Intelligent Adaption Across Space

Honors Thesis Paper by

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Abstract

All biological organisms deal with uncertainties in the world. To survive in this ambiguous ever-changing environment an organism must readily adapt to any presented uncertainties. These uncertainties refer to the intrinsic variables of positive rewards and negative punishments distributed throughout an organism's surroundings. In order to properly react to uncertainty, organisms possess functional brain mechanisms responsible for regulating fundamental behavior, such as decision making. Additionally, these processes are both heavily influenced by neuromodulations in the brain and learning experience of the individual animal. Thus, the skillful utilization of attention allows for the increased efficiency in the organism's search and evaluation of reward. The specific aim of our study was to confirm a paradigm to show that animals indeed learn to increase efficiency of search and direction of attention to get rewards as part of a larger study to look at neurocircuitry of uncertainty in the brain.

Introduction and Background

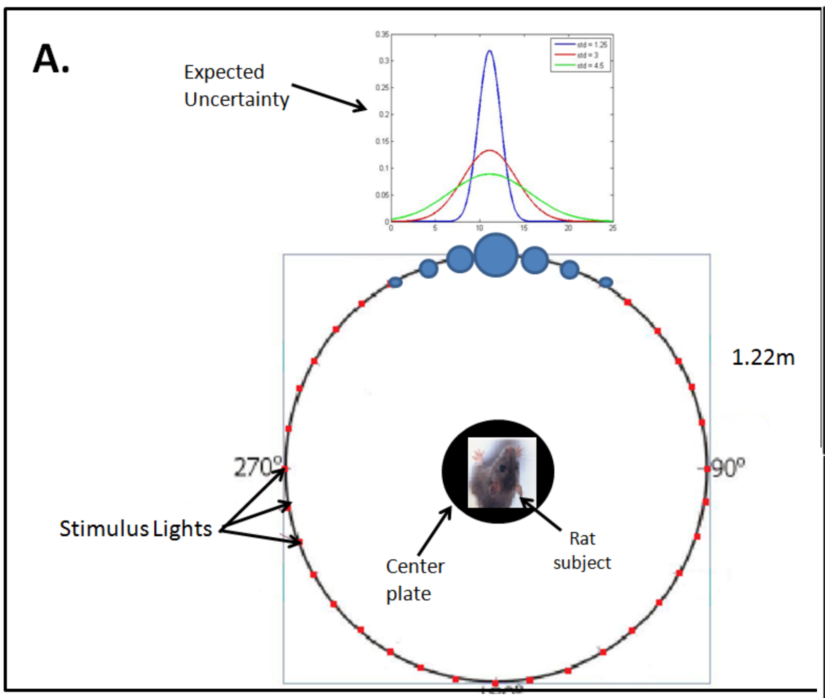
The world is a complex environment that is filled with various stimuli that can guide specific actions or distract the animal from a particular objective. In order to operate efficiently in any environment, the organism must be able to intelligently direct its sensory organs and attention to extract the most useful information. With this, the animal can effectively evaluate both threats and rewards within the environment.

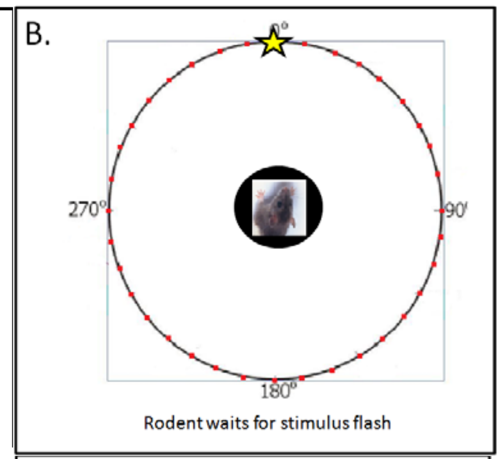
Living in a dynamic environment, humans also face the task of directing attention to resources, selecting the most significant stimuli, and evaluating rewards. An analogous example to further examine how the learning of statistical probabilities impact the role of attention can be observed in the hypothetical "real world" example of searching for a set of keys. Upon entering the house, often times people carelessly place their keys in a number of spots throughout their living space. When searching for the keys, it is understood that there are varying highly and lowly probable places where the keys can be found. For instance, there is a significantly higher probability for the keys to be found in a pants pocket, purse, or on the table top as opposed to being found in the refrigerator or shower stall. Thus, there is an "expected" and "unexpected" statistical distribution intrinsic to the environment. These statistical probabilities can be learned over many repeated trials of search and reinforced reward (finding the keys). Thus, the eventual familiarization with the task of looking for keys coincides with the increased efficiency in search and direction of attention.

