Behavioural Brain Research 298 (2016) 150–157

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

A novel turning behavior control method for rat-robot through the stimulation of ventral posteromedial thalamic nucleus

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HIGHLIGHTS

- A new turning behaviour control method for rat-robot is proposed.
- Stimulation on VPM results in turning behaviour without training.
- The new method shows stability and reliability through trials and period.
- This method also shows potential of quantitative control of the turning angle.

ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 28 October 2015
Accepted 2 November 2015
Available online 11 November 2015

Keywords:
Rat-robot
Ventral posteromedial thalamic nucleus
Turning behavior control

ABSTRACT

The concept of a rat-robot was initially introduced in 2002, bringing to the field, a novel area of research using modern research into neuroscience and robotics. This paper brings to the table, a study into the method best used for navigation systems in a rat-robot. Current research is epitomized by the use of reward-based spatial navigation, combining the concept of an induced reward sensation as well as a 'virtual touch' sensation to control the movement of the rat-robot. However, such methods are plagued by limitations affecting the success rate as well as preparation procedures which may have varying effects on different rats, even under similar conditions. Hence, this paper studies the stimulation of two different portions of the brain to induce a turning motion within the rat, namely the Ventral Posteromedial (VPM) thalamic nucleus as well as the Barrel-Field (BF) cortex and demonstrates the preferential usage of VPM as the choice use of navigational control in a rat-robot.

1. Introduction

The merging of the fields of neuroscience and bio-robotics began in the mid-1990s [1,2]. By applying artificial electrical stimulation in the antennal lobe of a cockroach, the turning and forward movements could be observed and controlled [1]. In 2002, an article published in Nature introduced a method of training rats on a navigational task using artificially introduced electrical commands into the brain [3]. Combined with appropriate training procedures, the rat-robot could accomplish sophisticated tasks, such as searching within a complex maze or moving on a preset route with difficult terrain. Animal robotics—the field of research in the use of electrical stimulation to control the actions of an animal has since been developing rapidly. These methods have been implemented in other animals as well (including rabbits [4], dogs [4], sharks [5], cows [6], pigeons [7,8]).

The basic idea of animal locomotor control was to mimic the sensory perceptions, thus inducing changes of animal behavior. Thereby, a key question is what brain area should be targeted for electrical stimulation. A number of brain areas have been tested for rat's locomotor control, including primary somatosensory cortex (S1), medial forebrain bundle (MFB) [3], ventral posterolateral nucleus of the thalamus (VPL) [8], amygdala nucleus (AMY) [8], the pendunculopontine tegmental nucleus (PPTg) [9], and the dorsal periaqueductal gray nucleus (dPAG) [10].

Critical to the navigational control of an animal-robot, one essential component is the successful control of its turning behav-

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http://dx.doi.org/10.1016/j.bbr.2015.11.002
0166-4328/

ior. As we [11] and others [3] have previously demonstrated, a successful rat-robot system can be created by implantation of electrodes into the MFB as reward and the barrel cortex (S1BF) peeling off the insulatingarea as virtual directional cues for turning [3]. The stimulation in S1BF simulate somatosensory input from the head and face, especially the whiskers area [12,13], encountering a boundary or barrier, which the rat would tend to turn away from. Since somatosensory input is received and processed by the hemisphere contralateral to the side of the body that is touched, the rat is expected to turn in the direction ipsilateral to the stimulation. This sensory discrimination based on cortical electrical micro-stimulation method has long been developed and verified on the rat somatosensory cortex [14] and auditory cortex [15], monkey proprioceptive cortex [16,17] and human visual cortex [18]. However, the control of the turning behavior of the reported rat-robot is highly dependent on the training procedure, as the rats need to get used to the electrical stimulation on the barrel cortex and learn to link the stimulation with the right turning direction. This training procedure involves reward stimulation of MFB, requiring experienced trainers for about 1 or 2 weeks. This coupled stimulation exhibits a large variability in the results produced. Hence, it would be an advance to eliminate the element of voluntary movement from the control mechanism, producing a more reliable control mechanism for animal robotics. With regards to the proposed rat-robot system, the control of turning behavior via the stimulation of the barrel-cortex may also possibly have some other better yet unutilized replacement site of stimulation. The peripheral sensory information from the body and head need to be organized in the ventral posterolateral (VPL) and ventral posteromedial (VPM) [19] thalamic nuclei respectively, before it can be transmitted to the sensory cortex. A recent paper published by Dr. Joseph Francis also thoroughly described the topography of the cutaneous representation within the rat's VPL nucleus [20], indicating the thalamus might be a promising target for inputting artificial sensory information.

