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Contributions of MT and LIP to Perceptual Decision-Making: Systematic Comparison of Different Manipulation Methods

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ABSTRACT: Decision-making involves multiple neural processes across many different brain areas. In perceptual decision-making, the middle temporal area (MT) and lateral intraparietal area (LIP) are important. Brain activity needs to be manipulated to understand the causal role of a brain area. Past studies have used varied task designs with only one method of manipulation applied to a single brain area, making it extremely difficult to pinpoint the precise contribution of a given area. We performed an analysis, examining twelve studies involving different types of neural manipulation within the same motion discrimination task. We examined four different types of neural manipulation: microstimulation, lesions, reversible inactivation, and optogenetics. We found that the results of the reviewed studies are most compatible with the following. The effects of manipulations are much larger for MT than for LIP. This suggests that MT provides the primary input for decision-making, whereas LIP refines the resulting saccadic eye movement to allow saccades to a specific visual field region. We also found that microstimulation is the most robust mode of manipulation, perhaps because it provides inputs to neurons that carry the most informative signals. This paper highlights the importance of adopting similar experimental designs to understand causal roles.

KEYWORDS: Behavioral and Social Sciences; Neuroscience; Perceptual Decision-Making; Neural Manipulation; Motion Discrimination.

Introduction

Although the brain can be divided into many different regions using various methods, determining the unique function of each region remains highly challenging. Among all brain systems in mammals, the visual cortex is perhaps the most thoroughly investigated. In primates, the visual cortex has been separated into more than 30 distinct areas based on their anatomical and functional properties.[1] A general method for characterizing the causal role of a specific brain region involves altering its activity and then measuring the resultant effects on behavior.[2] These alterations can result in behavioral changes; thus, comparing the results can reveal certain things.

This paper examines the effect of altering two brain regions involved in decision-making using the following manipulation methods: electrical microstimulation, lesions, drug-infused inactivation, and optogenetic inactivation. Regarding the behavioral paradigm, we focus on visual perceptual decision-making using a motion discrimination task (see General Task Design) and compare the contributions of areas MT and LIP in this task. We used MT and LIP because they have been implicated in perceptual decision-making, and many studies use the same experimental paradigm (REFs).

First, these four methods of altering brain activity are reviewed, then their effects on decision-making are compared.

Electrical Microstimulation:

Electrical microstimulation is an invasive method of activating neurons by inserting the tips of microelectrodes into the cortex so that the electrodes are close to the target neurons. This allows the stimulation of very low tissue volumes at very low amplitudes of current (typically 10μA).[3] It allows us to stimulate a very small and precise area of target neurons. Neuroscience often uses microstimulation to determine a causal relationship between cortical activity and brain function.[1] In microstimulation, the current is provided for a very short period. Some studies provide current information from the onset of the random dot motion until the choice is made, often less than 1 second.[4]

Permanent Inactivation by Lesioning:

If we test the performance on a specific task, both with and without a specific brain region, we can determine the extent to which the brain region contributes to the specific function of the task. This is the principle that lesions rely on. Lesions or ablations are the permanent removal or destruction of nervous tissue. They have been widely explored in the past to study brain function. There are two main types of lesions: physical and chemical. Physical lesions have several disadvantages, with the most significant being the undercutting of fibers underlying the cortex. Chemical lesions most often include the injection of neurotoxins or acids (ibotenic or kainic). It is very difficult to ensure that lesions only affect the intended area, as some neighboring regions could be damaged too, or some parts of the intended area could be spared. Since lesions are often irreversible, the temporal length is the entire duration of the study from the lesion's onset.[5] Over long periods after lesions, other brain areas may start to compensate. Some studies vary the time from the lesion at which the experiment is conducted.[6]

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Reversible Pharmacological inactivation:

Reversible inactivation is often produced by intracerebral injection of neural-blocking drugs (in the pharmacological sense) to study the function of specific structures in the brain.[7] Behavioral defects immediately after the inactivation can elucidate the contribution of a given brain area to that function. These drugs are most often injected through micropipettes or hypodermic cannula. This is especially useful if the target is small and the experimenter needs to prevent damage to overlying structures. This may not be easy to control, though. However, there is often difficulty in matching the size and shape of the inactivated region to the target, so ways to determine the spread of inactivating agents must be developed.[8] Muscimol, a GABA-A agonist, is used frequently in inactivation studies.[9] The effects of muscimol persist for 12-24 hours.[7]

