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Precision rodent whisker stimulator with integrated servo-locked control and displacement measurement

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Abstract

We developed a high speed voice coil based whisker stimulator that delivers precise deflections of a single whisker or group of whiskers in a repeatable manner. The device is miniature, quiet, and inexpensive to build. Multiple stimulators fit together for independent stimulation of four or more whiskers. The system can be used with animals under anesthesia as well as awake animals with head-restraint, and does not require trimming the whiskers. The system can deliver 1–2 mm deflections in 2 ms resulting in velocities up to 900 mm/s to attain a wide range of evoked responses. Since auditory artifacts can influence behavioral studies using whisker stimulation, we tested potential effects of auditory noise by recording somatosensory evoked potentials (SEP) with varying auditory click levels, and with/without 80 dBA background white noise. We found that auditory clicks as low as 40 dBA significantly influence the SEP. With background white noise, auditory clicks as low as 50 dBA were still detected in components of the SEP. For behavioral studies where animals must learn to respond to whisker stimulation, these sounds must be minimized. Together, the stimulator and data system can be used for psychometric vigilance tasks, mapping of the barrel cortex and other electrophysiological paradigms.

Keywords

evoked response; voice coil; rodent; vibrissae; auditory

1. Introduction

The highly refined sensory system in rodents is an ideal model for studying sensory encoding and processing since they use their whiskers, or mystacial vibrissae, to gain information about the surrounding environment. Sensory systems in animals are sensitive to experimenter manipulations and the whiskers are easily accessible. The whisker layout on the rat's face is organized in easily identifiable rows and columns that are isomorphic to the arrangement of discrete anatomical units, called “barrels”, in the somatosensory cortex (Diamond et al., 2008; Petersen, 2007; Woolsey and Van der Loos, 1970). Environmental features discriminated by the whisker sensory system include object localization, size and shape of objects, and texture (Ahissar and Knutsen, 2008; Arabzadeh et al., 2004; Knutsen

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and Ahissar, 2009; O'Connor et al., 2010; Prigg et al., 2002). Conditioned learning paradigms using whisker stimulation aid in the understanding of information processing and plasticity in the somatosensory cortex (Diamond et al., 2008; Kublik, 2004; Walker et al., 2011; Wrobel et al., 1998). When using high density electrical electrode arrays, the individual whisker barrels can be mapped in space and independently studied (Benison et al., 2006; Hollenberg et al., 2006; Yeager et al., 2008). Hence, precisely controlled whisker stimulation is critical in studying the mechanisms involved in sensory processing. To ensure a precisely controlled stimulus, the system must be capable of stimulating single or multiple whiskers at precise velocities, amplitudes and time intervals, where these parameters can be varied from stimulus to stimulus. A good whisker stimulator must deflect specific whiskers with significant amplitude in any direction to produce a large evoked response. Moreover, the stimulus must have a negligible sound component if auditory stimuli could interfere with the experiment, a minimized ring out time, and a fast response time.

1.1 Stimulus direction

One of the first aspects of whisker stimulation involves the stimulus direction. Rats use a rostral/caudal whisker motion, called whisking, to gain sensory information about their environment (Berg and Kleinfeld, 2003; Carvell and Simons, 1990), though we often observe whisking in a circular motion. Rostral/caudal mechanical stimulation is used by many investigators, however this direction is difficult to achieve in many scenarios. Dorsal/ventral stimulation can be used (Barth et al., 1993; Di and Barth, 1991; Tsytsarev et al., 2010), though neurons in the somatosensory cortex are differentially responsive to direction of whisker movement and velocities (Andermann and Moore, 2006; Simons, 1985). Additionally, the sequence in which whiskers are stimulated can affect the response due to varying response properties of neurons in the different cortical layers (Haupt et al., 2004; Simons, 1985). Thus, for some studies, stimulation protocols can greatly influence the character of the neural response, while for others, it may not be a critical aspect of the experiment.