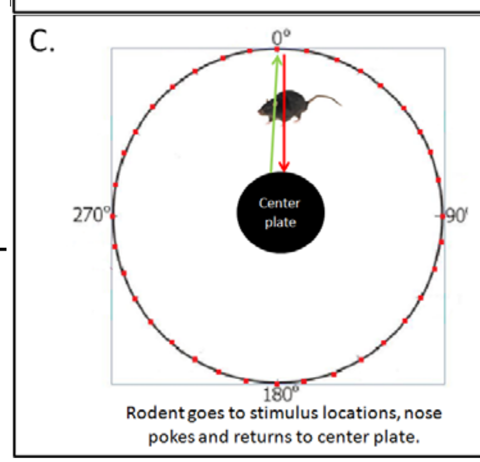
The learning of statistical probabilities has been previously described as adapting to "expected uncertainty" and responding to the "unexpected uncertainty" of an environment (Yu and Dayan, 2005). "Expected uncertainty" is defined as degrees of unreliability of predictive relationships in the environment that has been thought to be driven by the cholinergic system of the basal forebrain, which can be seen through the rodent incorporation of statistical probability learning in our study. Alternatively, "unexpected uncertainty" is described as significant changes in the environment that violate top-down expectations which can be observed in the behavioral performance when environmental conditions change.

The larger objective of the experiment encompassing my honors thesis is directed towards uncovering the detailed neurocircuitry involved with direction attention in the basal forebrain. It has been previously shown in vertebrate animals that the primary neuromodulatory systems include serotonergic, cholinergic, dopaminergic, and noradrenergic projections from the brainstem and BF to widespread regions of the neocortex (Briand et al., 2007). These neurons were also thought to project to the cortex in such a way that they could alter cortical activities to intelligently allocate attention resources and sensory organs (Zaborsky, 2003). Because of such relationships, inputs to basal forebrain from amygdala and prefrontal cortex may be considered significant in its relations to the organism's attention (Lin and Nicolelis 2008).

Being a subset of a much larger study, my honors thesis is designed to confirm a paradigm to show that animals learn to increase affinity of search to get rewards in a dynamic environment. To produce this attention-directing phenomenon, we constructed an experiment to assess rodent subjects within a 'probability uncertainty task.' In this task, the rat searched for a specific light stimulus within a circular arena (Figure 1). As a light in its periphery flashed, the rat must detect it and poke its nose into the hole of the correct light fixture demonstrating the understanding for a reward. This 'probability uncertainty task' allowed for "expected uncertainty" to be manipulated directly through the spatial distribution of flashing lights. Within each trial, a Gaussian distribution of lights is flashed with a set center light and given standard deviation. The center lights and spreads differed across stimulus location to build "expected uncertainties" of events in the arena. This task grants researcher control of the statistical environment by manipulation of conditions and variables. In addition, the task also facilitates a methodology to further understand rodent learning and its direction of attention. Through the systematic manipulation of the probabilities of light stimuli, we can better examine whether rodents demonstrate predictive inferences under different conditions of stimulus by comparing their accuracy performance to the presented light probability distribution.







(figures adapted from Kichman, Chiba, Nitz)

Figure 1. Rodent "probability uncertainty task" **A.** The circular area contains a marked center plate and 36 light fixtures. Light flash locations follow a variation of selected Gaussian distribution. **B.** The experimental paradigm consists of quick flashes to which the rat must direct its attention towards, remember, and react. **C.** After observation of the stimuli, the rat is attains a reward by going to the correctly flashed light stimuli, and returning to the center plate in a distinct manner.

Methodology

The 'probability uncertainty task' utilized a large circular arena (with a diameter of 1.22 meters) with 36 light fixtures with nose poke holes located at a 10-degree offset around the circumference and a smaller circular plate in the center (Figure 1A).

We first began training a new rat subject with human handling to reduce the fear responses caused by interactions with the experimenter and the surrounding environment. After desensitization, the rat was introduced to the arena for an adequate amount of time daily to acclimate to the novel environment. Following, a systematic method of incremental training allowed for the rat to eventually associate positive reward with remaining on the center plate until a light fixture was flashed, running to the correct light, poking its nose into the fixture to mark its choice and returning to the center plate to await reward. The subjects were only rewarded pieces of Cheerios when they poke their noses into the correct fixture and were given nothing when they fail.