Optogenetics:

Optogenetics is a neuromodulation approach that controls neural activity using light. Target neurons are genetically modified to express light-sensitive proteins. After this modification, the neurons can be stimulated or silenced with millisecond temporal accuracy in the presence of light.[10] In this paper, we will only look at the silencing of such modified neurons. Recent advances in optogenetic control show a single-cell spatial resolution.[11] The temporal resolution of optogenetic inactivation is in the order of milliseconds.[12] However, this temporal profile is limited by rebound activity. When the light is removed, the spike rate (known as 'rebound activity') rises above baseline and gradually returns to baseline over hundreds of milliseconds. This rebound activity depends on the light duration and intensity.[13]

Discussion

This paper compares the above four manipulation methods using existing literature. We compare papers from a specific motion discrimination task to test the effect on visual perceptual decision-making. Twelve papers were used, all with the same random dot motion task (described below), so the results can be directly compared. The bias and change in slope of the psychometric function, along with the change in reaction time, were compared. The figures were estimated to determine the median in some experiments where exact statistics were not presented. While the experimental design varied slightly in some experiments, the general experimental design is explained below.

General Task Design:

Monkeys were trained to perform the motion discrimination task (Figure 1). The monkeys had to indicate the net direction of motion in a random dot display by making a saccadic eye movement towards one of the choice targets. A random fraction of dots was displaced in apparent motion, called percent coherence. The remaining dots were moving randomly. Positive percent coherence indicates net movement in the preferred direction, and negative indicates in the null direction. In some studies, monkeys received a reward (a drop of water or juice) upon choosing the target towards which there was a net movement of dots. Response time is defined as the interval between the onset of the random dot motion and the time when the monkey makes the saccadic eye movement.

There are several ethical concerns for this type of task, particularly regarding the invasive procedures. The manipulation methods, such as microstimulation and lesioning, require the insertion of electrodes into the brain or the intentional destruction of specific brain regions. Furthermore, implanting head-holding devices and eye position coils could also require invasive surgery. This can cause significant pain and long-term harm to the test subjects. Moreover, the use of rewards such as water and juice is also ethically concerning if the monkeys are deprived of these rewards to motivate performance.

Monkey Preparation:

One or more rhesus monkeys (Macaca mulatta) were used in each study. Details of surgical, training, and recording procedures have been previously published.[14] The monkeys were implanted with a head-holding device and a search coil for eye position. The monkeys were pointed towards a computer monitor on which the visual stimulus was presented. For the spatial and temporal resolution of the manipulation method, refer to specific subsections in the introduction.

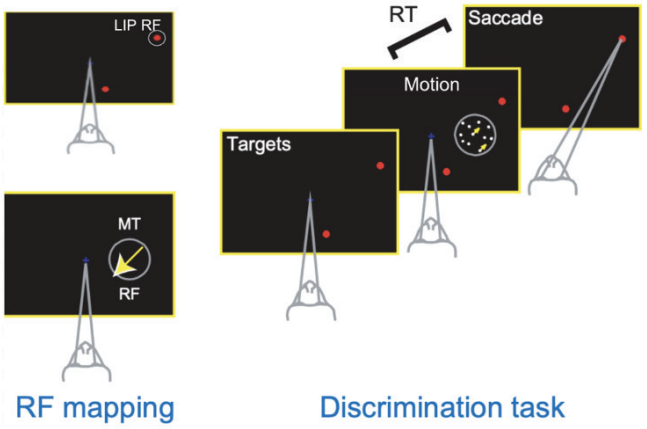

Figure 1: Task Design - monkeys chose the direction of motion based on the random dot motion display. The direction was either in the preferred or the null direction of neurons whose activity was altered. The monkey made a saccadic eye movement to one of the two targets (marked in red). The location of targets can vary in different experiments, but this doesn't affect the results. Note the difference in the area of the receptive field of MT and LIP neurons. RF represents the receptive field. RT represents response time.

Summary of Individual Studies' Results:

In this section, the results of each study used for the analysis are summarized and tabulated. The tables below show the change in the slope of the psychometric function, the bias of the psychometric function, and the change in reaction time. This helps determine the effect of manipulating the specific area.