1.2 Freely moving animals

Active whisking in freely moving and restrained rats has been used to study tactile discrimination (Arabzadeh et al., 2004; Krupa et al., 2001b; O'Connor et al., 2010; Prigg et al., 2002). One problem with freely moving behavioral tasks is that they can be physically demanding and limit the number of trials per day. Active whisking is a natural behavior but the experimenter is not able to control the deflection amplitude, the duration of the stimulus, or the stimulus interval. Under these conditions, the use of high-speed or infrared-sensitive video cameras allows tracking of whisker kinematics and whisking strategies in freely moving paradigms (Krupa et al., 2001b; O'Connor et al., 2010; Stuttgen et al., 2006). While active whisking can tell us much about sensory processing of complex stimuli, most of our experiments require precisely controlled event correlated responses.

1.3 Stimulation techniques

Different techniques have been developed for experimenter delivered whisker stimulation with the simplest being manual stimulation using a brush or fingers (Hallett et al., 2010; Jablonska et al., 1999; Siucinska and Kossut, 1996). Although it is inexpensive and relatively easy to deliver, manual stimulation has a time resolution on the order of seconds or minutes instead of milliseconds, making it difficult to time-lock the stimulus to an event if desired. Mechanical techniques include the use of air puffs (Gener et al., 2009; Sachdev et al., 2003), solenoid/speakers (Barth et al., 1993; Krupa et al., 2001a; Rousche et al., 1999; Sachdev et al., 2003; Topchiy et al., 2009), magnets (Knott et al., 2002; Melzer et al., 1985; Tsytsarev et al., 2010), piezoelectric devices (Arabzadeh et al., 2004; Quairiaux et al., 2007) and servo-controlled mechanisms (Ewert et al., 2008). Air puffs can be loud, depending on

the control mechanism, and it is difficult to control the intensity of the air stream and account for delays associated with air movement, or the decline in pressure with distance as well as specifying the number of whiskers that are stimulated. Methods using magnets require attaching metal wires or magnetic paint to the whisker which may be uncomfortable for the animal. The animal may spend a great deal of time trying to remove the foreign objects which may cause unwanted stress or even the removal of whiskers. Piezoelectric devices are commonly used due to the fact that the amplitude and direction of stimulation can be varied but they produce a small deflection, are slow, and require high voltages (> 100 V) to drive the device which can cause significant electromagnetic artifacts. There are different types of piezoelectric devices such as bender and bimorph actuators with varying degrees of advantages and disadvantages, including noise level, cost, size, and availability. Speaker/solenoid driven stimulators are loud which is problematic in conditioned learning paradigms where the animal is supposed to respond only to whisker stimulation. We have observed animals that can discriminate between solenoids which sound slightly different. Electrical stimulation has also been used by inserting needles into the skin around the whisker pad and delivering an electric impulse through the whisker pad (Chakrabarti et al., 2008; Cohen and Castro-Alamancos, 2010) which can cause unnecessary pain to the animal and has limits to whisker specificity. In spite of their limitations, all of the above methods to stimulate whiskers have been used successfully in a variety of experiments. Depending on the question to be answered, the best method must be chosen. For the studies performed in our laboratory we require high temporal precision and quiet operation with large deflections, but the direction is less critical.

1.4 Conscious restrained animals

Many studies rely on anesthetized preparations to achieve precise whisker stimulation. Although the whiskers may sit in a position that differs from the awake or alert rat, the animal is not able to whisk during the experiment. Some investigators immobilize the whiskers by injecting lidocaine into the mystacial pad (Ewert et al., 2008) since the animals may produce a flinch response to the sound of the stimulator. Controlled whisker stimulation in the awake rat, especially in conditioned learning paradigms, can be difficult, but is necessary to correlate whisker stimulation to behavior. Since our intentions were to provide stimuli to waking animals which then provided a behavioral response, we hesitated introducing any additional manipulations that may cause variability, such as lidocaine injections, into the recordings. Paradigms involving conscious animals aid in the understanding of experience-induced and associative learning induced plasticity. Differences in the amplitude or latency of evoked potentials due to anesthetic properties and depth can be eliminated in an awake paradigm. Comparisons between studies using different anesthetics or awake versus anesthetized animals may be confounded by electrophysiological and metabolic differences under various anesthetics (Antunes et al., 2003; Berwick et al., 2002; Narimatsu et al., 2002; Rojas et al., 2006).

