DISSOCIATING THE BRAIN REGIONS INVOLVED IN PROCESSING OBJECTIVE AND SUBJECTIVE PERFORMANCE

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To everyone who has supported me during my Ph.D.

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LIST OF SYMBOLS AND ABBREVIATIONS

aPFC	Anterior prefrontal cortex
dlPFC	Dorsolateral prefrontal cortex
FEF	Frontal eye field
fMRI	Functional magnetic resonance imaging
GLM	General linear model
MFG	Middle frontal gyrus
MT+	Motion-sensitive visual-temporal area
MTG	Middle temporal gyrus
MVPA	Multi-voxel pattern analysis
ROI	Region of interest
RT	Response time
SPL	Superior parietal lobule
TMS	Transcranial magnetic stimulation

SUMMARY

When making perceptual decisions, easier tasks produce higher task accuracy and, naturally, higher confidence levels. We recognize the two distinctive cognitive processes and sometimes even experience inconsistency between objective and subjective performance. However, it is challenging to judge exactly how objective and subjective performance affect different brain regions due to the foundational law of covarying human performance. Previous studies looked into the association between different brain areas with objective and subjective performances. Nevertheless, they have been unable to adjudicate which type of performance was responsible for the activations in which subregions of the brain due to strong covariance between the two. In the current study, I aimed to reveal which brain regions are activated by objective and subjective performance, respectively. The study used a visual stimulus where clouds of red and blue dots with different numbers were presented. The task for subjects was to determine which color was more frequent. After they made a decision, subjects evaluated the confidence in their decision. The experiment was a 2 x 2 factorial design, where one factor was task difficulty (i.e., Easy and Difficult conditions) and the other was the number dots presented (i.e., High and Low conditions). The stimulus was selected based on the previous studies conducted in my lab. The pilot studies together indicated that Low condition reliably generated lower confidence level than the High condition, while the task performance was higher in Low condition. On the other hand, task performance and confidence level covaried together in Difficult and Easy conditions. From the observation in the pilot tests, I expected that by comparing High and Low conditions to Difficult and Easy conditions, I would be able to

find brain regions associated with either perceptual decision or confidence evaluation. I planned three functional magnetic resonance imaging (fMRI) data analyses. First, contrast tests between Easy and Difficult conditions, and High and Low conditions. Combinations of different contrast tests would show how the subjective and objective performance individually affect different brain regions. Second, I planned to analyze the functional data using multi-voxel pattern analysis (MVPA) to find any regions revealed in the contrast tests can distinguish reliably different levels of task performance and confidence. Finally, I planned on doing connectivity analyses to examine how the brain regions are connected differently for the decision and confidence processes. However, the behavioral results of the current study did not dissociate task performance and confidence level in High and Low conditions. In the planned contrast tests, I found activations in bilateral post-central gyrus, left middle frontal gyrus (MFG) and superior parietal lobe (SPL), and right occipital and cerebellum areas were greater for Easy compared to Difficult condition. Also, middle cingulate cortex and right SPL activated greater for Low condition compared to High condition. However, because there was no clear dissociation between accuracy and confidence, it is hard to interpret what those activated regions are associated with. Moreover, none of the regions were able to distinguish either task difficulty or confidence level in the planned MVPA analysis. While the main experimental conditions did not show the dissociation effect, I found weak dissociation in decision and confidence responses between Difficult-High and Difficult-Low conditions. Given the observation, rather than performing the planned functional connectivity analysis, I conducted exploratory contrasts between Difficult-High and Difficult-Low condition. When contrasting the two conditions each other, I found left middle temporal gyrus (MTG) and right SPL were activated more in Difficult-Low condition compared to Difficult-High condition. Importantly, the right SPL cluster was similar to the right SPL observed in Low > High contrast test. The current study was unfortunately not able to draw a strong conclusion about the task performance and confidence level, and the brain regions associated with those cognitive processes. Nevertheless, partial data of the study showed weak dissociation effect. To understand how the brain computes two cognitive processes that are seemingly separable, it is important to create stable conditions where task performance and confidence level are dissociated and investigate how the brain differently associated with those processes.

CHAPTER 1. INTRODUCTION

1.1 Subjective confidence in perceptual decision-making studies

After making a perceptual decision, people can retrospectively assess how certain they are of their previous choice. The judged level of certainty in a previous decision is called decision confidence (Gold & Shadlen, 2007; Koriat, 2016). How well humans perform in making perceptual decisions and rating their confidence level is reflected in the objective task accuracy and subjective confidence level. However, the task performance and confidence level have strong tendency of changing together. For instance, people usually have a high confidence level for correct trials, while the opposite is the case for incorrect trials (Koizumi et al., 2015; Peirce & Jastrow, 1884; van den Berg et al., 2016).

Subjective task performance has also been investigated as a measurement of metacognition. Metacognition, which is a ‘sense of knowing’ or ‘thinking about thinking’, shows our cognitive ability to assess the quality of perceptual decision (Fleming et al., 2012; Shekhar & Rahnev, 2018). Metacognition plays a critical role in both the perceptual decision-making and confidence judgment processes. The cognitive function allows people to select strategically and retain particular information (Koriat, 2007; Metcalfe & Shimamura, 1996; Shimamura, 2000). Nelson and Narens (1990) distinguished metacognition into two levels: the object- and meta-level. The object-level is where the basic information processing of external objects happens, while the meta-level is where a higher cognitive process on the object-level takes place. According to the theory, the subjective confidence judgment corresponds to the meta-level.

Notwithstanding the strong relationship between the objective and subjective performance, several studies have shown that perceptual decision and decision confidence are not always congruent. Sometimes subjects rated their confidence level as high at incorrect trials or low even though the decision was correct (Fleming et al., 2014; Morales et al., 2018; Rahnev et al., 2012). Such differences might occur from different evidence used in perceptual decision-making and confidence judgment processes. While the perceptual decision is driven equally by congruent and incongruent evidence of a decision, the decision confidence is more influenced by evidence that supports the previous decision (Maniscalco et al., 2016; Peters et al., 2017; Zylberberg et al., 2012). Moreover, even though largely overlapping regions are activated by both objective and subjective performance, some unique brain areas are only activated for the subjective confidence judgment process (Yeon & Rahnev, 2020). Previous studies together indicate that the objective and subjective performance are processed separately to a certain degree.

1.2 Brain regions associated with the objective and subjective performance

The perceptual decision-making process can be distinguished into three stages. The first stage is where an observer first places one's attention to an object (i.e., 'selection'). The second stage is where the observer adjusts a decision criterion and makes a decision (i.e., 'criterion setting'), and the last stage is where the observer judges whether the decision is correct (i.e., 'evaluation') (Posner, 1980; Rahnev et al., 2016). Previous perceptual decision-making studies recognized that the frontal cortex is responsible for decision making and confidence judgment (Frith & Dolan, 1996; Kahnt et al., 2011; Koechlin & Hyafil, 2007; Smith & Jonides, 1999). Specifically, three subregions have been discussed heavily: frontal eye fields (FEF), dorsolateral prefrontal cortex (dlPFC), and anterior prefrontal cortex (aPFC). The three brain regions are supposed to have a temporal hierarchy in perceptual decision making. The higher cognitive process is assumed to be computed in the more anterior part of the frontal region (**Figure 1**) (Heekeren et al., 2008; Koechlin & Summerfield, 2007; Rahnev et al., 2016; Sterzer, 2016).