Microstimulation Studies:

Study 1. a (Table 1) microstimulated specific neurons in MT to test its effect on the bias of the psychometric function and the change in reaction time. In this study, a liquid reward was provided for a choice of direction for the net

movement of dots. Unlike the typical 10μA of current, 5μA was used in these experiments. While the authors didn't measure the change in slope of the psychometric function, it has been determined visually to be insignificant. Based on the bias monkeys' psychometric functions, 1. a found that microstimulation added 13.7±1.3% and 27.2±1.2% motion coherence in the preferred direction of the stimulated neurons for monkeys B and N, respectively. At times, despite the microstimulation, monkeys still chose the null direction when motion coherence was highly negative. They also noticed changes in RT when microstimulation took place versus when it didn't. When the monkeys chose the preferred direction of stimulated neurons, RT was lower on average (Monkey B: 39±8 ms; Monkey N: 37±5 ms). When the monkeys chose the null direction of neurons stimulated, RT was higher on average (Monkey B: 44±7 ms; Monkey N: 58±4 ms). The study also classified microstimulation as similar to adding motion coherence in the preferred direction of stimulated neurons to reach the same RT threshold (Monkey B: 11.6±1.4%; Monkey N: 17.4±1.1%). It is noticeable that the addition of motion coherence in the bias of the psychometric function was more than the apparent addition of motion coherence in RT for both monkeys.

Study 1. b (Table 1) tested the change in psychometric function (slope and bias) due to microstimulation. This study used three monkeys and averaged results. The experimenters also provided a liquid reward when the correct choice was made. The authors found that microstimulation statistically affected the slope in 12 out of 65 experiments ($p<0.05$). In 10/12 of these experiments, microstimulation flattened the slope, adding noise to the visual stimulus and reducing sensitivity. In the case of the bias, microstimulation caused a statistically significant bias in 64% of experiments conducted (89/139). In 86 of these 89 experiments (97%), microstimulation caused a shift of the psychometric function towards the preferred direction of the neurons stimulated. As determined from Figure 6B in study 1. b, the median shift fell in the range of 6-8%, adding motion coherence towards the preferred direction of the neurons stimulated.

Study 1. c (Table 1) is an older study that measured the effect of microstimulation on only the bias of the psychometric function for 3 separate monkeys. In this study, out of the 62 total microstimulation trials, 30 caused a significant effect (48.4%). In 29/30 of these significant experiments, microstimulation shifted the function leftwards, indicating increased preferred directions. The median shift leftwards was in the range of 2-4% motion coherence, as determined from Figure 2 in Study 1. c. However, the authors observed the monkeys as biased towards the null direction, so the actual shift caused by microstimulation was probably greater.

Study 1.d (Table 1) explores how specific parameters of microstimulation (frequency and amplitude of current) impact the monkey's performance in the random dot motion task. Other microstimulation experiments usually use a current amplitude of 10μA and a frequency of 200 Hz. For these regular values, the slope change of the psychometric function was -0.001 PPD/% Corr., which is a small but significant change. Also, this slope change is consistent with study 1. b since both show that microstimulation flattens the slope. Moreover, with these regular thresholds of current amplitude and frequency, the mean shift caused by microstimulation was 13% motion coherence towards the preferred direction of the stimulated neurons. This experiment also varied current amplitude (5, 10, 20, 40, 80μA) and frequency (25, 50, 100, 200, 500 Hz). The study found that the slope strictly decreased as the current frequency increased. An increase in current frequency also saw an increase in the bias of the psychometric function and the equivalent visual stimulus (higher current frequency meant more bias towards the preferred choice). However, such a simple trend was not observed for changes in current amplitude. As the current amplitude increased, the psychometric function's slope strictly decreased (similar to changes in frequency), but the bias did not always increase (there was a lot more noise). This study did not measure RT.

Table 1: Effect of microstimulation in MT on slope and bias of psychometric function and RT.