The present paper describes a miniature stimulator system that is capable of producing precisely controlled whisker stimuli. We designed and implemented a voice-coil based stimulation device which consists of 1–2 mm glass capillary tubing with an integrated drive coil that mobilizes a permanent magnet coupled to a hooked wire that in turn is attached to the whisker. The system includes a servo driver that controls the actuator in a close-loop mode where dynamic feedback regulates the output position and speed. Since the glass capillary tubing is small, several devices can be packed together to stimulate several whiskers independently with precise time intervals and amplitudes, ensuring the stimulus can be systematically repeated. The compact and lightweight design can produce stimulation velocities up to 900 mm/s with minimal sound component (< 45 dBa). Time intervals and amplitudes are controlled by an analog signal through a computer interface.

We used the device to stimulate individual whiskers in the restrained rat while recording somatosensory evoked potentials (SEPs). We recorded responses to stimulation velocities up to 900 mm/s to test the ability of whiskers to respond to high velocity movements. Since auditory cues must be minimized, we tested the effects of auditory noise (clicks) on the evoked potentials recorded over the barrel cortex by stimulating whiskers paired with and without a variety of auditory clicks of varying decibel levels (40, 45, 50, 60 dBa). These conditions were tested with and without 80 dBa white noise to determine if background noise will mask the auditory click that can accompany whisker stimulators (Galvez et al., 2007; Stuttgen et al., 2006; Walker et al., 2011).

2. Materials and Methods

The whisker stimulator was based on voice coil technology and consisted of three main components: (A) computer interface with controller; (B) a servo driver; and (C) the whisker actuator as shown in Figure 1. The computer interface consisted of a digital output that controlled a laboratory built USB port based digital-to-analog converter, which provided a command signal to the servo-driver. The servo-driver compared the command signal to the actuator position and delivered current to the drive coil to set the desired position. The whisker actuator was constructed from a glass pipette with a permanent magnet coupled to a hooked wire into which the whisker was placed. Three coils were mounted around the glass pipette; one drove the actuator and the others kept track of actuator position.

2.1 Assembly

The whisker actuator produced mechanical stimuli and was constructed from four elements, built from glass capillary tubing as separate entities and then integrated into a single unit. All cut pieces were smoothed to insure a precise fit without binding. The piston element (Figure 2A) contained a permanent magnet and formed the unit that deflects the whisker with a piston-like action. The cylinder element (Figure 2B), housed the piston element inside the tubing and served as the structure onto which the servo-control components (Figure 3) could be mounted on the outside of the tubing. The servo-control element (Figure 3) consisted of position detection coils and a drive coil to control the output position of the piston element. The housing element (Figure 4) encased the actuator and was the means of attachment for the unit during use. Additional details and circuit board Gerber files for constructing the device can be obtained by contacting the corresponding author.

2.2 Drive and control electronics

The servo drive controller energized the drive coil in the whisker actuator (Figure 5) and set the position based on a position detection output. This circuit took an input “command signal” from 0 to 2V, which was proportional to the desired position of the whisker actuator. The servo controller compared the input signal with the actual “position signal” of the whisker actuator from the feedback circuit to calculate the “error signal”. Low pass and high pass filters processed the actual position signal to reduce overshoot and ring out in the output. The “error signal” and the “filter output” were added together, providing the “torque signal” to the power amplifier, which in turn energized the drive coil. Two additional coils, including the “position coil” and “reference coil” provided a heterodyne output, proportional to the actual position of the magnet with the position coil.

2.3 Surgical procedures

To measure evoked responses associated with whisker stimulation, 20 female Sprague-Dawley rats (Simonsen Laboratories, Gilroy, California, USA) were implanted with physiological electrodes for a variety of chronic studies. To record evoked potentials from the somatosensory cortex while stimulating individual whiskers, rats were progressively

accustomed to restraint conditions in custom designed wraps by a method previously described (Topchiy et al., 2009; Walker et al., 2011). All procedures were in accordance with the “Guide for the Care and Use of Laboratory Animals” and were approved by the Washington State University Animal Care and Use Committee. Food and water were available *ad libitum*.

