula locations and the magnitude of circling.

In summary, Experiment 1 demonstrated dosage dependence and anatomical specificity in the effects of carbachol administration to the SC. Observation of the animals exhibiting rotational behavior reveals that the intensity of the behavior is most pronounced in the first few minutes following the injection. In pilot experiments with larger doses of carbachol, however, rotations were seen as long as 20 min after the time of injection. The behaviors exhibited by rats with low doses of carbachol injected into the SC appeared to be natural and investigatory, except that the animals moved predominantly in the contralateral direction. With larger doses, however, the pattern of rotations had a more "compulsive" appearance, and the turning occurred in tighter circles and at a faster rate.

Rotational behavior was observed following carbachol injections into the SC but not after administration into the MRF. Dissociation of SC and MRF behavioral effects have also been observed following bilateral procaine injections; administration of the drug to the SC produced immobility, but hyperactivity was observed after injection into the MRF [7].

The postural immobility observed in MRF animals following carbachol administration might be related to Nakajima's [35] finding that potassium injections into this area produced momentary immobility. In cats, carbachol injections into the MRF or the pontine areas near the locus coeruleus have been reported to produce atonia [16, 60, 61]. Wet dog shakes have been observed following intraventricular carbachol injections [59], and the results of Experiment 1 raise the possibility that these shakes might be mediated by a neural system that includes the SC.

EXPERIMENT 2

Experiment 1 showed that stimulation of the SC of the rat with small amounts of the cholinomimetic carbachol produces dose-dependent rotations contralateral to the site of injection. The elicitation of circling also appears to be anatomically specific, since microinjections more ventral into the midbrain did not produce circling.

If the rotational behavior is indeed due to stimulation of cholinergic receptors by carbachol, then prior administration of a cholinergic antagonist should reduce or eliminate the carbachol-induced circling. Experiment 2 tested carbachol

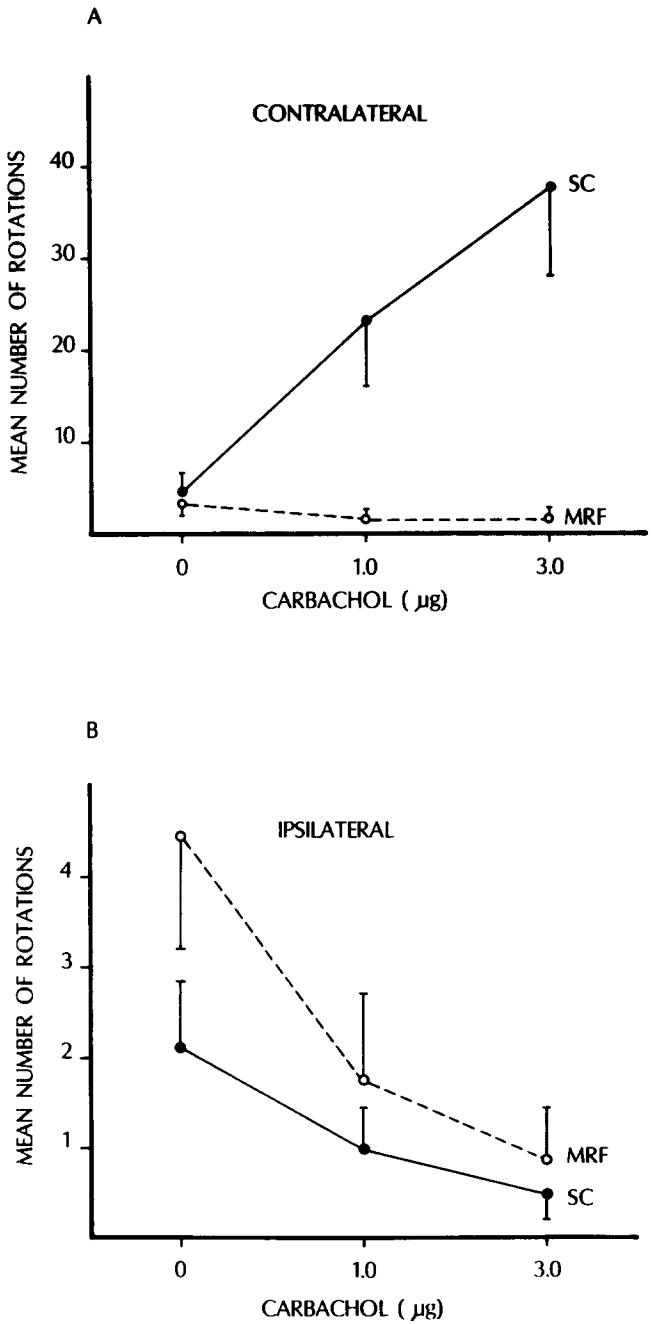

FIG. 1. Mean number of contralateral (A) and ipsilateral (B) 360° rotations after injections of 0 (isotonic saline vehicle), 1.0 or 3.0 μg carbachol into the SC or MRF. Note change in ordinate scale.

stimulation of the SC following muscarinic receptor blockade with scopolamine or nicotinic blockade with mecamylamine.