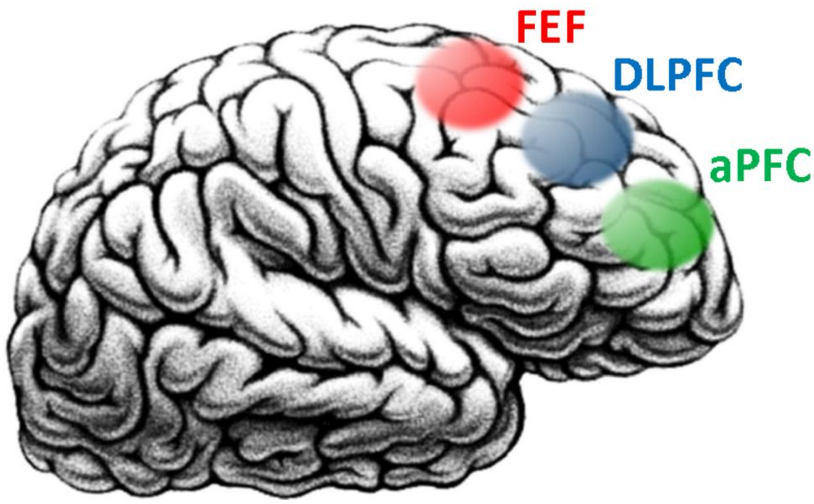

Figure 1. Locations of frontal eye fields (FEF), dorsolateral prefrontal cortex (dlPFC), and anterior prefrontal cortex (aPFC). The three subregions of the frontal cortex are supposed to have a temporal hierarchy, where the higher cognitive process is computed in the more anterior part of the brain (The figure is retrieved from Sterzer (2016)).

FEF is the brain area that, in humans, is located at the intersection of the superior frontal sulcus and the precentral sulcus (Vernet et al., 2014). As the name indicates, the brain region is closely related to eyes and is responsive to saccadic eye movements (Ruff et al., 2006; Scerra et al., 2019; Vernet et al., 2014). Many non-human primate studies have shown decision-related activation in FEF (Basu & Murthy, 2020; Ding & Gold, 2012; Ferrera et al., 2009; Gold & Shadlen, 2000). Also, in humans, the region is activated when performing decision-making tasks (Heekeren et al., 2004; Rahnev et al., 2016; Thiery et al., 2019; Yeon et al., 2020). However, unlike the motion-sensitive brain region (MT+)

(Salzman & Newsome, 1994), FEF represents accumulated evidence for perceptual decisions (Ding & Gold, 2012; Ferrera et al., 2009; Gold & Shadlen, 2000; Schall, 2000).

dlPFC refers to the area around the middle frontal gyrus in humans (Cieslik et al., 2013). The region is associated with controlling actions, especially processed through the top-down information processing (Cieslik et al., 2013; Koechlin et al., 2003; MacDonald et al., 2000). In perceptual decision-making studies, dlPFC has shown relationship with the subjective confidence level. The level of activation in dlPFC changes depending on the confidence level rated by subjects (Fleck et al., 2005; Henson et al., 2000; Lau & Passingham, 2006; Morales et al., 2018; Shekhar & Rahnev, 2018). While dlPFC is also associated with the objective task accuracy (Yeon et al., 2020), the region seems to be responsible more for the subjective performance. When the repetitive transcranial magnetic stimulation (TMS) was applied at bilateral dlPFC, subjects incorrectly rated their confidence level while the decision task performance was intact (Rounis et al., 2010; Ruby et al., 2018). Also, a lesion in dlPFC only affects the subjective performance, but not the perceptual ability (Lau & Passingham, 2006).

aPFC is the foremost area of the frontal cortex (Ramnani & Owen, 2004), which is significantly expanded in humans compared to other species (Semendeferi et al., 2001). The region is responsible for computing confidence level (Allen et al., 2017; Baird et al., 2013; Fleming & Dolan, 2012; Rouault et al., 2018; Yokoyama et al., 2010). The activation of the brain region showed a positive relationship with the subjective performance (Baird et al., 2013; Rahnev et al., 2015) and studies have demonstrated that the area can decode the confidence level (Morales et al., 2018). Moreover, deficits in the brain region weaken one's metacognitive ability (Fleming et al., 2014; Shimamura, 2000; Shimamura & Squire, 1986).

Although it is relatively clear that FEF processes sensory information perceived, how the objective and subjective performance are associated with dlPFC and aPFC is controversial. For example, Rounis et al. (2010) observed decreased objective task accuracy and metacognitive ability after delivering TMS on dlPFC, while Bor et al. (2017) argued that they did not find the same effect. In a recent study, researchers delivered online TMS on dlPFC and aPFC, and found decreased subjective performance when the stimulus was delivered at dlPFC, but metacognitive ability was increased when TMS was delivered at aPFC (Shekhar & Rahnev, 2018). The researchers interpreted the result as that dlPFC processes sensory evidence and relays the information to aPFC.

Distinguishing the exact brain regions that are related to the separate objective and subjective performance is tricky because of highly interacting perceptual decision and decision confidence processes. In theory, the two cognitive processes are computed based on the same information, which suggests that the same brain circuit might be responsible for both objective and subjective performance (Fetsch et al., 2014; Galvin et al., 2003; Kepecs et al., 2008; Kiani & Shadlen, 2009; Pouget et al., 2016; Sanders et al., 2016). On the other hand, other studies support that perceptual decision and decision confidence are processed at least using partially separate neural circuits (J. W. Bang et al., 2019; Fleming et al., 2015; Mueller & Weidemann, 2008; Rahnev et al., 2011; Rounis et al., 2010; Samaha et al., 2016; Song et al., 2015; van den Berg et al., 2016; Yeon et al., 2020; Zylberberg et al., 2012). Therefore, the specific brain regions that are activated by the separate objective and subjective performance can only be achieved when we dissociate the two types of performance.

1.3 Previous efforts to dissociate objective and subjective performance

How can we generate objective and subjective performance that are dissociated from each other? One possible way to achieve the dissociation is changing the strength (i.e., mean) and reliability (i.e., variance or noise) of sensory signals. Several research groups have tried to create visual stimuli that give rise to various levels of subjective performance while controlling for the objective performance (Boldt et al., 2017; de Gardelle & Mamassian, 2015; Desender et al., 2018, 2019; Koizumi et al., 2015; Navajas et al., 2016; Samaha et al., 2016; Spence et al., 2016; Zylberberg et al., 2016). These studies typically created experimental conditions that match the signal-to-noise ratio (d') but vary the physical level of evidence of the signals (Morales et al., 2019). For example, when confidence criteria are fixed while one condition has larger variance of the internal evidence distributions than another condition, the same decision would generate different level of confidence (**Figure 2**).

Different studies have utilized different task stimuli to generate dissociated task performance and confidence level. Some studies used multiple color patches in a screen while manipulating the mean and variabilities of the colors. The task for subjects is to figure out the mean color (**Figure 3A**) (Boldt et al., 2017; Desender et al., 2018). In some other studies, researchers utilized Gabor patches that have different signal strengths for a target and a non-target direction (**Figure 3B**) (Koizumi et al., 2015; Samaha et al., 2016).