Rats were anesthetized with 5% isoflurane for induction and 2.4–2.6% for maintenance. Flunixin (1.1 mg/kg) and penicillin (10,000 ui/kg) were injected prior to the initial incision. A craniotomy was performed over the right hemisphere to chronically implant a high density 64 (8x8) channel electrode array (individual electrode diameter = 250 μ m, spaced 400 μ m apart) over the barrel region of the somatosensory cortex (Hollenberg et al., 2006; Topchiy et al., 2009; Yeager et al., 2008). In addition, frontal and parietal electroencephalographic (EEG) brain activity was measured using stainless steel screw electrodes and two ground screw electrodes were placed 1 mm lateral and 1 mm caudal to the lambda-midline intersection. Two multi-stranded stainless steel wires were threaded subcutaneously to the bottom of the rib cage and bilaterally into the neck muscles to record heart rate (EKG) and muscle activity (EMG), respectively. Animals were allowed one week for recovery before being re-accustomed to restraint conditions.

2.4 Data Collection

Stimulator performance was assessed by recording command signals simultaneously with position output using a custom data acquisition system (Rector and George, 2001). Evoked responses were recorded and EEG was filtered between 0.1 Hz and 3.2 kHz, amplified by a factor of 1000, and sampled at a rate of 20 kHz. Auditory clicks were paired with whisker stimulation to test the effects of noise on the SEP recorded over the barrel cortex. We placed our reference over the cerebellum, in order to record distant signals. With a local somatosensory reference, the auditory component can be reduced, however for behavioral experiments, we needed to assess whether the animals could hear the stimulator because we do not want learning to occur in response to the sound. Auditory stimuli included potential contributions from the stimulator, and additional sound produced by a speaker including 40, 45, 50 and 60 dBa clicks paired with and without 80 dBa continuous white noise to determine if background noise will mask responses to auditory clicks. Once the animals were calm in the recording setup (Figure 6) an individual whisker was stimulated under four conditions of 1) whisker stimulation with no auditory click or background white noise, 2) whisker stimulation with 80 dBa background white noise but no auditory click, 3) whisker stimulation with an auditory click but no white noise, 4) whisker stimulation with an auditory click and 80 dBa background white noise. Averaged evoked potentials were recorded to test if the stimulator alone (not touching any whisker but active) in the presence or absence of continuous white noise produced an auditory response recorded in the barrel cortex. To test if the auditory click not paired with whisker stimulation produced and evoked response recorded over the somatosensory cortex, 60 dBa clicks were presented with and without 80 dBa white noise. 100 averages for each condition were recorded at an interstimulus interval of 1–2 s.

2.5 Data Analysis

Statistical analysis was performed using Friedman’s analysis (SPSS version 16.0, SPSS Inc., Chicago IL, USA) to account for changes in evoked potential peak amplitudes when auditory clicks were paired with whisker stimulation in the presence or absence of background white noise. SEP component measurements were normalized to the 0 dBa recording that occurred on the same day as the sessions with auditory clicks paired with whisker stimulation. Chi squared tests were run to show significance between the 0 dBa recording and the various auditory click levels (40, 45, 50, 60 dBa). A correlation coefficient

(r) was calculated to determine if the change in peak SEP amplitude correlated roughly to the increase in decibel levels. Evoked responses were averaged using Octave, an open source data analysis package (www.octave.org).

3. Results

3.1 Stimulator Performance

The position output of a typical stimulator is shown within the inset of Figure 7. The whisker deflection distance and the stimulator velocity increased with increasing stimulator voltage. Between 1.8 and 2.0 mm maximal deflection was achieved with a maximum velocity of 900 mm/s. The actuator ring out time lasted approximately 20 ms when activated by a 1.4 V pulse of 2 ms of duration. The short ring out time was the result of under damped feedback that continuously corrected the output. The command pulse that initiated a deflection was 2 ms long. Since the magnet motion was slower than the command pulse, the deflection continued beyond the end of the command signal, peaking at 2 ms, with a small damped ring due to insufficient suppression by the feedback control circuit. Ringing could have been further suppressed, but the slow response time of the system could lead to instability and oscillations. Different stimulators performed differently based on how they were constructed, thus the actual velocity distance produced by a given input voltage must be calibrated for each device built. Figure 8 illustrates the SEP amplitude from a typical animal associated with stimulator velocities ranging from 0 to 900 mm/s. The evoked response was proportional to velocity but approached saturation at velocities greater than 700 mm/s.