Once the subject was determined to have demonstrated understanding of the 'probability uncertainty task,' experimental assessments of the behavioral paradigm began (Figure 1B and 1C). Each session's data (85 days: Rat NS1 and 106 days Rat: NS2) consisted of 100 trials with light sequences selected at random from a previously determined center light and distribution. For instance, Rat NS1 was administered the environmental test conditions of center light set to light fixture 16 as the distribution varied from to 3, 1.25, to 4.5 over different days (Table 1). Rat NS2 was administered differing parameters (center 23 and distribution varying from 1.25, 3, 1.25, to 4.5) in order to account for possible confounds (Table 2).

Assessments of the rats' behavioral performances were recorded at the finish of each light sequence trial. The rat's head direction, spatial scanning behavior, running path trajectory, speed, and accuracy response to a light was recorded. For incorrect trials, various types of errors were recorded; including errors of omission, commission, preservation, impulsivity, and spatial accuracy. The speed and accuracy of each rat's response to the lights were expected to reflect the uncertainty of the environment. It was expected that the rats' behaviors should evolve from erratic to fluid scanning of the environment matching the underlying distribution of provided light stimuli. Particularly key to understanding the behavior repertoire of the rat was comparing the provided probability distribution against the correct performance percentage of each rat.

Much of the experimental data surrounding the neuronal firing patterns of the basal forebrain was derived during the 'perching' activity of the rat on the center plate (Figure 1B). During this period, the rats demonstrated utilizing its full attention by waiting and actively seeking out the next light flash. The sought behavior of rats was rewarded when selecting the appropriate flashed light fixture. By noting the successes of the nose pokes throughout each trial, we were able to deduce the learning abilities and limitations of each rat. To further analyze these features, a series of MATLAB programs broke down, integrated, and filtered the important aspects of each trial, making it easier to visualize the particular phenomena and providing insight into the rats' behaviors.

Table 1.
Chart of NS1's center and spread conditions

	Center	Spread
Condition 1 (45 sessions)	16	3 (medium)
Condition 2 (25 sessions)	16	1.25 (narrow)
Condition 3 (15 sessions)	16	4.5 (wide)

Distribution of sessions and conditions used for analysis. Rat NS1 started with a medium distribution, continuing onto a narrow, and finally wide distribution.

Table 2.
Chart of Rat NS2's center and spread conditions

	Center	Spread
Condition 1 (47 sessions)	23	1.25 (narrow)
Condition 2 (37 sessions)	23	3 (medium)
Condition 3 (8 sessions)	23	1.25 (narrow)
Condition 4 (14 sessions)	23	4.5 (wide)

Rat NS2 started with a narrow distribution, continued onto medium, narrow again and lastly onto wide distribution.

Data Analysis

From preliminary results, it was hypothesized that given the 'probability uncertainty task' the rodent would readily adapt to and learn the statistical probability of the varying environmental distributions (Figure 2). To demonstrate this phenomena of behavioral learning in a given task poking its nose at a flashed light fixture, rats were expected to match the probability frequencies of given light stimuli distributions. Thus, when trained and presented with a narrow condition, the rat was expected to perform at a higher percent accuracy (especially at the center light) attending to only a few highly probable light stimuli. Conversely, under wide distribution, the rat was expected to match the statistical environment by allocating its attention broadly.