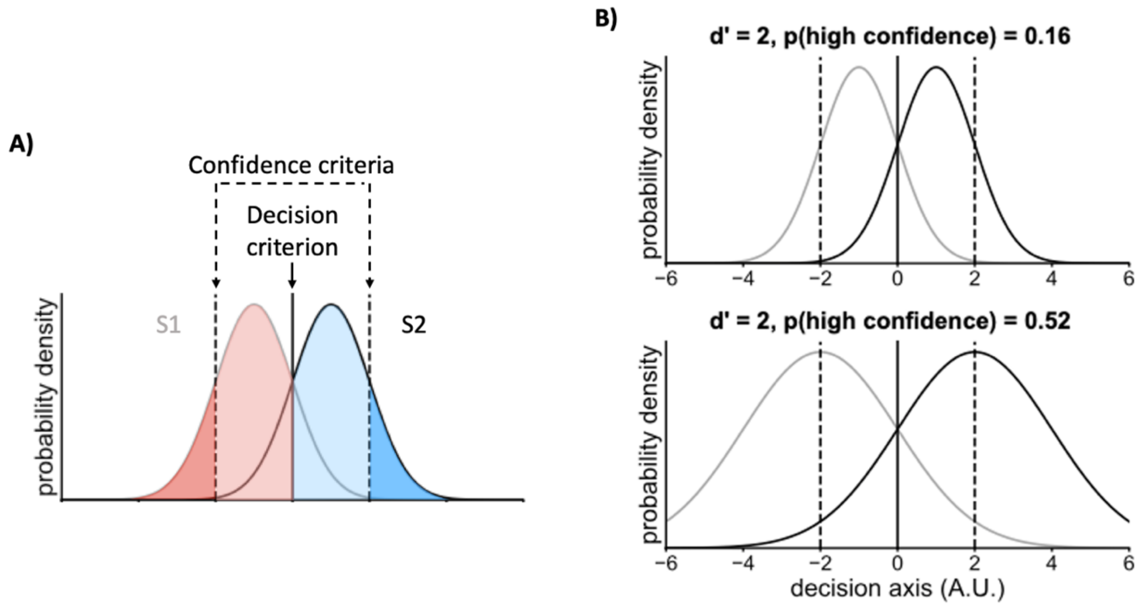

Figure 2. A case of dissociated task performance and confidence level based on signal detection theory. (A) In signal detection theory, subjects distinguish two sensory signals (e.g., S1 and S2) based on a decision criterion (solid line). If a given stimulus exceed the decision criterion, then subjects would select S2. If it does not exceed the criterion, then subjects would select S1. Subjects would have high or low confidence level depending on whether a given stimulus situates inside or outside of the confidence criteria (dotted lines). If a sample go beyond the criteria (i.e., outside of the criteria; areas with solid red and blue colors), then subjects would rate their confidence level high. On the other hand, if a given sample is placed inside of the criteria, then subjects would have low confidence (areas with transparent red and blue colors). (B) Different subjective confidence level while keeping the objective task performance the same can be achieved by modulate the variance of signals. When subjects have the same sensitivity (d') to two pairs of signals, the distinction task accuracy would be similar. However, a pair of signals with a large variance (bottom) would result in higher confidence level than when signals have a small variance (top). Figures retrieved and adjusted from Morales et al. (2019).

Also, some studies recruited randomly moving dot stimuli. The proportion of the coherently moving dots kept changed during the presentation in one condition, while it was stable in the other condition (**Figure 3C**) (Desender et al., 2019; Zylberberg et al., 2016). Lastly, researchers also used randomly moving dot stimuli, where they manipulated the degree of variance in the dot motion (**Figure 3D**) (de Gardelle & Mamassian, 2015; Spence et al., 2016).

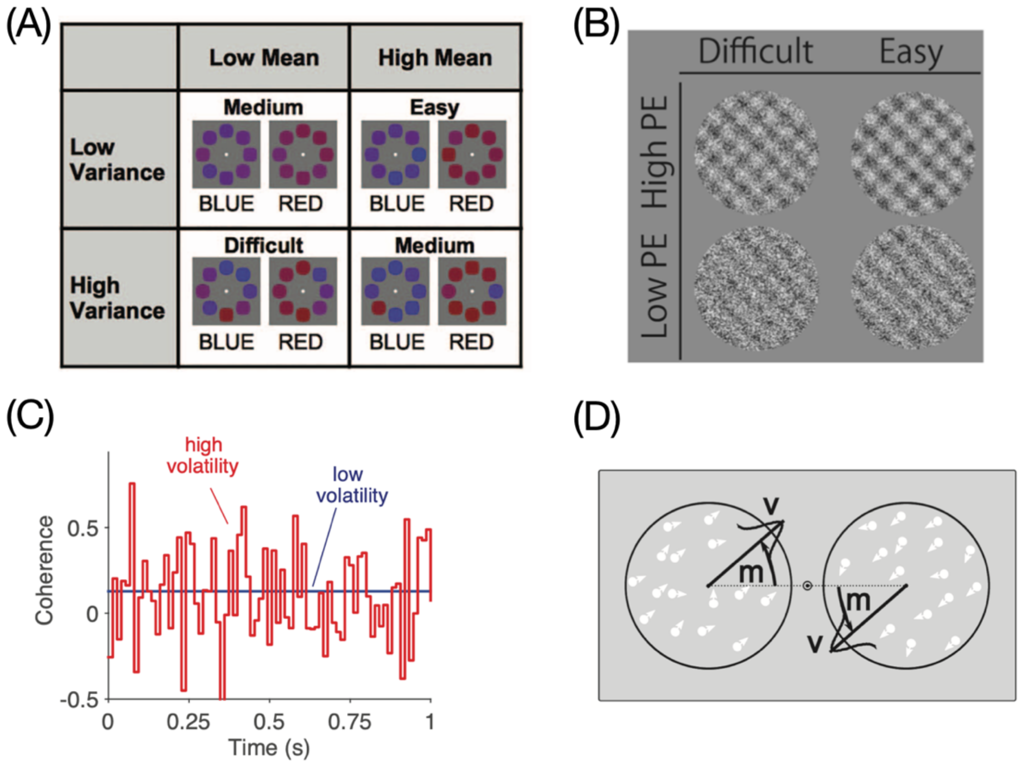

Figure 3. Stimuli used for dissociating objective and subjective performance. (A) In studies utilized color patches, researchers varied the reliability of sensory signals by manipulating the variances of color across the patches (The figure is retrieved from Boldt et al. (2017)). (B) When using Gabor patches, the strength of positive and negative evidence signals are manipulated (The figure is retrieved from Koizumi et al. (2015)). (C) An example trial that demonstrates how coherence level in moving dots changed in a high- (red line) and low-volatility (blue line) condition (The figure is retrieved from Zylberberg et al. (2016)). (D) In another type of randomly moving dot stimuli, the variance of dots' motion (noted as 'v' in the figure; 'm' indicates the mean direction of dots) was manipulated to vary the reliability level of the signal. The figure is retrieved from de Gardelle & Mamassian (2015).

1.4 Research idea of the present study

The research on dissociating objective and subjective performance is at a very early stage. Not only have some studies found different results with conceptually similar manipulations (Boldt et al., 2017; Desender et al., 2018, 2020; Spence et al., 2016; Zylberberg et al., 2016), but also not enough is known about how subregions in the brain are associated with the objective and subjective performance. Through the current study, I aimed to reveal the brain correlates of objective task performance and subjective confidence level using functional magnetic resonance images (fMRI).