3.2 Evoked Responses with Auditory Clicks

Auditory clicks at various decibel levels (40, 45, 50, 60 dBa) paired with whisker stimulation resulted in an additional middle latency response (MLR) (3–5 ms) and late P2-N2 (20–35 ms) components observed in the SEP recorded over the barrel cortex (Figure 9). Louder clicks evoked larger early and late components. The control tests with the whisker stimulator active near the animals face, but not stimulating a whisker (top trace of each panel, No Stim 0dB) with and without the presence of 80 dBa white noise did not produce a SEP indicating that the animals could not hear the voice-coil based stimulator. Auditory clicks tested at 60 dBa without whisker stimulation (bottom trace of each panel, No Stim 60 dBa) produced an auditory evoked response with two peaks occurring at 3–10 ms and 20–30 ms recorded from electrodes over the barrel cortex, which matched additional components observed during whisker stimulation with auditory clicks.

3.2.1 Changes in peak amplitudes with auditory clicks—We observed significant changes in peak amplitudes with and without 80 dBa background white noise (Figure 10). While the signal to noise ratio and sample size was too small to obtain group statistical differences in the MLR component, the correlation coefficients ($r = 0.90$ (no white noise), $r = 0.83$ (white noise)) indicate that there is a trend of larger MLR components with louder auditory clicks as expected. A chi squared test resulted in significant changes ($p < 0.001$) for all decibel levels with and without white noise when compared to the 0 dBa condition. The P2-N2 peak also increased significantly ($p < 0.05$, Freidman's ANOVA, $r = 0.82$) without 80 dBa white noise present as the auditory click level increased. Peak amplitudes increased ($p < 0.001$, Chi-square test) with 40, 45, 50 and 60 dBa clicks as well as during the 60 dBa No Stim condition when compared to the 0 dBa condition. The P2-N2 peak changed significantly ($p < 0.05$, Freidman's ANOVA, $r = 0.60$) in the presence of white noise but only showed individual differences ($p < 0.001$, Chi-square test) when comparing the 0 dBa to the 50 dBa, 60 dBa and 60 dBa No Stim conditions, suggesting that the white noise masked the effects of 40 and 45 dBa clicks for this condition.

We observed a significant change in the P1-N1 peak ($p < 0.05$, Friedman's ANOVA) when whisker stimulation was paired with auditory clicks in the absence of white noise. Further analyses identified that the N1 component also changed significantly under the same condition ($p < 0.05$), which suggests that the alteration of the N1 was responsible for the changes observed in the P1-N1 peak. The lowest detectable level of our sound equipment is 40 dBa thus, we could not quantify sound produced lower than 40 dBa.

4. Discussion

We developed a stimulator that can achieve up to 900 mm/s deflection velocity with 1.8 mm total deflection. For SEP recordings, our single trial stimuli of approximately 1 mm produced robust responses. Indeed, since the whisker follicle/stretch receptor responds in proportion to velocity, the higher velocities are more interesting. The data showed that deflection velocities at this speed approach saturation of the SEP and therefore, a stimulator faster than 700 mm/s may not necessary to achieve larger amplitudes. Most other stimulators are limited to 100–400 mm/s which correspond to distances between 250 and 700 μm while our studies show that whiskers can respond to over 600 mm/s velocity. Our focus has been on larger whisker excursions to generate robust ERPs. Certainly smaller excursions are possible with the system as described using lower amplitude control voltage with overall better performance. With smaller deflection amplitudes, the compensation circuitry could be tuned better with less chance for oscillation. Advantages of our system include the ability to precisely control the deflection amplitude, stimulus duration and stimulus interval with minimal noise. It is not necessary to trim/cut the primary or surrounding whiskers providing a more natural setting for experiments. Trimming the whiskers may induce plasticity and change the size of the receptive field for trimmed whiskers (Armstrong-James et al., 1994; Diamond et al., 1993; Diamond et al., 1994). The stimulator is relatively quiet and does not produce additional components when implementing studies involving electrophysiology or add an auditory stimulus with conditioned learning paradigms. Whisker stimulation can be time locked to an event and is precise to a timescale of milliseconds. The system can accommodate four or more separate stimulators that can stimulate whiskers either together or in separate temporal sequences. Whisker stimulation can be performed on awake, head restrained animals as well as anesthetized animals. The system is relatively simple and inexpensive to construct.