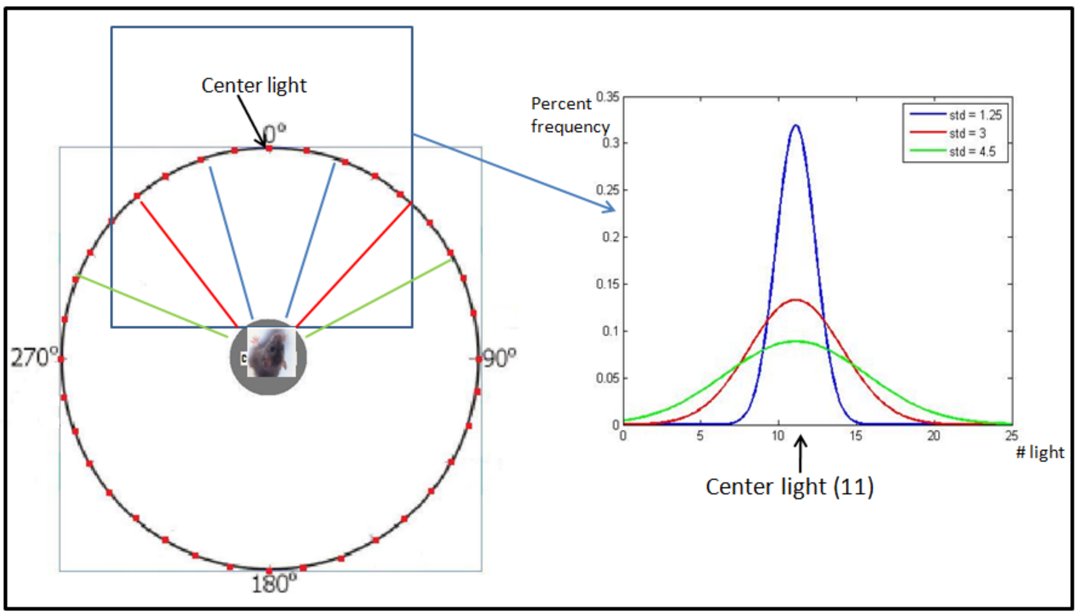


Figure 2. Break down of the provided Gaussian distributions of narrow (standard deviation 1.25), medium (standard deviation 3), and wide (standard deviation of 4.5). In the arena task, the rat, over time, was expected to eventually adjust attention resources according to the provided distributions over a period of time.

Thus far, approximately 130 days of behavioral data has been recorded for two different rat test subjects (NS1 and NS2) and a selected portion (the first 86 days for Rat NS1 and first 106 days for Rat NS2) of the data has been used for further analysis. To begin, both rats NS1's and NS2's behavioral data went through various transformations (Figure 3) to test which methods of analysis allowed better interpretation of the behavioral data. This transformation catered to the notion that the provided Gaussian distribution assumes normality and thus, succeeding light offset (ie. +/-1, +/-2…) away from the center light should be presented to each rat at a fairly equivalent frequency. By folding the data as such, visualization of each rat became clearer.

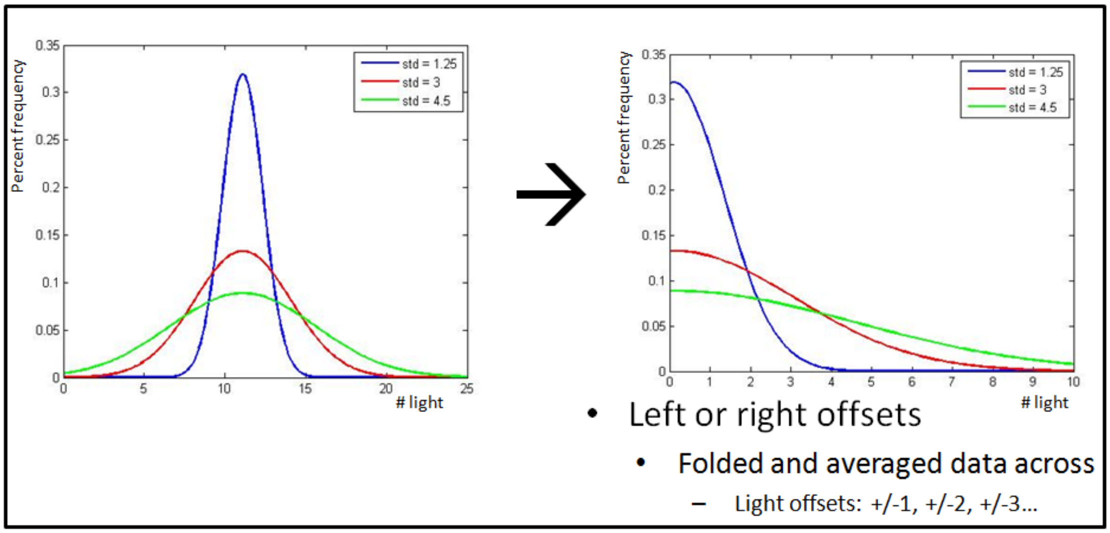


Figure 3. Gaussian narrow, medium and wide distributions transformed. To analyze data, both offsets +/-1, +/-2, +/-3… lights away from center are averaged across days.