I tried to generate conditions where the objective task accuracy and subjective confidence level are dissociated from each other based on pilot studies conducted in my lab. The current study presented a number of dots colored in either red or blue, and subjects were asked to answer which color was more frequent and then rated their confidence level of the decision. The experiment was a 2 x 2 factorial design, where one factor modulated the task difficulty (i.e., Easy vs. Difficult) and the other modulated the number of dots presented (i.e., Low vs. High). Dissociation in task accuracy and confidence level between Low and High conditions had observed in the pilot tests. This manipulation is conceptually similar to previous manipulations of positive evidence (Koizumi et al., 2015; Peters et al., 2017; Samaha et al., 2016; Song et al., 2015) bias that rely on the idea that confidence ratings are disproportionately influenced by evidence supporting the decision and tend to ignore evidence against it. Increasing the number of dots tends to increase both the confirmatory and disconfirmatory evidence, and therefore the observed increase in confidence can be thought of as an example of a positive evidence bias. The principal idea for the functional data analyses for the present study was comparing the condition with dissociated objective and subjective performance to the condition with covarying two performances.

Unfortunately, the main experiment did not show the behavioral effect of dissociated task performance and confidence level that previously observed. The planned general linear model (GLM) analysis revealed several brain regions in Easy > Difficult contrast test and Low > High contrast test including bilateral post-central gyrus, superior parietal lobule (SPL), left middle frontal gyrus (MFG), middle cingulate gyrus, and occipital and cerebellum regions. Nonetheless, any of the activated regions could distinguish either task difficulty or the number of dots presented in multi-voxel pattern analyses (MVPA). While the main conditions did not generate dissociated decision and confidence responses, I found weak dissociation effect between Difficult-High and Difficult-Low conditions. When compared the two conditions in a separate GLM, the result revealed higher activation in left middle temporal gyrus (MTG) and right SPL in Difficult-Low condition. Although the present study did not find brain regions strongly associated with either task performance or confidence level, it highlights the importance of research in dissociated objective and subjective performance.

CHAPTER 2. PILOT EXPERIMENTS

The experiment design of the current study stemmed from a project conducted in my lab. Three experiments were performed in the project (Pilot Experiments 1, 2, and 3). The details of the current study's experiment were decided based on the three pilot experiments. This section explains the three pilot studies in details and how the current study was planned.

2.1 Methods

2.1.1 Subjects

Twenty-five (Pilot Experiment 1 and 2) and fifteen (Pilot Experiment 3) healthy subjects participated in three pilot studies. All subjects had a normal or corrected-to-normal vision. The subjects were compensated with either \$10 or one credit for courses for participation. The study was approved by the Georgia Tech Institutional Review Board. All pilot studies were behavioral experiments.

2.1.2 Stimulus and task

The pilot studies presented clouds of differently colored dots. Pilot Experiment 1 presented two to four colors of dots in each trial (Red, Green, Blue and White; dot size = 5 pixels). Pilot Experiment 2 and 3 presented two to three colors of dots (Red, Green, and Blue). All dots were displayed randomly within 8° in radius from the center of the screen with black background color. At each trial, one color was presented more frequently than the other color. The task for the subjects was to indicate the dominant color and then evaluate their subjective confidence level about their previous decision using a four-point scale (lowest, low, high, and highest).

Pilot Experiment 1, 2, and 3 had eight, six, and twelve conditions each. Different condition presented different number of dots. Among the conditions, I want to introduce the first two conditions in Pilot Experiment 1 and 2, and all twelve conditions in Pilot Experiment 3, which are relevant to the current study.

In Pilot Experiment 1, the first and second conditions presented only two clouds of colored dots, where the two colors were selected randomly among four colors (red, green, blue, and white). The first condition presented 100 and 85 colored dots each for the dominant and non-dominant color (i.e., [100, 85] condition). The second condition presented [100, 90] dots (i.e., [100, 90] condition). The number of dots in the non-dominant color compared to the dominant color was small in the [100, 85] condition than the [100, 90] condition. Therefore, the decision task would have been easier in the [100, 85] condition than the [100, 90] condition.

The two conditions of Pilot Experiment 2 also presented two clouds of colored dots among three possible colors (red, green, and blue). While Pilot Experiment 1 kept the number of dots with the dominant color the same between the two conditions, Pilot Experiment 2 changed the number of dominant dots but maintained the same ratio of the dots between the dominant and non-dominant colors. In the first condition of Pilot Experiment 2, [100, 75] dots were presented (i.e., [100, 75] condition) and the second condition presented [80, 60] dots (i.e., [80, 60] condition). The ratio of the dots in the non-dominant color compared to the dominant color was the same as 75% between the two conditions.

In Pilot Experiment 3, three clouds of colored dots (red, green, and blue) were presented where the first two frequently presented colors are the focus of the current study. The first six conditions presented generally the greater number of dots than the last six conditions. Meanwhile, the ratio of the first two frequently presented colors was matched for between the two conditions that six conditions apart (e.g., the ratio was matched between the condition 1 and condition 7, condition 2 and condition 8, etc.). The exact numbers and ratios of the three clouds of dots in each condition can be found in **Table 1**.

Table 1. The number of dots and ratio between the three clouds of colored dots in Pilot Experiment 3. Twelve different conditions presented three clouds of colored dots in different numbers and ratios. The ratio of between the first two frequently presented colors was matched between the first and last six conditions the last six conditions (e.g., the ratio of the condition 1 was matched to condition 7, condition 2 to condition 8, etc.). However, the first six condition presented generally the greater number of dots than the last six conditions.

Condition #	Number of dots			Total number of dots	Ratio		
1	98	84	72	254	1	0.86	0.73
2	98	84	60	242	1	0.86	0.61
3	98	84	48	230	1	0.86	0.49
4	98	72	72	242	1	0.73	0.73
5	98	72	60	230	1	0.73	0.61
6	98	72	48	218	1	0.73	0.49
7	84	72	62	218	1	0.86	0.74
8	84	72	52	208	1	0.86	0.62
9	84	72	42	198	1	0.86	0.5
10	84	62	62	208	1	0.74	0.74
11	84	62	52	198	1	0.74	0.62
12	84	62	42	188	1	0.74	0.5

In each trial, a white fixation dot was presented for 500ms, and then a stimulus was presented for 500ms. The number of dot clouds and the number of each colored dots were determined according to the condition. The conditions were presented interleaved, and the order of the conditions was random. The colors of dominant and non-dominant dot clouds were also decided in a random order. After the stimulus offset, the subjects indicated which color of the dots was dominant among all possible colors. The keys used for the decision response were ‘z (Red)’, ‘x (Green)’, ‘c (Blue)’, and ‘v (White; for Pilot Experiment 1 and 2)’ and subjects answered using their left hand. Then, the subjects evaluated their subjective confidence level about the previous decision, using a four-point scale. Subjects used four different keys (‘N (1, Lowest)’, ‘M (2, Low)’, ‘< (3, High)’, and ‘> (4, Highest)’) and answered with their right hand (**Figure 4**). The stimulus was created on MATLAB (R2016a) using the Psychtoolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