Based on this hypothesis, this paper has proposed a novel navigational control method for a rat-robot, through the stimulation of the VPM thalamic nucleus region. This region is proposed largely due to its function in its natural state, which is the conveying of facial sensory information along the trigeminothalamic tract, towards the postcentralgyrus, the primary processing center for touch sensations. Hence, it is proposed that through the artificial electrical stimulation of the VPM thalamic nucleus, a virtual touch sensation, as a more 'solid' directional cue for the rat as opposed to the directional cues from the whiskers, which can be used as a control command for the turning behavior of rat-robot. The influence of different VPM electrical stimulation parameters on the turning behavior of the rat-robot were also comprehensively evaluated in this research work, as well as the comparison of the turning behavior between the rat-robot with the new VPM stimulation method and the old barrel-cortex stimulation method. These studies aim to prove that the electrical stimulation on the VPM area could provide a reliable, highly efficient and quantitative method for controlling the turning behavior of a rat-robot, which can ultimately be utilized in the navigational system.

2. Material and methods

2.1. Subjects

Nine male Sprague–Dawley rats (200–300 g) were used. One group received barrel-cortex stimulation (BF group, $n = 4$, identified as BF No.1–4.) and another group received VPM stimulation (VPM group, $n = 5$, identified as VPM No.1–5). All rats were housed individually with food and water *ad libitum*. All procedures used in the study were in accordance to the guide for the care and use of laboratory animals (China Ministry of Health) and the protocols approved by the Zhejiang University Animal Care and Use Committee.

2.2. Stimulating electrodes

Stimulating electrodes were made from pairs of insulated Nichrome wires (A-M Systems, Formvar-Insulated Nichrome Wire, Diameter: Bare 0.002 in., Coated 0.0026 in.). The Nichrome wires were twisted to form a bipolar electrode, with a 0.4 mm vertical separation between two tips. 0.3 mm of each tip was then exposed by peeling off the insulating formvar layer via sharp-pointed tweezers under microscope (as shown in the left of Supplementary Fig. 1B).

2.3. Animal surgery

All rats were given at least 3 days to acclimatize to the laboratory environment before surgical implantation. The surgical procedures were carried out as previous report [11]. Briefly, the rat was anesthetized with 1.0% pentobarbital sodium (i.p. 5 mg/kg), and placed in a stereotaxic apparatus (Stoelting Co, U.S.A). Two 0.8 mm diameter craniotomies were made to permit introduction of the stimulating electrodes bilaterally to VPM (−2.8 mm posterior to the bregma (AP), ±2.6 mm to the midline (ML) (Paxinos and Watson's rat brain atlas. See Supplementary Fig. 1A, blue dots). The stimulation electrodes were then stereotaxically inserted through the craniotomy to target VPM thalamic nucleus bilaterally (AP: −2.8 mm, ML: ±2.6 mm, DV: +6.0 mm). Craniotomies were covered with a layer of cyanoacrylate glue (Beijing Compont Medical Devices Co., Ltd.) and covered with dental acrylic (Vertex Self Curing Cold-curing acrylic denture repair material, Vertex-Dental B.V., the Netherlands).

The surgery procedure performed on the BF group was similar to that of the VPM group, except for the location of stimulating electrodes implanted at the center of the bilateral BF cortex (AP: −1.8 mm, ML: ±5.0 mm, DV: +2.5 mm. See Supplementary Fig. 1A, red dots) and another two electrodes were implanted on both sides of the MFB area (AP: −3.8 mm, ML: ±1.6 mm, DV: +8.2 mm. See Supplementary Fig. 1A, green dots.) [21]. The electrical stimulation of the MFB area is akin to a "reward" feedback as used in the training procedure, which has been identified in previous studies [3,22].

Following the completion of surgery, each rat was housed individually in regular cages and given 7 days for full recovery.

2.4. Electrical stimulation and behavioral tasks

The electrical stimulation was delivered by a commercial programmable DC voltage electrical stimulator (Master-8, A.M.P.I., Israel) with a series of charge-balanced bipolar square waves, starting with the anode phase.

As is well learned in the late nineteenth century, the charge delivered per unit time is of vital importance in electrical stimulation in brain [23]. When the stimulation is short, the pulse frequency and the charge per pulse should be large; conversely, as stimulation duration increases, required charge strength decreases [24]. To optimize the turning behavior control, we examined 5 key parameters relevant to the charge delivered, including stimulation strength (voltage), pulse frequency, pulse duration, train duration (total stimulation time), and the wave shape of the pulse (Fig. 1A). An initial stimulation paradigm was settled according to the previous study of BF stimulation (Frequency: 50 Hz, pulse duration: 5 ms, train duration: 0.5 s, wave shape: symmetrical square wave). The stimulation strength was determined individually.

After post-surgery recovery period, both VPM and BF groups were first tested their turning behavior without any training