METHOD

Animals

Six male Long-Evans rats weighing 450–550 g were used. They were housed in conditions identical to those described in Experiment 1.

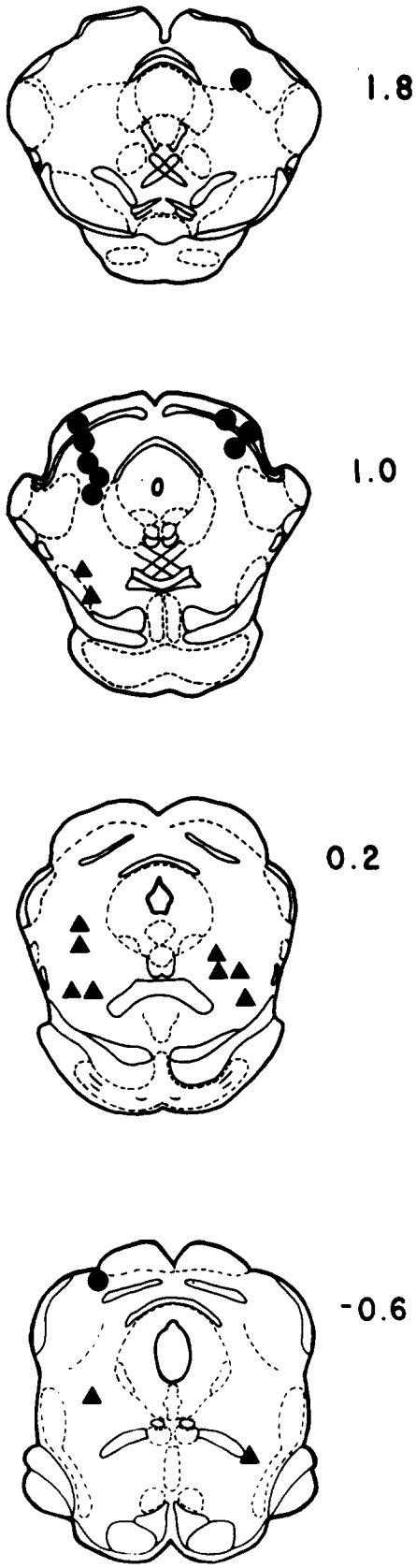

FIG. 2. Histological results for Experiment 1 illustrating cannula placements in the SC (circles) or MRF (triangles). Diagram adapted from Pellegrino and Cushman [39].

Apparatus and Procedure

The apparatus and procedures used in Experiment 2 were the same as those described in Experiment 1 except that all animals had cannulas placed in the SC. After 7 days of post-operative recovery, animals underwent 6 days of behavioral testing. On each day of testing, each animal received two microinjections (0.5 μl) in sequence, separated by a 2–3 min interval. The first injection was either of isotonic saline (vehicle), mecamylamine (2.5 μg, Sigma Chemical Co.), or scopolamine methylbromide (5 μg, Sigma Chemical Co.). The second injection was of either isotonic saline or carbachol (2 μg). Chemicals were defrosted to room temperature just prior to each day's testing, and each animal received a different sequence of drug injections during the experiment. Animals were then observed for rotation, rearing, grooming, head and/or body shakes, and convulsions for a 5 min period. Data were recorded by an observer who was unaware of which drug had been injected. Histological verification was made of cannula placements as in Experiment 1.

RESULTS AND DISCUSSION

As in Experiment 1, carbachol produced a significant increase in 360° rotations contralateral to the site of injection in 5 of the 6 animals. Subsequent data analyses were made on the animals that circled to study the combined effects of cholinergic blocking agents. When the injection of carbachol was preceded by an injection of either mecamylamine or scopolamine, the number of contralateral rotations did not change in comparison to the saline control condition (see Fig. 3A). This interaction of the first drug injected and the second drug injected was statistically significant, $F(2,8)=7.66$, $p<0.02$. There were no statistically significant effects on the number of ipsilateral responses (see Fig. 3B). Seizures and shaking were observed following carbachol treatment after saline, but not if carbachol was preceded by either antagonist. Figure 4 illustrates the histological results, showing that all cannulas were located in the intermediate layers of the SC.

The results of Experiment 2 confirm those of Experiment 1 in showing that cholinergic receptor stimulation induces contralateral orientations in rats. In addition, Experiment 2 indicates that both nicotinic and muscarinic receptors play a role in the effect of carbachol. Future experimentation using successively lower doses of antagonists might eventually determine a more selective effect than was shown here, but research on carbachol-induced aggression after microinjections in the hypothalamus in cats has also indicated that both nicotinic and muscarinic receptors are necessary for the effects of carbachol [46].

EXPERIMENT 3

Experiment 2 showed that carbachol administration into the SC induces a circling response that is dependent upon the availability of both muscarinic and nicotinic cholinergic receptors. Experiment 3 was designed to study whether the effects of carbachol would generalize to another chemical that stimulates cholinergic receptors, i.e., acetylcholine itself. Administration of acetylcholine was accompanied with physostigmine to prevent rapid breakdown of the acetylcholine by acetylcholinesterase.