<table>
<tr><th>Study</th><th>Change in the slope of the psychometric function</th><th>Bias of psychometric function</th><th>Change in reaction time</th></tr>
<tr><td>1.a[4]</td><td>Almost minimal (determined visually from psychometric function)</td><td><table><tr><td>Mnk. B</td><td>Mnk. N</td></tr><tr><td>13.7±1.3%</td><td>27.2+1.2%</td></tr></table>Increase in motion coherence towards the direction of the neurons which are stimulated.</td><td><table><tr><td></td><td>Mnk. B</td><td>Mnk. N</td></tr><tr><td>Pref direction choices</td><td>39±8ms</td><td>37±5 ms</td></tr><tr><td>Null direction choices</td><td>44±7 ms</td><td>58±4 ms</td></tr><tr><td>Motion coherence in pref.</td><td>11.6±1.4%</td><td>17.4±1.1%</td></tr></table></td></tr>
<tr><td>1.b[15]</td><td>In 12 out of the 65 experiments conducted, microstimulation had a significant effect on slope, and in 10 of these 12, microstimulation flattened the slope.</td><td>Microstimulation significantly affected 64% (89/139) of the experiments, with 86 (97%) causing increased preferred decisions. A median bias was determined in the 6- 8% motion coherence towards the preferred direction.</td><td>Not Applicable (NA) because the study doesn't measure it</td></tr>
<tr><td>1.c[16]</td><td>NA</td><td>30 experiments out of 62 had statistically significant effects of microstimulation with 29/30 being leftward, causing an increase in preferred direction.
The median shift was in the range of 2-4% motion coherence.</td><td>NA</td></tr>
<tr><td>1.d[17]</td><td>The mean slope change for the standard experiment (current amplitude 10μA and frequency 200 Hz) was -0.001 PPD/% Corr., which is small but significant.</td><td>The mean equivalent visual stimulus in the regular experiment was approximately 13% motion coherence.</td><td>NA</td></tr>
</table>

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Study 2 (Table 2) focused on the effect of microstimulation of area MST. The authors found that microstimulation in MST changed the slope on average by -0.006 PPD/% Correct, a small but significant change corresponding to the slope becoming flatter. It is noticeable that microstimulation in MST had a similar effect as microstimulation in MT (studies 1. b and 1.d), where the slope became flatter. The study also showed that microstimulation in MST biased the psychometric function leftwards, increasing motion coherence towards the preferred direction by a median value of 4-6% motion coherence. The direction of added motion coherence is the same when MST was stimulated versus when MT was stimulated. Microstimulation was statistically significant in 30 out of 46 trials (65%). Of these 30 trials, 29 (97%) added coherent motion in the preferred direction. The percentages of statistically significant experiments are similar to the results of studies 1. b and 1. c, where MT was stimulated.

Table 2: Effect of microstimulation in MST on psychometric function and RT.

Study	Change in the slope of the psychometric function	Bias of psychometric function	Change in reaction time
2[18]	A mean slope change of -0.006 PPD/% Correct is a small but significant difference from 0, corresponding to flatter psychometric functions.	Increase motion coherence towards the preferred direction by a 4-6% median value. Out of the 46 trials conducted, microstimulation significantly affected the monkey's perception in 30 trials. Of these 30 trials, 29 added coherent motion toward the preferred direction.	NA

Study 3 (Table 3) focused on the microstimulation of LIP to see its effect on the bias of the psychometric function and RT. The study used 2 monkeys. For Monkey B, microstimulation of LIP biased the psychometric function by adding 2.1% coherent motion in the preferred direction. In monkey S, microstimulation added 1% coherent motion in the preferred direction. It is noticeable that microstimulation in LIP biased the psychometric function less than MST (Table 2) and MT (Table 1). The average bias was in the same preferred direction for all 3 areas. When looking at choices made towards the preferred direction, microstimulation reduced reaction time by equivalent to adding coherent motion in the preferred direction (4.3% for monkey B and 1.7% for monkey S). For choices made towards the null direction, microstimulation increased the reaction time similarly, adding 7.7% coherent motion for monkey B and 1.6% for monkey towards the preferred direction. Here, we see that the LIP contributes more to the reaction time than the bias of the psychometric function since stimulating LIP changed the reaction time significantly more than the bias of the psychometric function. However, microstimulation in MT still had a greater change in reaction time (study 1. a) than in LIP.

Table 3: Effect of microstimulation in LIP on psychometric function and RT.

Study	Change in the slope of the psychometric function	Bias of psychometric function	Change in Reaction time
3[19]	Almost none, as determined visually from psychometric functions	For monkey B, LIP microstimulation biased decisions favor the preferred choice by an amount equivalent to adding 2.1% coherent motion. In Monkey S, microstimulation had the effect of adding 1.0% of motion coherence	Decrease in preferred direction choice times: For monkey B, stimulation reduced preferred direction reaction times by equivalent to adding 4.3% coherent motion toward the preferred direction. The effects for monkey S were equivalent to adding 1.7% coherence. Increase in null direction choice times: In monkey B, 7.7% coherent motion was added toward the preferred direction. In monkey S, the changes mimicked the addition of 1.6% coherence toward the preferred direction.