Using both rats' absolute percentage correct behavioral statistic, the t-test statistics (table 3) were computed by taking the averages of the last four percentage correct sessions of each rat (for rat NS1- medium:25-28, narrow: 48-51, and wide:64-67 and for rat NS2 - medium: 60-63, narrow:26-29, and wide: 78-81). The last four days of each condition was selected for analysis because of after many repeated sessions on a given distribution, the rat is expected to have adapted to the given environmental condition. The t-test statistics allowed for the considerations of the differential significances in the cross comparison of the averaged percentage correct behavioral data at each given condition (narrow vs. medium vs. wide). This t-test statistic was also used to compare differences of conditions at the center light offset 0 and continued onto offset 1, 2, and 3 (table 3 and 4). In addition, the standard errors and averaged means of percent accuracy of these four days were produced to compare accuracy between varying conditions for each individual rat (figure 4 and 5).

Results

After the analysis, both rat NS1 and rat NS2 exhibited significant results suggesting the developments and statistical differences in the adaptations to the environmental variations of the 'probability uncertainty task.'

Rat NS1 Results

Rat NS1 produced results displaying a statistically significant difference at the center offset light 0 (Figure 4A) between the narrow vs. wide and narrow vs. medium distributions at a robust significance level much lower than 0.001 (Table 3). For offset light fixture 3(figure 4B), the comparison between conditions yielded a statistical p-value of 0.017 and 0.04 for the narrow vs. wide and narrow vs. medium distributions respectively. Recorded data at center light offset 0 presented that the narrow condition produced the highest absolute percent correct. Conversely, at the center light offset 0, the lowest absolute percent correct was found at the wide distribution. At the light offset 3, results contrasted from those at center light offset 0 showing the narrow condition as having the lowest absolute percent correct and the wide conditions having the highest absolute percent correct.

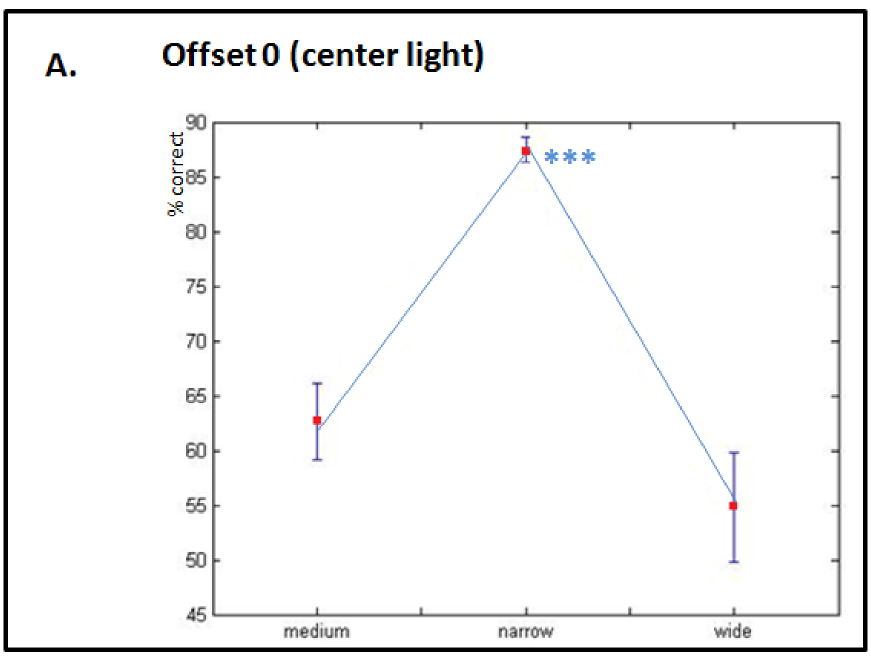


Figure 4. Comparison between conditions narrow, medium, and wide (x-axis) and the averages of absolute percentage correct of the last four behavioral data sessions (y-axis).

Figure 4A. Rat NS1's behavioral performance means and error bars at the center light offset 0.