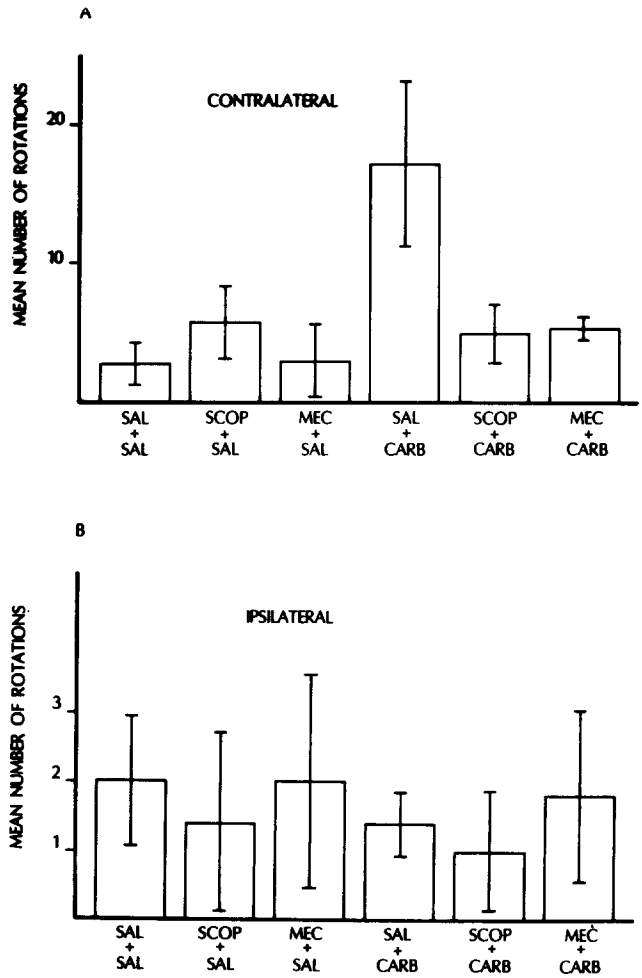

FIG. 3. Mean number of contralateral (A) and ipsilateral (B) 360° rotations following microinjections into the SC of isotonic saline (SAL), 2.5 μg mecamylamine (MEC), or 5.0 μg scopolamine (SCOP) followed by another injection of isotonic saline (SAL) or 2 μg carbachol (CARB). Note change in ordinate scale.

METHOD

Animals

Four female and four male Long-Evans rats weighing 300–500 g were purchased from Blue Spruce Farms (Atlamont, NY) and were maintained as described above. Surgery was performed two weeks after their arrival at the laboratory.

Procedure

Surgery, apparatus and testing procedures were identical to those described above. One week after cannula implantation in the SC, animals were tested for rotational behavior on 4 consecutive days. Each day, each animal received one microinjection (0.5 μl) into the SC of one of the following solutions: (1) isotonic saline (vehicle), (2) physostigmine (0.5 μg, Sigma Chemical Co.), (3) acetylcholine chloride (2.5 μg, Sigma Chemical Co.) and physostigmine (0.5 μg), or (4) acetylcholine chloride (5.0 μg) and physostigmine (0.5 μg). Each animal received a different order of treatments.