Permanent Lesion Studies:

Study 4 (Table 4) permanently lesioned both MT and MST and analyzed the effect on the bias of the psychometric function. This study tested the monkeys' visual perceptual decision-making twice, once soon after the lesion onset (5 weeks for monkey 1; 1 week for monkey 2) and once a long time after the lesion (12-24 months for both monkeys). During the first testing period, the study found the loss in motion signal threshold to be 3.2 lesion/intact for monkey 1 and 5 lesion/impact for monkey 2. When they tested the threshold 12-24 months after the lesion, the loss of motion signal threshold had decreased by 50% for each monkey (refer to table values). This further supports the claim made in the introduction that over a long period, other areas start to compensate for the loss in a particular area.

Moreover, the final effects (12-24 months after lesion) were also calculated as a change in motion signal to reach the same threshold. After the lesion was made, the original motion signal threshold for the monkeys (7.5±0.5% for monkey 1; 10±2% for monkey 2) increased significantly (10±1.5% for monkey 1; 23±1.2% for monkey 2). This meant that Monkey 1 needed about 3% more motion coherence, and Monkey 2 needed approximately 13% more motion coherence to reach the same threshold.

Table 4: Effect of lesions in both MT and MST on bias of psychometric function.

Study	Change in slope	Change in bias	Change in RT
4[20]	NA	**Permanent effects (12-24 months after lesion) –** Monkey 1- Motion signal had to be increased by 3% coherence to get the same threshold. Monkey 2 - Motion signal had to be increased by about 13% coherence to get the same threshold. **Temporary effects measured in lesion/intact:** Early in training: Loss in Monkey 1 ≈ 3.2; Loss in Monkey 2 ≈ 5 After behavioral testing: Loss in Monkey 1≈ 1.5; Loss in Monkey 2 ≈ 2.3	NA

Study 5 (Table 5) permanently inactivated MT in two monkeys to test how that changes the bias of the psychometric function. The study first measured the threshold of the psycho-

metric function before the injection (about 20±3% for monkey Y and 19±4% for monkey C). Then, they permanently inactivated a specific part of MT using muscimol injections. They tested the monkeys' visual perceptual decision-making various times after the inactivation. Forty-five minutes after the inactivation, the average increase in motion coherence to meet the same threshold was 31±22% (35±26% for monkey Y; 22±9% for monkey C). The threshold values further increased until 18 hours after the injection, with an average of 65±13% added motion coherence (monkey Y: 70±12%, monkey C: 57±11%). They tested the decision-making two days after the injection and found that all bias had disappeared. This is consistent with our earlier results, which show that other areas can compensate for a lost area. Note that this study tests both grating motion and random dot motion tasks, but we are only considering the results of the random dot motion since this is the same task for other experiments. This study found that MT plays a strong causal role in motion discrimination for random dot motion, consistent with other studies (Tables 1 and 4).

Table 5: Effect of lesions in only MT on the bias of psychometric function.

Study	Change in slope	Change in bias	Change in RT
5[6]	NA	Thresholds before injection: *Pre injection -* Monkey Y ≈ 20±3% Monkey C ≈ 19±4% Threshold after injection *+45 min –* Avg = 31±22% Monkey Y = 35±26% Monkey C = 22±9% *+18h -* Avg = 65±13% Monkey Y = 70±12% Monkey C = 57±11% *+2d -* Monkey Y ≈ 0% Monkey C ≈ -2±7%	NA

Reversible pharmacological inactivation studies:

Study 6 (Table 6) reversibly inactivated specific regions of MT using muscimol injections. The motion stimulus was placed in the region retinotopically matched to the inactivated MT neurons. Testing 2 monkeys, the study found a 68.5% reduction from baseline in the slope. The slope became statistically significant (p=0.002) flatter when inactivation occurred. The authors also moved the random dot motion outside the inactivated area and noticed that performance was restored, confirming that the effects were not due to general changes. The bias seen in the psychometric function due to the inactivation was almost negligible. However, it is important to note this may be prone to error, given that it was determined visually (the paper did not provide exact data).