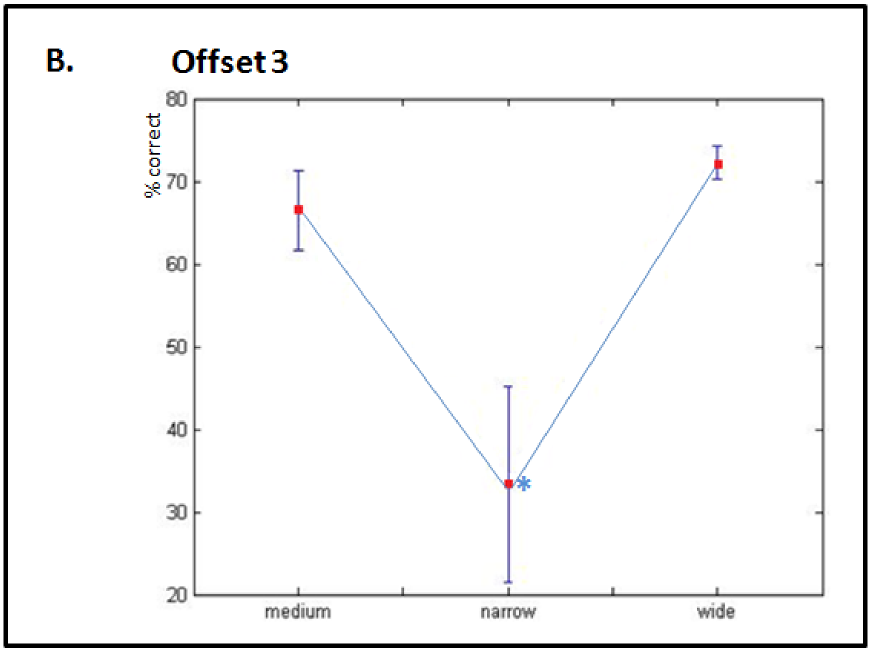


Figure 4B. Rat NS1's behavioral performance means and error bars at light offset 3 (+/-3 lights away from center light).

Table 3.

Offset	Wide vs. Nar dist.	Nar vs. Med dist.	Med vs. Wide dist.
0 (center light)	***0.0007336	***0.0005329	0.25231
1	0.24523	***0.0003323	0.1332
2	0.75162	0.81698	0.89959
3	*0.017313	*0.040286	0.30983

T-test statistics using the averages of the last four distribution sessions (medium: 25-28, narrow 48-51, and wide 64-67) for rat NS1 to compare differences between conditions and between offsets

Rat NS2 Results

Rat NS2 produced similar results mirroring rat NS1's results to a statistically variable degree. Rat NS2's results at center light offset 0 produced statistical p-values greater than 0.44 for the comparisons between narrow vs. medium vs. wide (Table 4). These center light offset's increasingly high p-value may be attributed to the behavioral variable in rat NS2's repertoire, the variations in the provided training sessions, or the small pool of data (four sessions) drawn to perform this t-test statistic. Despite having highly varied p-value, rat NS2 presented an inverse phenomena mimicking rat NS1's average percent correct results at each specific condition. At the center light offset 0, rat NS2 performed the 'probability uncertainty task' with much higher accuracy at the narrow distribution as compared to the wide distribution (Figure 5C). Also similar to rat NS1's performance at offset 3, rat NS2's narrow distribution proved to have the lowest percent accuracy with wide error bars while the wide distribution has a considerably higher percentile correct(Figure 5D).

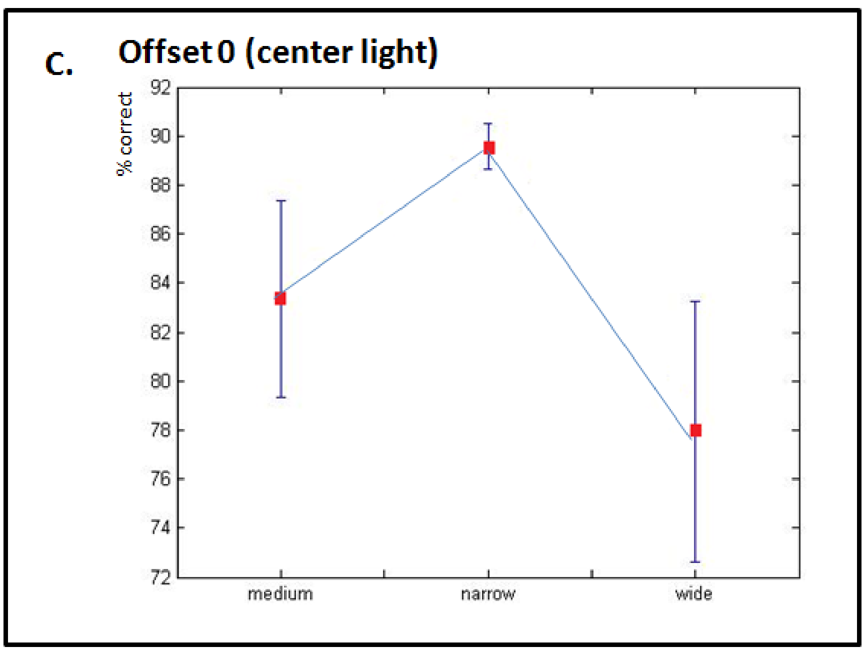


Figure 5. Comparison between conditions of narrow, medium, and wide (x-axis) and the averages of absolute percentage correct of the last four behavioral data sessions (y-axis).