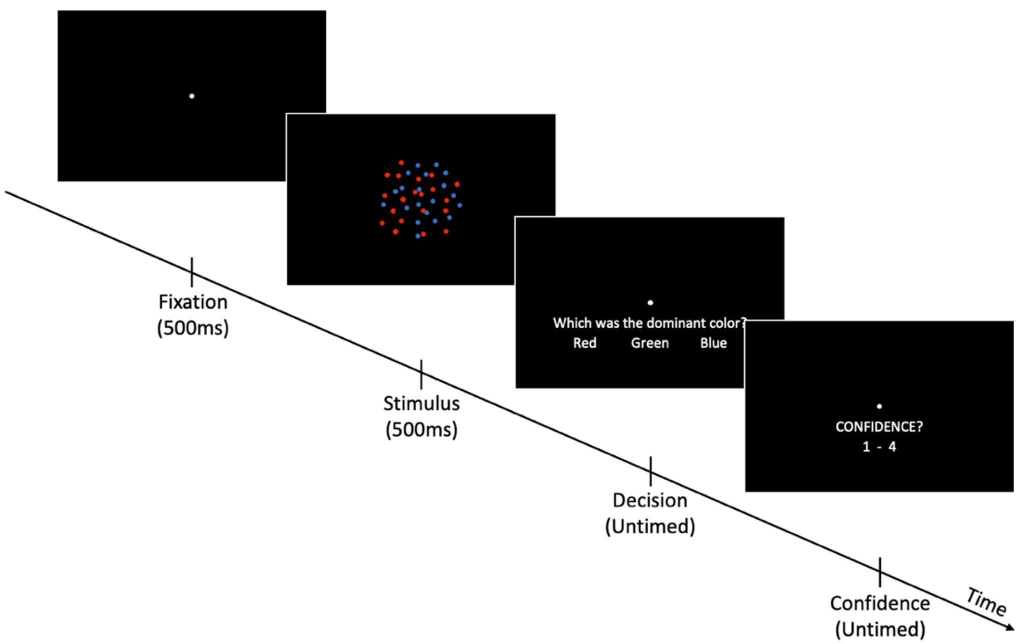

Figure 4. Example of a single trial in pilot experiments. In each trial, a white fixation dot was presented for 500 ms, then a stimulus presentation screen followed for 500 ms. After the stimulus offset, subjects judged which color was presented most frequently. Once they made a decision, the screen presented a confidence judgment prompt, and subjects evaluated their confidence level on a four-point scale. Both decision and confidence responses were untimed. While the figure depicts an example of a possible trial in Pilot Experiment 2, the design of all three pilot experiments were the same and the only

differences were the number of colors used (Pilot Experiment 1: red, green, blue and white; Pilot Experiments 2 and 3: red, green, and blue).

2.1.3 Procedure

After the subjects arrived in the lab, the experimenter gave a brief verbal instruction about the experiment and subjects signed the consent form. The subjects conducted the task through a computer (iMac Late 2015, 21.5-inch display) in a dark room. They first underwent a training session before doing the main experiment. During the training session, subjects were given instructions of how to perform the task and practiced 90 example trials. After completing the training session, the subjects did the main experiment. Pilot Experiment 1 and 2 consisted of three runs of four blocks, and each block included 48 trials (3 runs x 4 blocks x 48 trials = 576 trials in total). Pilot Experiment 3 had four runs of five block, and each block consisted of 48 trials (4 runs x 5 blocks x 48 trials = 720 trials in total). The resting time between blocks was 15 seconds. The subjects could determine themselves to end the resting period between the runs.

2.2 Data analysis and results

The first condition of Pilot Experiment 1 (i.e., [100, 85] condition) presented the smaller number of dots in the non-dominant color compared to the second condition (i.e., [100, 90] condition). The first condition presented relatively more non-dominant dots (85% of the dominant dots) than the second condition (90% of the dominant dots). Therefore, the decision task would have been easier in the first condition for the subjects. Corresponding to the expectation, the first condition showed higher objective task accuracy (M = 66.7%, SD = 6.34%) than the second condition (M = 61.9%, SD = 6.03%, $t(24) = 3.98$, $p = 5.54 \times 10^{-4}$). Although the first condition also showed higher subjective confidence level (M =

2.76, SD = .29), the difference was not significantly large enough from the confidence level of the second condition (M = 2.73, SD = .35, t(24) = .977, *p* = .338; all tests are two-sided paired t-test) (**Figure 5**).

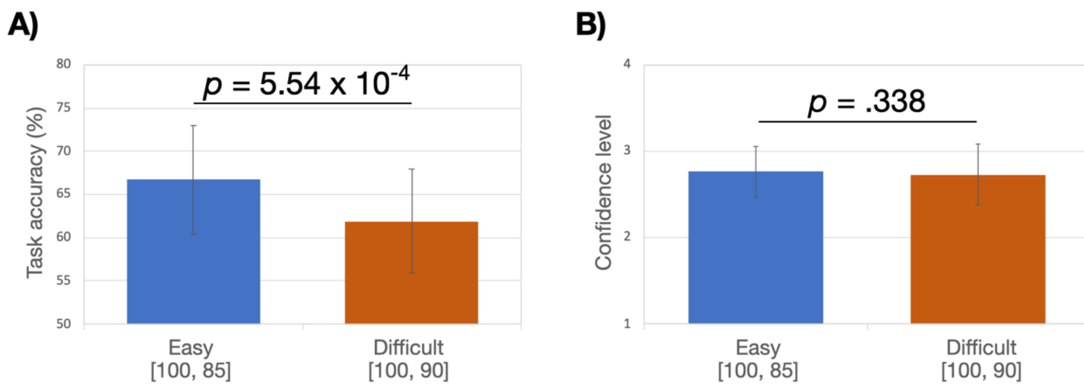

Figure 5. Task accuracy and confidence level of Pilot Experiment 1. The Easy condition presented smaller number of non-dominant color dots than the Difficult condition, which made the decision task easier. (A) The Easy condition showed higher task performance (M = 66.7%, SD = 6.34%) than the Difficult condition (M = 61.9%, SD = 6.03%; t(24) = 3.98, $p = 5.54 \times 10^{-4}$). Meanwhile, (B) the confidence level between the two conditions were not significantly different (Easy: M = 2.76, SD = .29; Difficult: M = 2.73, SD = .35; t(24) = .977, *p* = .338). The similar confidence levels between the two conditions might be due to the small difference in the number of non-dominant color dots between the two conditions.

The first two conditions in Pilot Experiment 2 presented two clouds of colored dots that consisted of [100, 75] and [80, 60] dots. The first condition presented greater number of dots than the second condition. Meanwhile, the ratio of the non-dominant dots relative to the dominant dots was kept the same between the two conditions (75% of the dominant dots). Because the dominant color ratio of the two conditions were matched, the decision task difficulty would have been similar. As expected, the task performances between the two conditions were not different ([100, 75] condition: M = 83.7%, SD = 7.21%; [80, 60] condition: M = 86.3%, SD = 7.36%; t(24) = 3.12, *p* = .005). However, the subjective confidence level was significantly lower when the stimulus presented the smaller number of dots ([100, 75] condition: M = 2.74, SD = .38; [80, 60] condition: M =2.93, SD = .39; t(24) = 6.44, $p = 1.15 \times 10^{-6}$) (**Figure 6**).