Many stimulators produce a sound greater than 50 dBa. Our data showed that an auditory stimulus produces additional components when recording SEPs. Most important, the use of continuous 80 dBa background white noise does not mask auditory components with clicks greater than 50 dBa. More data is needed to further explore the effects of auditory stimuli on SEPs recorded over the barrel cortex since the timing of the two stimuli could play a role in the variability due to the different latencies between both sensory systems. Auditory stimuli should be avoided when implementing behavioral studies where the animal is supposed to respond to whisker stimulation because we observe that animals can respond to the sound and not just the whisker stimulation. Continuous background white noise is a useful means to mask auditory stimuli that may be associated with many stimulators (Galvez et al., 2007; Stuttgen et al., 2006; Walker et al., 2011) as long as the auditory component is less than 50 dBa.

The described stimulator is useful for a variety of studies but has its limitations. The current design has an optimal deflection in the dorsal/ventral direction. With some modification of the device stimulation in the rostral/caudal direction is possible, which is the natural direction of whisker movement. Additionally, the current servo-control circuit was too slow to adequately track a 2 ms command signal, as can be seen in Figure 7, thus some modifications are needed to improve the stimulus velocity and subsequent ringing. For

example, a higher drive voltage would enable more current, and thus more force on the magnet. Also, a power amplifier with a higher bandwidth would enable faster response times. However since we achieved high velocities with the current device, faster velocities may not be required. The most important advantage of faster response times would minimize the ring out. The extended ring-out of the stimulator results from over compensation of the servo-control electronics, and is most noticeable when deflections are large (eg. > 1 mm). For single pulse stimuli as usually performed in our experiments, the ring out is of less concern. However for oscillatory and other temporal patterned stimuli, further work must be done to improve the ring-out artifact. For sinusoidal stimuli (Ewert et al., 2008) the feedback control circuitry could be optimized for specific frequencies, especially for smaller deflection amplitudes. Future development of the stimulator also requires further miniaturization to enable more devices packed in closer proximity.

Research Highlights

- We developed a high speed voice coil based whisker stimulator to deliver precise deflections of a single or group of whiskers.
- The system can be used with animals under anesthesia as well as awake animals with head-restraint.
- The stimulator can deliver 1–2 mm deflections in 2 ms resulting in velocities up to 900 mm/s.
- Since auditory artifacts can influence behavioral studies using whisker stimulation, we paired whisker stimulation with auditory clicks (40, 45, 50 and 60 dBA) and recorded somatosensory evoked potentials (SEP) in the presence and absence of continuous 80 dBA background white noise.

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Figure 1.

A block diagram illustrates the major components of the voice-coil based whisker stimulator system. A digital to analog converter and controller box (A) connected to the computer via a USB cable provided command signals. The servo driver circuit (B) energized a solenoid coil, maintained a constant position based on feedback, and provided position output to monitor actual position. A hooked wire (C) delivered the whisker stimulus.

Figure 2.

The stimulator assembly began with several pieces of glass capillary tubing and a permanent magnet. The piston element (A) comprised of an axially magnetized neodymium rare earth cylinder (a) (1 mm×4 mm) (Gaussboys Model #C0104, Portland, OR) which was epoxied within an 18 mm length of glass capillary tubing (b) (1.17 mm ID×1.5 mm OD), with the magnet's north pole flush to the top edge of the glass tubing. To assist in assembly, a 10 mm length of glass tubing (c) (0.58 mm ID×1.0 mm OD, colored gray in illustration) was inserted into the 18 mm glass capillary (a), making contact with the south pole of the magnet. Finally, an 18 mm length of 19 gauge hypodermic tubing (d) (19GA-RW 0.69 mm ID×1.07 mm OD; Small Parts, Miramar, FL) was epoxied within the piston, leaving a 14

mm tail extended beyond the capillary end. The hypodermic tubing was vertically aligned and centered within the glass capillary to insure smooth movement. Glass elements are outlined with a gray line to assist in visualizing the components.

The cylinder element (B) consisted of a 40 mm length of glass capillary tubing (e) (1.6 mm ID×2.15 mm OD) and a 4 mm length of 16 gauge hypodermic tubing (f) (16 GA-RW 1.194 mm ID×1.65 mm OD; Small Parts) that served as an internal stop. The latter was epoxied within the 40 mm glass tubing, ensuring the edges were flush and the stop vertically aligned within the tube. The piston element (A) was inserted into the 40 mm tubing of the cylinder element (B) coming to rest against the internal stop, as illustrated in picture C. The element must move up and down without binding and spin freely within the 40 mm tubing to optimize the motion and reduce noise during actuation.