Table 6: Effect of reversible pharmacological inactivation in MT on psychometric function.

Study	Change in slope	Change in bias	Change in RT
6[21]	Significant effect on sensitivity or slope - with a flatter slope and a 68.5% reduction from baseline.	Insignificant bias.	NA

Study 7. a (Table 7) reversibly inactivated specific regions of LIP using muscimol injections. In these experiments, one of the two targets was placed in the retinotopically matched region to the inactivated LIP neurons. The authors did not find statistically significant changes in the bias of the psychometric function or the slope change. There was a 3.7% reduction from the sloping baseline and a -0.4% motion coherence shift of psychometric function. While the change in slope and bias were in the same direction as MT inactivation, they were significantly smaller when LIP was inactivated.

Study 7. b (Table 7) reversibly inactivates specific regions of LIP using muscimol, similar to study 7. a. The findings of this study are the same as Study 7. a when considering the change in slope. Inactivation makes the slope slightly flatter, which is inconsistent among many trials and, therefore, insignificant. When looking at the bias of the psychometric function, this study produces a bias against controversial choices (opposite of the bias created in 7. a). This is not surprising because of the accompanying compensation from other neurons and the minimal bias magnitude. This study also finds that this psychometric function bias dissipates over many trials, which supports the idea that compensation by unaffected circuits comes into play.

Table 7: Effect of reversible pharmacological inactivation in LIP on psychometric function.

Study	Change in slope	Change in bias	Change in RT
7.a[21]	Statistically indistinguishable differences in the slope. (3.7% reduction from baseline)	Statistically insignificant bias (-0.4% shift).	NA
7.b[22]	Inactivation makes the slope flatter, causing decreased sensitivity to motion. The overall effect of sensitivity was inconsistent among trials.	Monkeys were biased against oppositional choices. Bias was statistically very small. As trials went on, the bias dissipated.	NA

Optogenetic Inactivation:

Study 8 (Table 8) injected specific regions of area MT in each monkey with an AAV vector to express redlight sensitive chloride pump jaws controlled by the CaMKIIa promoter. This study tested the changes in the psychometric function - bias and slope - when neurons of MT were inactivated by photo suppression. However, the experimental procedure for this study was slightly different. The monkeys had 3 choices instead of the regular 2 choices: null direction, preferred direction, or sure bet. In the sure bet choice, they would receive a smaller reward (compared to if the answer was null or preferred and correct) regardless of the motion direction. Photo suppression caused an increase in the slope of the psychometric function, which was associated with an increase in sensitivity. The suppression also biased the monkeys' decisions against the preferred choice. When the degree of suppression

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was more than 45%, there was a shift of -2.1±0.6% coherence of the psychometric function.

Nevertheless, this bias dissipated over a large number of trials. The bias during the first 500 trials was -3.5%±1.1% coherence, but the bias after 501 trials dissipated to - 0.7% coherence. Suppression of MT biased the confidence function (sure-bet choices) to the preferred direction. A similar trend followed in the confidence function, where the bias dissipated over large numbers of trials (refer to Table 8 for data). This further provides evidence of the compensation of non-suppressed neuronal circuits for suppressed ones.

Table 8: Effect of optogenetic inactivation in MT on the slope and bias of psychometric function.

Study	Change in slope	Change in bias	Change in RT
8[23]	Optogenetic suppression caused an increase in slope and an associated increase in sensitivity.	It caused a modest but significant bias (shift = - 2.1±0.6% coherence) when the degree of suppression was greater than 45%. The bias dissipated over later trials. In the first 500 trials, the bias was -3.5±1.1% coherence. After 501 trials, the average bias was -0.7%. The confidence function (sure-bet choices) was biased to the preferred direction by inactivation. This bias in the confidence function also slowly dissipated in later trials. In the first 500 trials, the bias was -3.8±1.9% shift. 501 trials onwards trials, the bias was 0.1%.	NA

Comparison Between MT and LIP:

When comparing how much LIP and MT each contributed to perceptual decision-making, it is first visible that LIP and MT both have similar qualitative effects. For example, if we compare studies in Table 1 and Study 3, we find that microstimulation of both LIP and MT bias the psychometric function in the same direction. Moreover, from Studies 6 and 7(a, b), we see that the inactivation of MT and LIP had the same qualitative change in slope. While these changes look similar, there are key differences. Firstly, the tested region of LIP overlapped with one of the two choices, whereas the tested region of MT overlapped with the motion stimulus. This directly limits the comparisons that can be made. Secondly, the magnitude of change in perceptual decision-making that occurred when LIP was altered was significantly smaller than when MT was changed (refer to Tables 1, 3, 6, 7). Even the change in RT when LIP was microstimulated compared to when MT was microstimulated was smaller (refer to Study 1. a and 3). It is also noticeable that the alteration of LIP had a much larger effect on RT than on bias or slope change of the psychometric function (Study 3).