Figure 5A. Rat NS2's behavioral performance means and error bars at the center light offset 0.

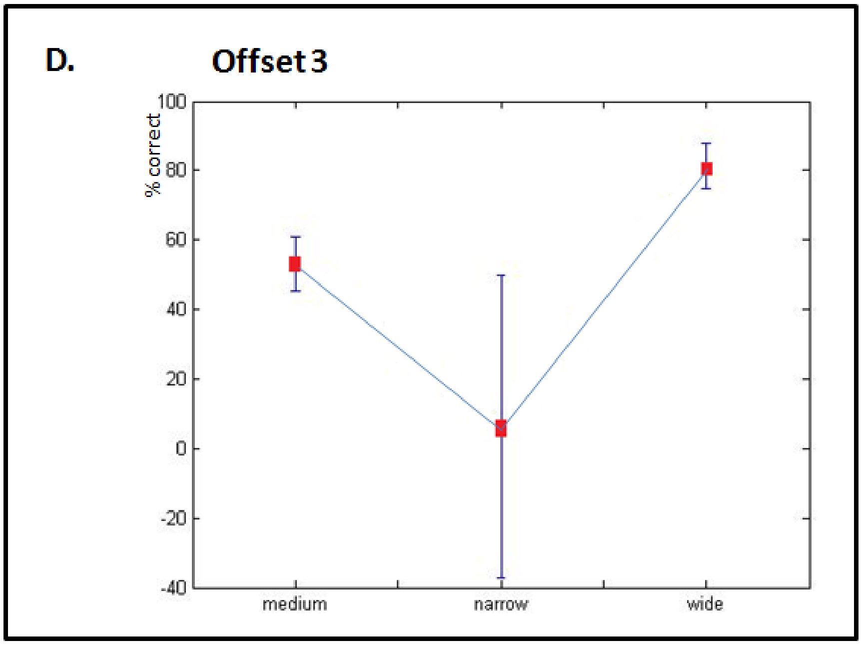


Figure 5B. Rat NS2's behavioral performance means and error bars at light offset 3 (+/-3 lights away from center light).

Table 4

Offset	Wide vs Nar dist.	Nar vs Med dist.	Med vs Wide dist.
0 (center light)	0.716606	0.918894	0.447870
1	0.84754	0.60264	0.504877
2	*0.020107	0.73605	* 0.039405
3	*0.013201	0.057572	* 0.032102

T-test statistics using the averages of the last four distribution sessions (medium: 60-63, narrow 26-29, and wide 78-81) for rat NS2 to compare differences between different conditions and offsets.

Discussion

It was originally hypothesized that if given a small set of highly probable light flashes (narrow distribution), the rats should be able to devote attention with ease (Figure 6B). After several training sessions on the narrow condition, the rats are expected to complete the 'probability uncertainty task' with fairly high accuracy. Conversely, given a large set of lesser probably light flashes (wide distribution), the rat must attend to a wide range of possible light stimuli. Because of this increased difficulty in search, a lower percent accuracy is expected.