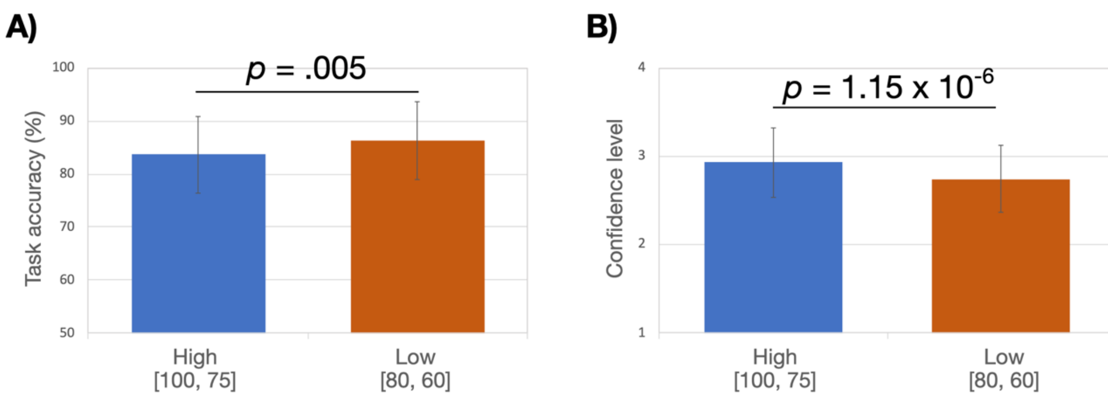

Figure 6. Task accuracy and confidence level of Pilot Experiment 2. When the lower number of dots were presented (M = 86.3%, SD = 7.36%), the task accuracy was higher than when the higher number of dots were presented (M = 83.7%, SD = 7.21%; t(24) = 3.12, p = .005). However, the confidence level between the two conditions was higher when the higher number of dots were presented (M = 2.93, SD = .39; Low: M = 2.74, SD = .38; t(24) = 6.44, $p = 1.15 \times 10^{-6}$). The ratio of the non-dominant color was the same between the two conditions, so theoretically the task difficulty between the two conditions would be the same.

In Pilot Experiment 1, while the task accuracy of the easy ([100, 85]) and the difficult ([100, 90]) conditions showed a large difference (4.8%), but the subjective confidence levels were almost the same (Difference = .027). In Pilot Experiment 2, because the task difficulty was matched between the two conditions, the objective performance was marginally differed by 2.6%. However, the subjective confidence level showed large deviation (Difference = .18). The results of Pilot Experiment 1 and 2 collectively demonstrated that people generally rate their subjective confidence level lower when the smaller number of dots were presented, even though the task difficulty was matched.

Using the result of Pilot Experiment 3, I further confirmed that the low number of dots causes lower subjective performance. To simplify the analysis, I focused on the first two frequently presented colors. The first six conditions generally presented the greater number of dots than the last six conditions. Moreover, the ratios of the second most frequently presented color relative to the dominant color were matched for each of the first and the last six conditions (**Table 1**). Specifically, the ratio of the second frequently presented color (non-dominant) compared to the dominant color was matched between condition 1-3 and 7-9 (86%), and condition 4-6 and 10-12 (73-74%). Because condition 1-3 and 7-9 presented relatively larger number of dots in the non-dominant color (i.e., greater noise; Difficult condition) than condition 4-6 and 10-12, discrimination task would have been easier in condition 4-6 and 10-12 (i.e., Easy condition).

As expected, compared to the difficult condition, Easy condition showed higher objective (Easy condition: M = 78.8%, SD = 7%; Difficult condition: M = 65.4%, SD = 6.3%; Difference = 13.4%, t(14) = 16.68, $p = 1.24 \times 10^{-10}$) and higher subjective performance (Easy condition: M = 2.62, SD = .402; Difficult condition: M = 2.52, SD = .428; Difference = .1, t(24) = 4.87, $p = 2.46 \times 10^{-4}$). On the other hand, condition 1-6 (i.e., High condition) presented comparatively the larger number of dots than condition 7-12 (i.e., Low condition; Average difference in the total number of dots = 33). Surprisingly, while the objective performance was similar between Low and High condition (Low condition: M = 71.4%, SD = 6.9%; High condition: M = 72.7%, SD = 6.3%; Difference = 1.3, t(14) = -1.72, p = .107), we observed again significantly lower subjective performance in the low condition (Low condition: M = 2.49, SD = .41; High condition: M = 2.64, SD = .42; Difference = .15, t(14) = -6.11, $p = 2.69 \times 10^{-5}$) (**Figure 7**).

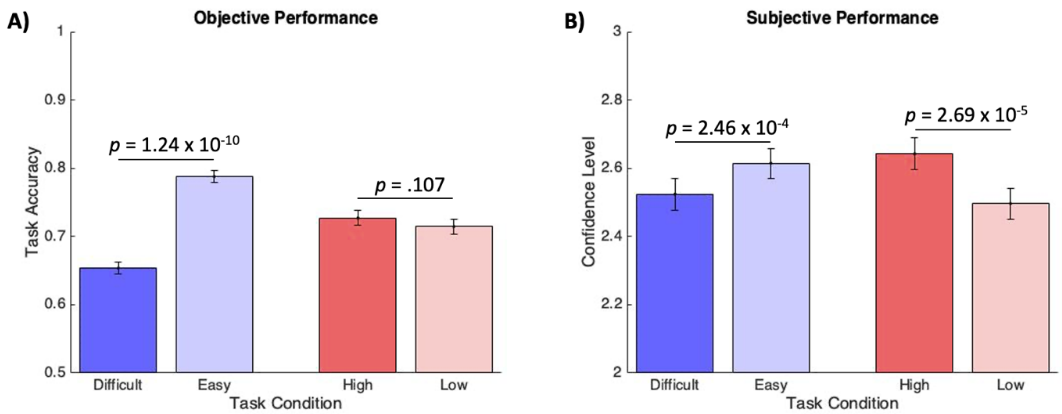

Figure 7. The objective and subjective performance in Pilot Experiment 3. For simplicity, the twelve conditions were grouped into Difficult (Conditions 1-3 and 7-9) and Easy (Conditions 4-6 and 10-12) conditions depending on the ratio of the dots in the non-dominant color relative to the dominant color, and the High (Conditions 1-6) and Low (Conditions 7-12) conditions depending on the total number of dots presented. (A) Easy condition showed higher objective and subjective performance compared to Difficult condition (left two blue bars). On the other hand, High and Low conditions showed almost the same objective task accuracy (right two red bars). (B) The subjective performance was higher in Easy condition compared to Difficult condition, as expected (left two blue bars). However, Low condition showed a much lower confidence level compared to High condition (right two red bars). The result demonstrated that Low condition results in substantially lower subjective confidence level than High condition, considering the small difference in the objective performance.

CHAPTER 3. METHODS

3.1 General experimental design

The three pilot tests together demonstrated that when a smaller number of dots are presented (i.e., Low condition), then people rate their confidence level relatively lower than when a greater number of dots are presented (i.e., High condition) (**Figure 8A**). Based on the findings, I designed the current study with two factors, which has two levels. The first factor was task difficulty, where the levels were easy and difficult. The second factor were the number of dots, where the levels were high and low.

Successful dissociation of objective task performance and subjective confidence level between High and Low conditions would make it possible to investigate brain regions associated with individual high (or low) objective or subjective performance through combinations of the four experimental conditions (**Figure 8B**). For instance, if a brain region is activated for Easy condition compared to the Difficult condition and the same region is detected in High condition, then it can be assumed that the region is associated with high subjective confidence level. Similarly, if a same brain region is activated for both Easy and Low conditions compared to Difficult and High conditions individually, then we can interpret that the region might be associated with high task performance.