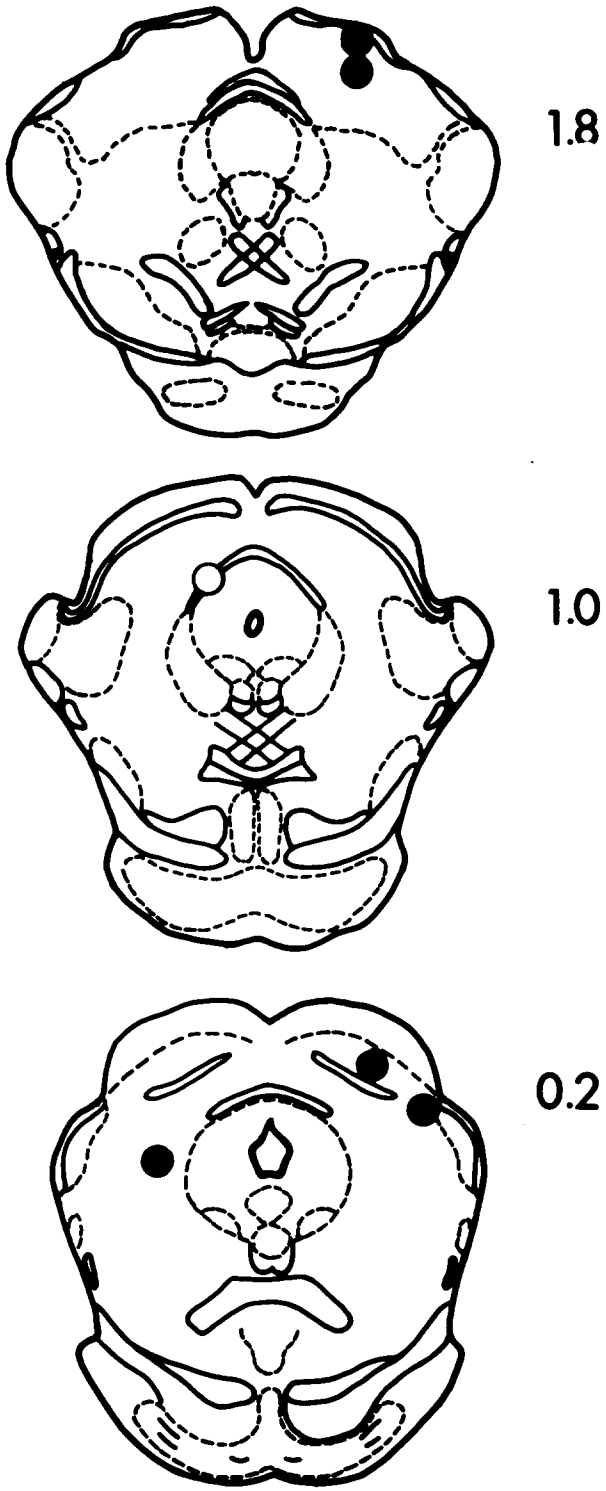

FIG. 4. Histological results for Experiment 2, showing cannula placements into the SC. One placement in which the cannula was located in the central grey/commissure of the SC (open circle) did not yield circling behavior.

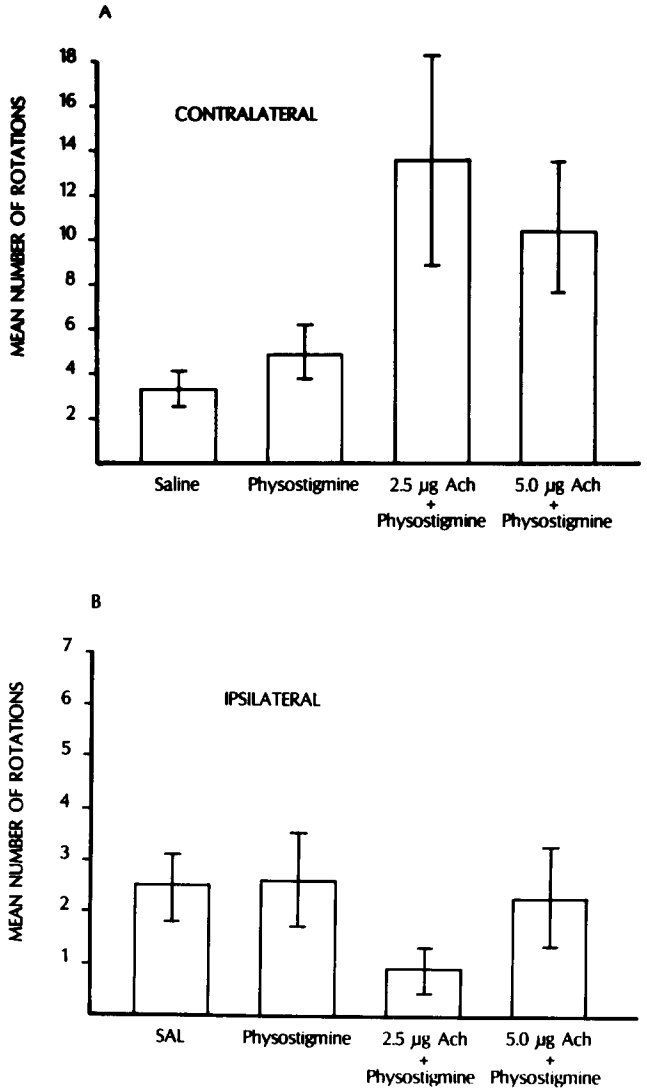

FIG. 5. Mean number of contralateral (A) and ipsilateral (B) rotations made by animals after SC microinjections of either isotonic saline, 0.5 μg physostigmine, 0.5 μg physostigmine and 2.5 μg acetylcholine, or 0.5 μg physostigmine and 5.0 μg acetylcholine. Note change in ordinate scale.

RESULTS AND DISCUSSION

Injections of acetylcholine in combination with physostigmine produced a significant increase in contralateral circling in comparison with the saline or physostigmine control treatments, $F(7,21)=3.36$, $p<0.05$ (see Fig. 5A). The effects of the experimental manipulations on ipsilateral circling did not attain statistical significance (see Fig. 5B). No convulsions were observed, but shakes were observed in 2 animals following administration of the low dose of acetylcholine and in 1 animal following the high dose of the neurotransmitter. Figure 6 shows the anatomical locations of the cannulas. All placements were in the SC, although the precise locations varied.