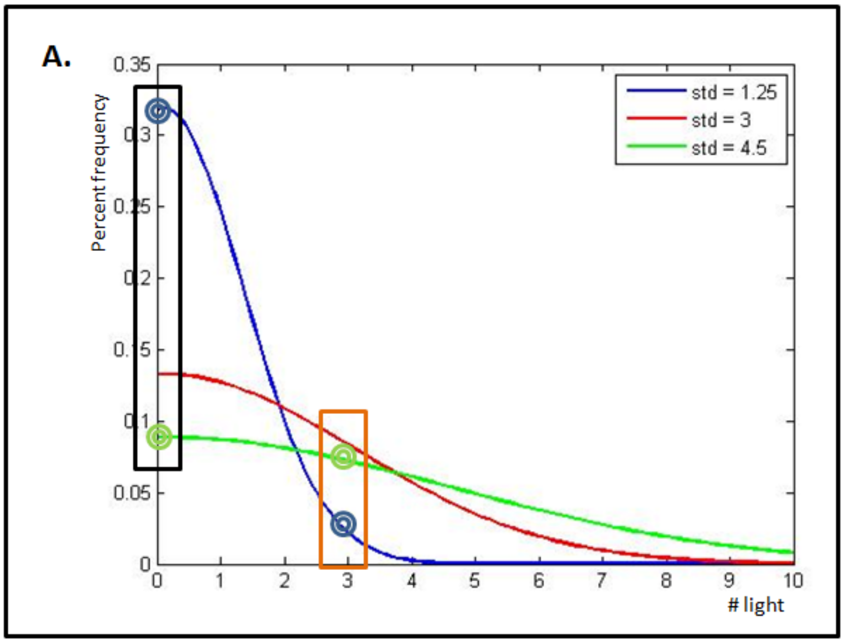


Figure 6A. The 'folded' averaged conditions data provided to each rodent. At the center light offset 0, there is a noticeably higher percent frequency of center lights given to the rodent with narrow (blue) condition as compared to the percent frequency of center lights given with the wide (green) condition. At the offset 3 light fixtures, there is an inverse in provided light frequencies where narrow (blue) condition is lower than wide (green) condition.

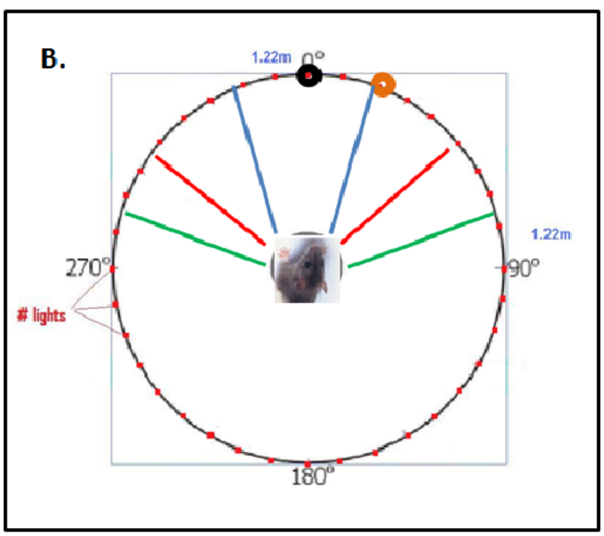


Figure 6B. Various statistical conditions of the environment of the arena task. Blue: narrow distribution, Red: medium distribution, Green: wide distribution. The center light (black donut) being the highest probable light. Offset 3 light (orange donut) having variable probability according to each particular conditions.

To learn and adapt to the statistical environment, the percentage correct of each rat should ideally match each given condition of the surroundings (Figure 6A). Therefore, with any given condition (narrow, medium, and wide) we expected the most probable light to be at center light offset 0 with the narrow distribution having the highest accuracy and the wide distribution having the lowest accuracy. As we have observed in rat NS1 and rat NS2's results (Figure 4A and Figure 5A), the hypothesis holds true.

The percent correct results, however, should not only match at the center light, but also at the various offset lights. For instance at offset 3, we noticed an actual inverse in the probability frequencies of the lights provided to the rats, with the narrow distribution providing less light flashes at offset 3 and wide distribution providing more (Figure 6A). In comparison among the narrow and wide distributions, with an offset of 3, both rats performed worse at the narrow distributions (Figure 4B and Figure 5B). Matching this inverse, both rats in our behavioral study continued to support our conclusion that rats are driven to adapt the probabilities of the statistical environment in order to maximize reward.

In conclusion, this behavioral 'probability uncertainty task,' confirmed that rats do learn to adapt to the variability of the dynamic environment in order to increase the efficiency of search and maximize rewards. These types of experiments and data analyses can one day lead to new developments in medicine by advancing current knowledge about behavioral mechanisms in the brain. Because my honors proposal focuses on a small subset of the entire study, future directions will ideally utilize results from this behavioral paradigm to clarify questions regarding the role of the basal forebrain. For example, how training could impact the organisms' ability to direct attention, how environmental factors influence performance, and how long-term and short-term learning abilities relate to the behavioral tasks. In order to gain holistic insight into the various underlying brain functions regarding uncertainty in the environment, future studies will be directed towards the formulation and analytical breakdown of neurological, temporal, behavioral and electrophysiological aspects of attention-directing behavior.

References

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