These differences suggest some important things about LIP and MT and their involvement in perceptual decision-making. We see that MT has a greater contribution to decision-making than LIP. In essence, MT makes the decisions, while LIP fine-tunes them. This is consistent with previous studies.[19]

A previous study has explored this in the context of a diffusion model,[19] showing that MT provides the momentary evidence accumulated into the decision variable represented by LIP neurons. As a result, a slight change in the firing rate of these neurons is represented as a function of time, and the combined influence of MT on the decision variable is significant. They have also shown that a change in the firing rate of LIP brings the decision variable closer to the bound. Still, the effect is not cumulative and, therefore, insignificant.

Comparison Between Different Manipulation Methods:

We now compare the magnitude and direction of the different manipulation methods on perceptual decision-making. We use studies from MT to compare the methods since we have at least one MT study for each method. Of the four manipulation methods (microstimulation, irreversible inactivation by lesions, reversible pharmacological inactivation, and optogenetic inactivation), microstimulation is the only one that biases the psychometric function toward the preferred direction. The other methods all bias decision-making in the null direction. This is unsurprising because microstimulation increases the electrical current in the target neurons, increasing activity, while the other inactivation methods reduce activity. It is important to note that the average magnitude of bias of the psychometric function when microstimulation occurred was greatest relative to other manipulation methods.

Moreover, microstimulation flattened the psychometric function's slope, reducing sensitivity to the stimulus. Surprisingly, pharmacological inactivation (reversible) also flattened the slope. On the other hand, optogenetic suppression of MT caused an increase in slope and an associated increase in sensitivity. We could not find studies that measured slope change for permanent lesioning. Furthermore, given that we have only 1 study for reversible pharmacological inactivation and optogenetic suppression, this result is unreliable.

Due to a lack of literature on this task design, more data was needed to compare RT changes between different manipulation methods.

Limitations:

Given that we could only compare studies with exactly the same task design, there were a limited number of studies. For example, for the manipulation method of optogenetics, there was only one study with this task design. At the same time, studies often tested very few monkeys, sometimes just 1 or 2. This small sample size of papers and of test subjects in each paper could have affected the results.

The motion discrimination task also varied slightly in some studies. For example, one of the microstimulation studies had a different current amplitude and frequency than the others. In lesion studies, the lesion could have spread over to nearby regions of tissues, which is difficult to predict and could have affected results.

Additionally, there was some variability in the preparation and training protocol for the monkeys before the experiment. For example, study 4 measured the monkeys both early in training and after a long time of training, which was different from other studies. These variations in training methods could have led to differences in the monkeys' performances.

Furthermore, choice bias is common in human and animal psychophysics, where subjects are biased toward a specific target. Some studies tested choice bias and adjusted their

conclusions, while others didn't. Another limitation is that few studies didn't give statistical data, such as median or mean, so they had to be estimated from graphs.

Conclusion

The primary findings are consistent with the idea that MT provides the primary input for decision-making. At the same time, LIP tunes the decision to allow saccades to a specific portion of the visual field.[21] It is also apparent that microstimulation is the most effective method of manipulating the brain activity of specific neurons because it can provide inputs to neurons that carry the most informative signals. This paper further emphasizes the importance of adopting similar experimental designs for understanding the brain. The studies that the International Brain Laboratory is conducting emphasize this importance as well.[24]

Considering that all parts of the oculomotor system are involved in this task, it is important to examine other involved areas, such as Frontal Eye Field (FEF) and Superior Colliculus (SC). In the future, a study should be conducted that manipulates all different areas of the oculomotor system, all with the same experimental design, to truly determine the causal contribution of each region. Additional studies could also involve targeted interventions, including localized stimulation, inhibition, or lesion techniques paired with high-resolution neuroimaging and behavioral assessments.

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