The results of Experiment 3 indicate that the contralateral circling observed in the earlier experiments can be elicited

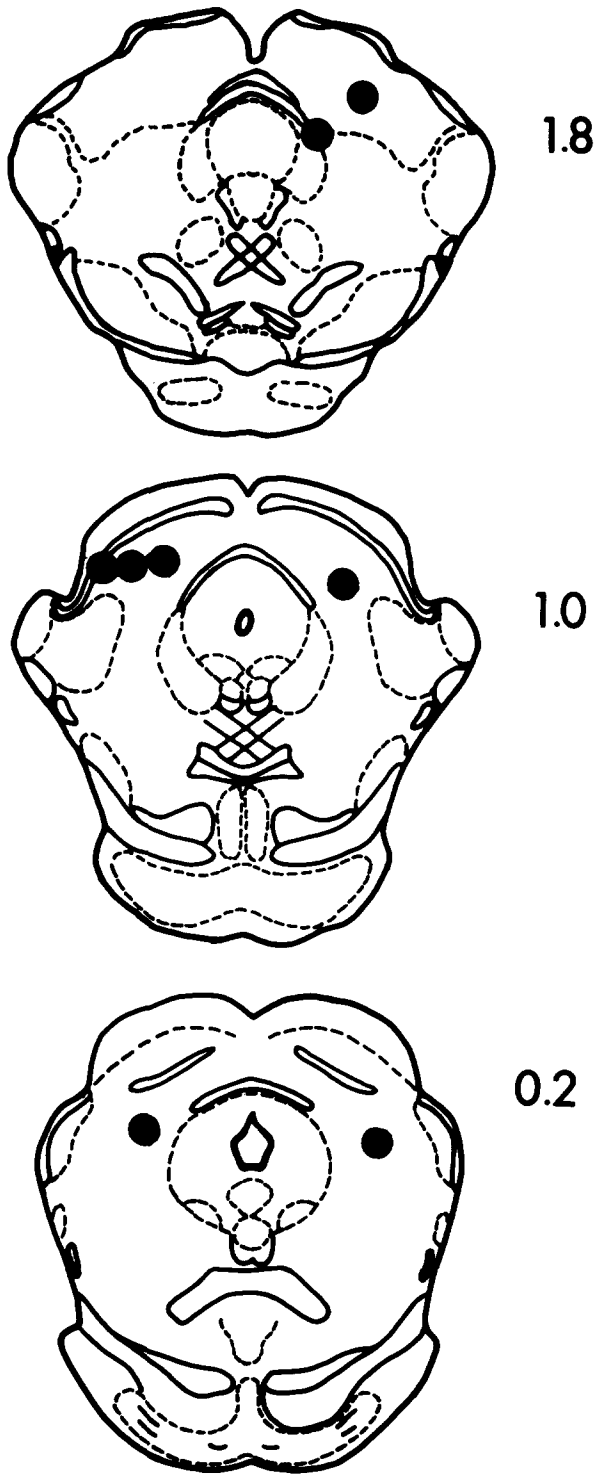

FIG. 6. Histological results for Experiment 3, showing placements of cannulas into the SC.

by cholinergic receptor stimulation with acetylcholine chloride as well as with carbachol. Thus, the circling is not specific to one chemical that stimulates cholinergic receptors.

GENERAL DISCUSSION

The present results have shown that pharmacological stimulation of the SC by the cholinomimetic carbachol produces contralateral rotational behavior in rats. The effects are dose-dependent, anatomically specific, and can be eliminated by antagonism of either muscarinic or nicotinic cholinergic receptors. They can also be obtained by intracollicular administration of physostigmine with acetylcholine. These results are particularly interesting in view of the evidence for both muscarinic and nicotinic cholinergic receptors in the SC [11, 12, 15, 20, 27, 47, 52, 63]. The contralateral rotational behavior following carbachol administration into the SC is consistent with the ipsiversive circling produced by lesions of that area [5, 8, 26, 53], and with electrophysiological investigations of SC connections with cervical spinal cord neurons that are probably involved in turning orientations [67]. The current findings also complement the evidence for contralateral eye, head, and body movements following electrical stimulation of the SC in cats and rats [18, 30, 49, 56]. Microinjections of acetylcholine into the pulvinar-lateralis posterior complex (an area receiving afferents from the SC) of the cat have also been reported to produce contralateral circling [34].

Other brain areas are also involved in circling and gross directional orientation. Rotational behavior results from microinjections of various substances into the nigrostriatal system, and GABA seems to be one important neurotransmitter in these effects (e.g., [9, 23, 29, 37, 38, 41, 50]). In addition, Aprison, Nathan and Himwich [1,2] described a rotational syndrome following administration of diisopropyl-fluorophosphate into the right carotid artery in rabbits. They related these results to asymmetric cholinesterase reductions in the left and right caudate nucleus and frontal cortex.

It is possible that some effects of nigrostriatal manipulations might be mediated via the SC. Some behavioral effects of apomorphine and amphetamine administration are absent in animals with SC lesions [40,44], and oral behavior induced by injections of the GABA agonist muscimol into the substantia nigra is also abolished by SC ablation [57]. Although there is inconsistent evidence concerning the role of the SC in rotational behavior following unilateral nigrostriatal lesions [6, 8, 22, 32, 42], neurochemical studies have strongly suggested the involvement of the nigrotectal tract in these effects [25]. Microinjections of the GABA agonist muscimol into the middle and deep layers of the SC produce ipsilateral rotational behavior and postural distortions, and injections of the GABA antagonist picrotoxin produce contralateral circling [21,25]. Gnawing and avoidance reactions also result from blockade of GABA receptors in the SC [43,45]. Picrotoxin-induced gnawing has been attributed to a GABA system that inhibits nigrotectal neurons, but the explosive motor behavior and avoidance responses are probably mediated by GABA interneurons which normally suppress sensory stimulation.