After the piston element (A) was inserted into the cylinder element (B), a 4 mm length of 17 gauge hypodermic tubing (17 GA-TW 1.21 mm ID×1.47 mm OD; Small Parts) (g), served as an external stop, and was soldered onto the tail component (d), leaving a gap of 3.5 mm between the fully extended tail piece and the bottom of the 40 mm glass tubing, giving the magnet a displacement range of 3.5 mm when actuated.

A 1 mm length of 23 gauge hypodermic tubing (h) (23 GA-RW 0.33 mm ID×0.635 mm OD; Small Parts) was soldered at the end onto a 71 mm length of music wire (i) (0.308 mm DIA, #SMW-012-36; Small Parts) that had a loop bent on the other end. This component was inserted into the tail component (d) during the last step in assembly, insuring that the wire was aligned with the brass tube of the housing element (Figure 4). The ruler marking on the left side of the figure indicates millimeter units.

Figure 3.

The servo-control element of the actuator consisted of intramedic polyethylene tubing (PE-280; Clay-Adams-Becton Dickinson, Parsippany, NJ) cut into three 4 mm lengths (a, b, d) and one 1 mm length (c) that, when positioned on the 40 mm glass tubing (cylinder element) (Figure 2B), delineated the placement for the reference (e), drive (f) and read coils (g). The top edge of the 1 mm length of PE tubing (c) was epoxied flush with the north end of the magnet in its fully extended, 'down' position (a 3.5 mm magnet displacement), and the top edge of one 4 mm length of PE tubing (d) was epoxied 5 mm below the the north end of the magnet; this 4 mm space marked the placement for the read coil (g). The bottom edges of the remaining 2 pieces (a, b) were epoxied at intervals 4 mm and 12 mm above the north

pole of the extended magnet, delineating placement of the reference coil (e) and drive coil (f). Excess epoxy was removed with a razor blade.

The three coils were wound using 42 gauge enameled magnet wire at 50 turns/4 mm/layer. The reference and read coils consisted of two layers (100 turns), the drive coil of 6 layers (300 turns), each held in place with a drop of super glue. A 70 mm length of wire was left at the beginning and end of each coil, and the wires were color-coded for identification for soldering to the circuit board. For coil protection and to reduce vibration, one length of shrink tubing at 9 mm (h) and one at 12 mm (i) were split and placed over the reference and read coils, respectively. A drop of super-glue held these baffles in place. Thermal compound was spread over the drive coil to aid in heat dissipation. The ruler marking on the left side of the figure indicates millimeter units.

Figure 4.

The housing element consisted of a 50 mm length of brass tubing (a) (3.55 mm ID×4.76 mm OD wall, #TTRB-05-36-03; Small Parts, Miramar, FL) notched at the top for attachment of the position detection circuit board (b, schematic in Figure 5). The cylinder, piston and servo-control structure (Figure 3) was threaded through the bottom of the brass tube, copper wires first, until only the bottom tip of the actuator extended out the bottom of the brass tube, and the color-coded coil wires were soldered to the circuit board. Two miniature coaxial connector cables, a twin coax (c) and a single coax (d) were soldered to the read and drive coils, respectively, on the circuit board, which led to the servo control circuit (Figure 5).

Finally, the music wire (Figure 2(i)) was soldered into the exposed actuator tip, insuring that the wire was vertically aligned within the brass tube. The brass tube was snapped into a machined delrin holder (e) that attached the entire unit onto an aluminum frame. The ruler marking on the left side of the figure indicates millimeter units.

Figure 5.

The servo driver control electronics consisted of a “COMMAND SIGNAL” input which was subtracted from the “POSITION SIGNAL” to obtain an “ERROR SIGNAL”. The position signal was also filtered with Low and High frequency filters to reduce overshoot and oscillations in the feed back. The sum of the “ERROR SIGNAL” and the filtered signals were combined to produce a “TORQUE SIGNAL” which was amplified by the LM675 power amplifier to energize the drive coil. Feed back from the position coil was then used to produce the “POSITION SIGNAL”. For simplicity, decoupling capacitors have been removed from this circuit diagram. V+ and V- are ± 40 V, and VDD and VSS are ± 5 V. To protect the drive coil from excessive current, a current monitor can also be implemented across the 0.01 ohm resistor connected to the drive coil.