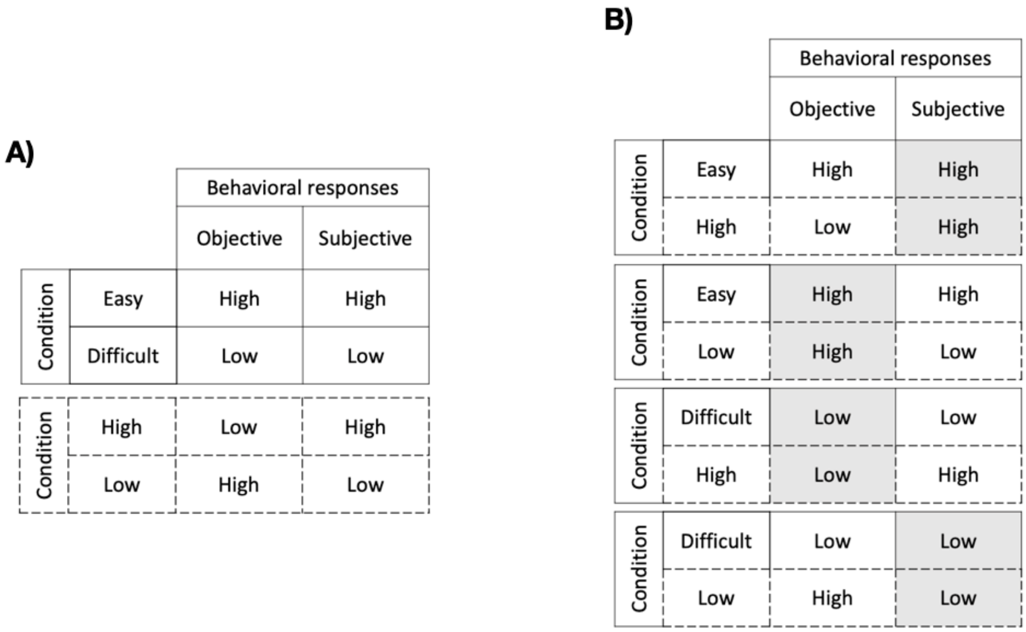

Figure 8. Design of the experiment and an overview of the data analysis. (A) From the pilot tests, I found that High condition generated relatively higher subjective confidence level than Low condition. Based on the previous studies, I designed the current study with a 2 x 2 factorial design. The first factor modulates task difficulty (Easy and High) and the second factor modulates the number of dots presented (High and Low). (B) Specific combinations of the experimental condition could reveal brain regions associated with individual high (or low) task performance and confidence level. For example, if a same brain region is found in Easy and High conditions compared to Difficult and Low conditions, the region might be associated with high subjective confidence level. Similarly, if a same brain area is revealed in Easy and Low conditions compared to Difficult and High conditions individually, it can be assumed that the region is associated strongly with high objective task performance.

The number of dots presented for each of the four conditions (i.e., Difficult-High, Difficult-Low, Easy-High, and Easy-Low) were decided based on the pilot test results (**Table 2**). Across the three pilot tests, I looked into the objective task performances and subjective confidence levels of four different combinations of the number of dots presented (i.e., [100, 90], [100,85], [100, 75], and [80, 60] dots for the dominant and non-dominant colors). Moreover, I estimated expected task performance and confidence level of three unexplored combinations of dots (i.e., [100, 88], [100,80], and [80, 70] dots for the dominant and non-dominant colors). From the observed and estimated performances, four combinations of the number of dots were selected. The four conditions were selected where the two Difficult conditions (red boxes in **Table 2**) would produce low task performance and confidence level than the two Easy conditions (blue boxes in **Table 2**), and the two High conditions (boxed conditions in the top of **Table 2**) would generate relatively higher confidence level compared to the task performance than the two Low conditions (boxed conditions in the bottom of **Table 2**)

Table 2. The number of dots used for individual four conditions. Based on the observed behavioral responses, objective task performance and subjective confidence level of three unexplored conditions were estimated. From the observed and estimated result, four individual conditions for the current study were selected. Red boxes indicate Difficult condition while blue boxes indicate Easy condition. Two High conditions (top) are supposed to generate lower task accuracy but higher confidence level than two Low conditions (bottom).

High Condition

Observed/Expected	Observed	Expected	Observed	Expected	Observed
# Dominant dots	100	100	100	100	100
# Non-dominant dots	90	88	85	80	75
Ratio	0.9	0.88	0.85	0.8	0.75
Objective performance	61.9	64.3	66.7	76.5	86.3
Subjective performance	2.78	2.77	2.76	2.85	2.93

Low Condition

Observed/Expected		Expected			Observed
# Dominant dots		80			80
# Non-dominant dots		70			60
Ratio		0.88			0.75
Objective performance		61.7			83.7
Subjective performance		2.58			2.74

3.2 Subjects

Fifty-two subjects initially participated in the study. We aimed for a larger sample size than most traditional fMRI studies in order to maximize the power to find potentially subtle differences in activation between regions that are driven primarily by objective vs. subjective performance. However, no formal power analysis was performed. Two subjects were excluded from the data analysis: one subject quit the experiment and the other subject showed negative m-ratio (-.053) (Maniscalco & Lau, 2012) (25 females; mean age = 26 years old; age range = 19-40 years old). Subjects were all right-handed and had normal or corrected-to-normal vision. No subject had history of neurological disorders and screened for MRI safety before they went to the scanner. They received 20,000 KRW (about 18 USD) for their participation. The study was approved by the review board of Ulsan National Institution of Science and Technology (UNISTIRB-20-30-C).

3.3 Stimulus and task

The experimental stimulus and task were similar to the pilot experiments. The stimulus screen presented a number of dots in a black background which were painted in either red or blue colors. On each trial, subjects were asked to figure out which color was more frequently presented. After they made decision responses, subjects rated their confidence lever for the decision in a four-rating scale.

A single trial began with a white fixation dot at the center of the screen, which was presented randomly between 500-1500 ms (**Figure 9**). A task stimulus was followed at the offset of the fixation point (500 ms). The stimulus screen presented dots (dot size = 5 pixel) dispersed randomly within 3° from the center of the screen. After the stimulus presentation, a decision response prompt was given and lasted until subjects made a response. Once subjects responded, a confidence rating prompt was followed and also lasted until subjects made a confidence response.

The experiment had two factors, task difficulty and the number of dots presented. In Difficult-High condition, [100, 90] ([dominant, non-dominant]) dots were presented, while Difficult-Low condition presented [80, 70] dots. The Easy-High condition presented [100, 80] dots and the Easy-Low condition presented [80, 60] dots.

Subjects used an MRI compatible button box for the decision and confidence responses. For the decision responses, subjects answered with the buttons located at their right index (red) and middle finger (blue). For the confidence responses, they used all four buttons and rated their confidence level in a 4-point scale (1: the lowest (index finger) – 4: the highest (little finger)).

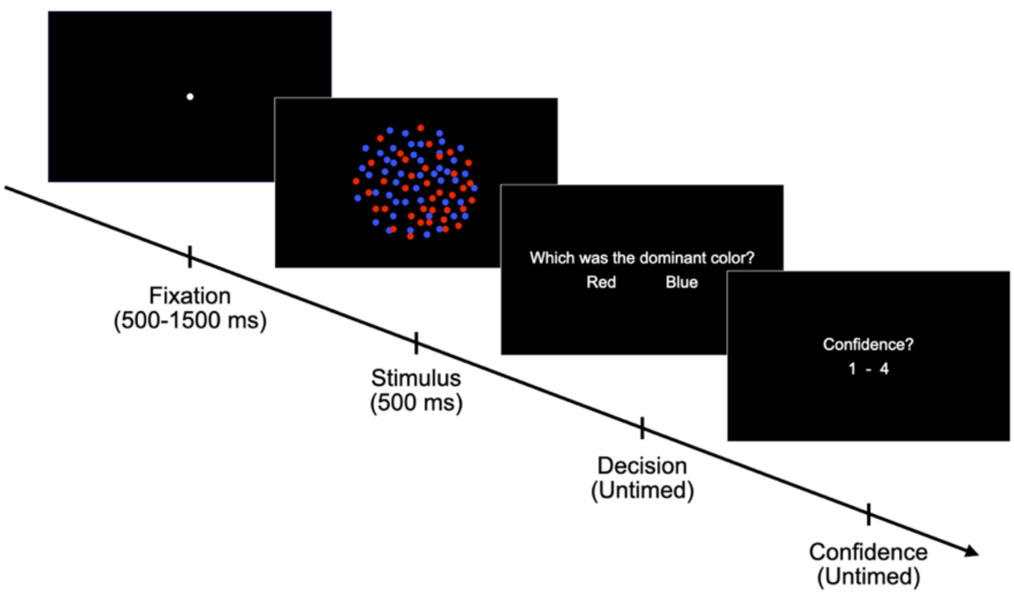

Figure 9. Design for a single trial in the main experiment. A trial began with a white fixation dot on a black screen and then a stimulus screen was followed. After the stimulus offset, subjects were asked to answer the dominant color and their confidence level of their previous decision. Both decision and confidence responses were untimed.