Seizure activity elicited by carbachol microinjections into the SC has been observed previously [48]. In mice, convul-

sions and running fits elicited by intracollicular injections of antivitamin B drugs have been related to decreases in GABA [64–66]. Similarly, explosive motor behavior and delayed seizures have been reported following bilateral injections of picrotoxin into the SC of rats [21,43].

ACKNOWLEDGEMENTS

The authors thank Anne Darling and David Tewksbury for their work in producing the illustrations in this paper, Clifford Lyons for his involvement in pilot work related to this research, and Jonathan Vaughan for his extensive comments on an earlier draft of this manuscript.

REFERENCES

1. Aprison, M. H., P. Nathan and H. E. Himwich. A study of the relationship between asymmetric acetylcholinesterase activities in rabbit brain and three behavioral patterns. *Science* **119:** 158–159, 1954.
2. Aprison, M. H., P. Nathan and H. E. Himwich. Cholinergic mechanism of brain involved in compulsive circling. *Am J Physiol* **184:** 244–252, 1956.
3. Bigl, V. and W. Schober. Cholinergic transmission in subcortical and cortical visual centers of rats: No evidence for the involvement of primary optic system. *Exp Brain Res* **27:** 211–219, 1977.
4. Chalupa, L. M. and R. W. Rhoades. Responses of visual, somatosensory and auditory neurons in the golden hamster's superior colliculus. *J Physiol* **270:** 595–626, 1977.
5. Cooper, R. M., B. H. Bland, L. A. Gillespie and R. H. Whitaker. Unilateral posterior cortical and unilateral collicular lesions and visually guided behavior in the rat. *J Comp Physiol Psychol* **72:** 286–295, 1970.
6. Crossman, A. R. and M. A. Sambrook. The neurological basis of motor asymmetry following unilateral nigrostriatal lesions in the rat: The effect of secondary superior colliculus lesions. *Brain Res* **159:** 211–213, 1978.
7. Dean, P., P. Redgrave and G. Lewis. Locomotor activity of rats in open field after microinjection of procaine into superior colliculus or underlying reticular formation. *Behav Brain Res* **5:** 175–187, 1982.
8. Di Chiara, G., M. Morelli, A. Imperato and M. L. Porceddu. A reevaluation of the role of superior colliculus in turning behavior. *Brain Res* **237:** 61–77, 1982.
9. Di Chiara, G., M. Morelli, M. L. Porceddu and G. L. Gessa. Evidence that nigral GABA mediates behavioral responses elicited by striatal dopamine receptor stimulation. *Life Sci* **23:** 2045–2051, 1978.
10. Di Chiara, G., M. L. Porceddu, M. Morelli, M. L. Mulas and G. L. Gessa. Evidence for a GABAergic projection from the substantia nigra to the ventromedial thalamus and to the superior colliculus of the rat. *Brain Res* **176:** 273–284, 1979.
11. Ellis, J. and W. Hoss. Analysis of regional variations in the affinities of muscarinic agonists in the rat brain. *Brain Res* **193:** 189–198, 1980.
12. Fibiger, H. C. The organization and some projections of cholinergic neurons of the mammalian forebrain. *Brain Res Rev* **4:** 327–388, 1982.
13. Finlay, B. L. and S. J. Cairns. Relationship of aberrant retinotectal projections to visual orienting after neonatal tectal damage in hamster. *Exp Neurol* **72:** 308–317, 1981.
14. Finlay, B. L., S. E. Schneps, K. G. Wilson and G. E. Schneider. Topography of visual and somatosensory projections to the superior colliculus of the golden hamster. *Brain Res* **142:** 223–235, 1978.
15. Francis, A. and N. Schechter. Putative cholinergic receptor activity in the deafferented rat superior colliculus. *Brain Res* **183:** 224–228, 1980.