Figure 6.

Pictures of the experimental setup show a typical recording with (A) two servo control circuits mounted on an aluminum plate providing current to the drive and position coils located inside the brass tubing which drive the stimulators. Slots were cut in the metal plate to allow easy movement of the stimulators to reach the desired whisker. The rat's body was restrained in a custom designed wrap (see text) and the head was further restrained using earbars which are inserted into a hollow square tube located on the back of the head stage. (B) Amplifier boards were connected to the head stage to record the electrophysiology during whisker stimulation. The whiskers were stimulated by placing them inside a hook at the end of the actuator. A sipper tube was placed in front of the rat's face to record licks in response to whisker stimulation. A light located above the sipper tube can be used to signal fluid availability during conditioned learning paradigms.

Figure 7.

Deflection distance (triangles) and velocity (circles) of the whisker stimulator increased in proportion to input voltage. The inset graph shows the position output of a typical stimulator at 1.4 V given a 2 ms long command signal. The inset graph demonstrates the slow response profile of the stimulator since the position output does not closely follow the command signal. Nevertheless, the velocity as measured by the position output slope can be used to determine stimulus rate. Also, note a small amount of ring-out in the position after the command signal (see text).

Figure 8.

The somatosensory evoked potential (SEP) (thick gray line) recorded from a typical animal during whisker stimulation shows that the SEP was proportional to the velocity of the actuator as shown in panel (A). The thin black line is the position output from the actuator. The vertical black line represents the stimulus time. Gray numbers indicate velocity and black numbers indicate total deflection for each trace. The SEP amplitude increased with increasing stimulator velocity as shown in panel (B). The SEP amplitude approached saturation at velocities greater than 700 mm/s.

Figure 9.

Examples from two rats illustrate somatosensory evoked potentials (SEP) recorded during whisker stimulation using a stimulus voltage of 1 V. The top two panels show evoked potentials during various dBa levels (0, 40, 45, 50 and 60) without white noise. The bottom two panels show evoked potentials with white noise present. The SEP peaks are labeled in the upper left panel (MLR = middle latency response). The first trace in each panel shows that there was no response observed when the stimulator was active but not stimulating the whisker with and without 80 dBa background white noise. The addition of a 60 dBa click under these conditions (bottom trace in each panel) resulted in the appearance of the MLR and P2-N2 components with and without 80 dBa white noise. These additional auditory response components appeared when auditory clicks ≥ 50 dBa were paired with whisker stimulation even in the presence of 80 dBa background white noise.

Figure 10.

Mean (+ S.E.M.) peak SEP amplitude changes with varying decibel levels in the presence or absence of 80 dBa background white noise with a stimulator voltage of 1 V. All sessions with whisker stimulation paired with auditory clicks (40, 45, 50, 60 dBa) were normalized to the 0 dBa condition for this analysis. The correlation coefficients for the MLR component ($r = 0.90$ (no white noise), $r = 0.83$ (white noise)) indicated a trend for increased peak amplitudes with increasing decibel levels. All MLR peak amplitudes with the various decibel levels with and without white noise showed significant increases when compared to the 0 dBa condition using a chi squared test (& = $p < 0.001$). The P2-N2 peak changed significantly (* = $p < 0.05$, Freidman's ANOVA) with and without the presence of 80 dBa

background white noise. All P2-N2 peak amplitudes increased with auditory clicks when compared to the 0 dBa condition with no white noise present ($p < 0.001$) but only the 50, 60 dBa and the 60 dBa No Stim conditions were significant when white noise was present ($p < 0.001$). The P1-N1 peak significantly changed ($p < 0.05$, Friedman's ANOVA) when auditory stimuli were paired with whisker stimulation in the absence of white noise as seen in the middle right panel. The N1 component of this peak changed significantly ($p < 0.05$, Friedman's ANOVA) suggesting that the alteration of the N1 was responsible for the changes observed in the P1-N1 peak.