16. George, R., W. L. Haslett and D. J. Jenden. A cholinergic mechanism in the brainstem reticular formation: Induction of paradoxical sleep. *Int J Neuropharmacol* **3:** 541–552, 1964.
17. Goodale, M. A., N. P. Foreman and A. D. Milner. Visual orientation in the rat: A dissociation of deficits following cortical and collicular lesions. *Exp Brain Res* **31:** 445–457, 1978.
18. Hess, W. R., S. Burgi and V. Buchner. Motorische funktion des tektal- und tegmental-gebeities. *Monatsschr Psychiatr Neurol* **112:** 1–52, 1946.
19. Hoover, D. B. and D. M. Jacobowitz. Neurochemical and histochemical studies of the effect of a lesion of the nucleus cuneiformis on the cholinergic innervation of discrete areas of the rat brain. *Brain Res* **170:** 113–122, 1979.
20. Hung, S. and J. Schmidt. Some observations on the binding patterns of α-bungarotoxin in the central nervous system of the rat. *Brain Res* **157:** 213–232, 1978.
21. Imperato, A. and G. Di Chiara. Behavioral effects of GABA-agonists and antagonists infused in the mesencephalic reticular formation-deep layers of the superior colliculus. *Brain Res* **224:** 185–194, 1981.
22. Imperato, A., M. L. Porceddu, M. Morelli, G. Faa and G. di Chiara. Role of dorsal mesencephalic reticular formation and deep layers of superior colliculus as output stations for turning behavior elicited from the substantia nigra pars reticulata. *Brain Res* **216:** 437–443, 1981.
23. Kaakkola, S. and I. Kaariainen. Circling behavior induced by intranigral injections of GABA and muscimol in rats. *Psychopharmacology (Berlin)* **68:** 31–36, 1980.
24. Kayama, Y., Y. Fukuda and K. Iwama. GABA sensitivity of neurons of the visual layer in the rat superior colliculus. *Brain Res* **192:** 121–131, 1980.
25. Kilpatrick, I. C., G. L. Collinridge and M. S. Starr. Evidence for the participation of nigrotectal gamma-aminobutyrate-containing neurones in striatal and nigral-derived circling in the rat. *Neuroscience* **7:** 207–222, 1982.
26. Kirvel, R. D. Sensorimotor responsiveness in rats with unilateral superior colliculus and amygdaloid lesions. *J Comp Physiol Psychol* **89:** 889–891, 1975.
27. Kobayashi, R. M., M. Palkovits, R. E. Hruska, R. Rothschild and H. Yamamura. Regional distribution of muscarinic-cholinergic receptors in rat brain. *Brain Res* **154:** 13–23, 1978.
28. Lund, K. and F. Fonnum. Evidence for glutamate as a neurotransmitter in the corticofugal fibers to the dorsal lateral geniculate body and the superior colliculus in rats. *Brain Res* **151:** 457–467, 1978.
29. McGeer, P. L., E. G. McGeer and J. J. R. Campbell. Rotatory effects of intracerebral tetanus toxin injections. *Exp Neurol* **67:** 363–367, 1980.
30. McHaffie, J. G. and B. E. Stein. Eye movements evoked by electrical stimulation in the superior colliculus of rats and hamsters. *Brain Res* **247:** 243–253, 1982.
31. Midgley, G. C. and R. C. Tees. Orienting behavior by rats with visual cortical and subcortical lesions. *Exp Brain Res* **41:** 316–328, 1981.
32. Morelli, M., A. Imperato, M. L. Porceddu and G. di Chiara. Role of dorsal mesencephalic reticular formation and deep layers of superior colliculus in turning behavior elicited from the striatum. *Brain Res* **215:** 337–341, 1981.
33. Mort, E., S. Cairns, H. Hersch and B. Finlay. The role of the superior colliculus in visually guided locomotion and visual orienting in the hamster. *Physiol Psychol* **8:** 20–28, 1980.
34. Motles, E., Y. Ely and Z. Elazar. Role of the pulvinar-lateral posterior nucleus complex in turning behavior. *Physiol Behav* **25:** 921–929, 1980.
35. Nakajima, S. Effects of chemical injection into the reticular formation of rats. *J Comp Physiol Psychol* **58:** 10–15, 1964.

36. Okada, Y. Distribution of γ-aminobutyric acid (GABA) in the layers of superior colliculus of the rabbit. *Brain Res* **75:** 362–365, 1974.
37. Olpe, H. and W. P. Koella. Rotatory behavior in rats by intranigral application of substance P and an eledoisin fragment. *Brain Res* **126:** 576–579, 1977.
38. Papadopoulos, G. and J. P. Huston. Removal of the telencephalon spares turning induced by injection of GABA agonists and antagonists into the substantia nigra. *Behav Brain Res* **1:** 25–38, 1980.
39. Pellegrino, L. J. and A. J. Cushman. *A Stereotaxic Atlas of the Rat Brain*. New York: Appleton-Century-Crofts, 1967.
40. Pope, S. G., P. Dean and P. Redgrave. Dissociation of d-amphetamine-induced locomotor activity and stereotyped behavior by lesions of the superior colliculus. *Psychopharmacology (Berlin)* **70:** 297–302, 1980.
41. Reavill, C., P. Jenner, N. Leigh and C. D. Marsden. Turning behaviour induced by injection of muscimol or picrotoxin into the substantia nigra demonstrates dual GABA components. *Neurosci Lett* **12:** 323–328, 1979.
42. Reavill, C., N. Leigh, P. Jenner and C. D. Marsden. Dopamine-mediated circling behaviour does not involve the nigro-tectal pathway. *Exp Brain Res* **37:** 309–316, 1979.
43. Redgrave, P. and P. Dean. Collicular picrotoxin alleviates akinesia but not sensory neglect in rats with bilateral 6-hydroxydopamine lesions of ventral midbrain. *Psychopharmacology (Berlin)* **75:** 204–209, 1981.
44. Redgrave, P., P. Dean, T. P. Donohoe and S. G. Pope. Superior colliculus lesions selectively attenuate apomorphine-induced oral stereotypy: a possible role for the nigrotectal pathway. *Brain Res* **196:** 541–546, 1980.
45. Redgrave, P., P. Dean, W. Souki and G. Lewis. Gnawing and changes in reactivity produced by microinjections of picrotoxin into the superior colliculus of rats. *Psychopharmacology (Berlin)* **75:** 198–203, 1981.
46. Romaniuk, A. and H. Golebiewski. Midbrain interaction with the hypothalamus in expression of aggressive behavior in cats. *Acta Neurobiol Exp* **37:** 83–97, 1977.
47. Rotter, A., P. M. Field and G. Raisman. Muscarinic receptors in the central nervous system of the rat. III. Postnatal development of binding of [3H] propylbenzylcholine mustard. *Brain Res Rev* **1:** 185–205, 1979.
48. Routtenberg, A. and J. Olds. Stimulation of dorsal midbrain during septal and hypothalamic self-stimulation. *J Comp Physiol Psychol* **62:** 250–255, 1966.
49. Schaefer, K. P. Unit analysis and electrical stimulation in the optic tectum of rabbits and cats. *Brain Behav Evol* **3:** 222–240, 1970.
50. Scheel-Kruger, J., J. Arnt and G. Magelund. Behavioral stimulation induced by muscimol and other GABA agonists into substantia nigra. *Neurosci Lett* **4:** 351–365, 1977.
51. Schneider, G. E. Contrasting visuomotor functions of tectum and cortex in the golden hamster. *Psychol Forschung* **31:** 52–62, 1967.
52. Segal, M., Y. Dudai and A. Amsterdam. Distribution of an α-bungarotoxin binding cholinergic nicotinic receptor in rat brain. *Brain Res* **148:** 105–119, 1978.
53. Sprague, J. M. The superior colliculus and pretectum in visual behavior. *Invest Ophthalmol* **11:** 473–482, 1972.
54. Stein, B. E. and J. P. Dixon. Properties of superior colliculus neurons in the golden hamster. *J Comp Neurol* **183:** 269–284, 1979.
55. Straschill, M. and J. Perwein. Effect of iontophoretically applied biogenic amines and of cholinomimetic substances upon the activity of neurons in the superior colliculus and mesencephalic reticular formation of the cat. *Pflugers Arch* **324:** 43–55, 1971.
56. Syka, J. and T. Radil-Weiss. Electrical stimulation of the tectum in freely moving cats. *Brain Res* **28:** 567–572, 1971.
57. Taha, E. B., P. Dean and P. Redgrave. Oral behavior induced by intranigral muscimol is unaffected by haloperidol but abolished by large lesions of superior colliculus. *Psychopharmacology (Berlin)* **77:** 272–278, 1982.
58. Tiao, Y.-C. and C. Blakemore. Functional organization in the superior colliculus of the golden hamster. *J Comp Neurol* **168:** 483–504, 1976.
59. Turski, L., W. Turski, S. J. Czuczwar and Z. Kleinrok. Evidence against the involvement of serotonergic mechanisms in wet dog shake behavior induced by carbachol chloride in rats. *Psychopharmacology (Berlin)* **73:** 376–380, 1981.
60. Van Dongen, P. A. M. Locus coeruleus region: Effects on behavior of cholinergic, noradrenergic, and opiate drugs injected intracerebrally into freely moving cats. *Exp Neurol* **67:** 52–78, 1980.
61. Van Dongen, P. A. M., L. E. Broekkamp and A. R. Cools. Atonia after carbachol microinjections near the locus coeruleus in cats. *Pharmacol Biochem Behav* **8:** 527–532, 1978.
62. Vincent, S. R., T. Hattori and E. G. McGeer. The nigrotectal projection: A biochemical and ultrastructural characterization. *Brain Res* **151:** 159–164, 1978.
63. Wamsley, J. K., M. S. Lewis, W. S. Young and M. J. Kuhar. Autoradiographic localization of muscarinic cholinergic receptors in rat brain stem. *J Neurosci* **1:** 176–191, 1981.
64. Yamashita, J. and Y. Hirata. Running fit induced by injection of semicarbazide into the superior colliculus of the mouse. *J Nutr Sci Vitaminol* **23:** 467–470, 1977.
65. Yamashita, J. and Y. Hirata. Running fits induced by direct administration of semicarbazide into the superior colliculus of the mouse. *Neurosci Lett* **8:** 89–92, 1978.
66. Yamashita, J. and Y. Hirata. Running fits and γ-aminobutyric acid of the superior colliculus of the mouse. *J Nutr Sci Vitaminol* **25:** 15–22, 1979.
67. York, D. H. and J. E. Faber. An electrophysiological study of nigro-tectal relationships: A possible role in turning behavior. *Brain Res* **130:** 383–386, 1977.