3.4 Procedure

At the arrival to the lab, subjects were given verbal explanation about the study goal and task procedure. Subjects were then screened for the MRI safety and provided a written consent form. Subjects were put into the scanner right afterwards, and there was no practice session outside the scanner.

After subjects were placed in the scanner, their anatomical brain images were first collected. During the collection of anatomical images, detailed instruction about the task was given through a screen behind the scanner. To calibrate the luminance of red and blue colors for individual subject, a set of 20 trials were presented after the instruction. The calibration trials presented the equal number of red and blue colored dots for 2 seconds (80 dots each). Subjects were asked to decide which color was more frequently presented. There was no true answer because the number of each color was the same. The luminance of the chosen color was reduced by 20 in the first six trials, by 10 in the next eight trials, and by five in the remaining trials (max luminance = 255). The final luminance values of the red and blue colors were used for the rest of the experiment. Following the calibration session, 90 practice trials were given to make subjects more familiar to the task. The practice trials began with easy level (e.g., longer stimulus presentation time), but gradually matched the difficulty of the task to the main experiment. For the practice trials, feedback was given for the first 50 trials.

The main experiment began after the practice session. Functional images of the brain were collected while subjects performed the main experiment. The experiment consisted of 6 runs and a single run had 16 blocks. Each block presented 8 trials (6 runs x 16 blocks x 8 trials = 768 trials in total). There were 5-seconds short resting time between the blocks. Two subjects quit the experiment after the 5th run. One subject could not complete the 6th run due to the time constraint and completed until 11th block of 6th run. Three other subjects completed only half (8 blocks) of the last 6th run. The remaining 44 subjects completed all six runs.

3.5 fMRI acquisition and preprocessing

The MRI data were collected on a 3T MRI system (Magnetom Prisma; Siemens) located at the IBS Center for Neuroscience Imaging Center in Sung Kyun Kwan University, South Korea. A 64-channel head coil was used to collect the data. Anatomical images were acquired using T1-weighted MPRAGE sequences (FoV = 256 mm; TR = 2300 ms; TE = 2.28 ms; 192 slices; flip angle = 8°; voxel size = 1.0 x 1.0 x 1.0 mm^3). Functional images were collected using $T2^*$-weighted multi-band accelerated EPI sequence (Xu et al., 2013) (FoV = 200 mm; TR = 2000 ms; TE = 35 ms; 72 interleaved slices; flip angle = 90°; voxel size = 2.0 x 2.0 x 2.0 mm^3).

For the MRI data preprocessing, SPM12 (Wellcome Department of Imaging Neuroscience, London, UK) was used. Three dummy scans were removed for the scanner equilibration. All images were first converted from DICOM to NIFTI and then origin was manually set at the anterior commissure. The functional images then were preprocessed with de-spiking, slice-timing, and realignment procedures. The anatomical images were processed with segmentation, and skull-removed brain images were generated by using the white and gray matter of the segmented anatomical images. The coregistration procedure was applied to the skull-removed images and the functional images of individual subjects. The functional images then normalized and smoothened with 6 mm full-width-half-maximum (FWHM) Gaussian kernels.

3.6 Behavioral analysis

Average task accuracy and confidence level were calculated and compared jointly for each factor (i.e., Difficult, Easy, High, and Low), as well as for the four individual conditions (i.e., Difficult-High, Difficult-Low, Easy-High, and Easy-Low). For the statistical comparisons, two-sample t-test was performed. Also, to examine possible interactions between the two factors, ANOVA analyses on task accuracy and confidence level were performed. In addition to that, response time (RT) for decision and confidence answers were also calculated and compared.

3.7 Planned fMRI analyses

The first analysis I performed was the GLM analysis. The GLM analysis is the very basic analysis in fMRI. The aim of the analysis was to find brain regions activated separately by the objective task performance and subjective confidence level. Two sets of analyses were conducted. In the first set of analysis, a design matrix contained regressors for Difficult and Easy conditions was created. In the second set of analysis, a design matrix included regressors for High and Low conditions. Other than the regressors related to the experiment factors, the design matrices also included one regressor for between-block periods, six regressors related to head movement (three translational and three rotational regressors), four tissue regressors (white matter, cerebrospinal fluid and bone, soft tissue, and air and background), and a constant term. The regressors were defined for individual runs. Therefore, for subjects who completed all six runs of experiment had 84 regressors in a design matrix (6 runs x (2 factor-related + 1 between blocks + 6 head movement + 4 tissue + 1 constant regressors) = 84 regressors).

In order to find out brain regions associated with either task performance or confidence level, I compared the Difficult and Easy regressors each other in the first set of analysis (Difficult > Easy and Easy > Difficult), and the High and Low regressors in the second set of analysis (High > Low and Low > High). Individual level results were fed into group analysis. The statistical maps were thresholded with $p < .001$ (uncorrected) and cluster size ≥ 80 for display.

The second planned analysis of the study was the MVPA analysis. The analysis complements univariate analysis (i.e., GLM analysis) by incorporating multiple voxels' activations together (Haynes & Rees, 2006; Kriegeskorte, 2011; Norman et al., 2006). Multivariate decoding is one of the most popular methods, which gives great sensitivity and specificity in finding patterns of brain responses to a particular category (Hebart et al., 2015).

The MVPA analysis aimed to find whether any regions revealed in the previous GLM analysis (ROIs) can distinguish the levels of task accuracy and confidence. Different combinations of the experimental conditions were expected to generate different level of task accuracy and confidence (**Figure 10**). For instance, higher task accuracy would be observed in Easy and Low conditions compared to Difficult and High conditions. Considering that, Easy-Low condition would generate the highest task accuracy, while Difficult-High condition would show the lowest task accuracy. On the other hand, both Easy-Low and Difficult-High conditions would generate a moderate level of confidence.

Similarly, Easy and High conditions were expected to generate higher confidence level compared to Difficult and Low conditions. Therefore, Easy-High condition would generate the highest confidence level, and Difficult-Low condition would show the lowest confidence level, while the task performance would be moderate level for both conditions.

Task difficulty \ Quantity of dots	Low (HA, LC)	High (LA, HC)
Easy (HA, HC)	[HA, HA] = HA [HC, LC] = MC	[HA, LA] = MA [HC, HC] = HC
Difficult (LA, LC)	[LA, HA] = MA [LC, LC] = LC	[LA, LA] = LA [LC, HC] = MC

Figure 10. Plan for generating two decoding models to find ROIs that can distinguish different levels of task accuracy and confidence. The table shows expected level of task performance and confidence for the four individual conditions of the experiment. For instance, Easy-Low condition would show the highest task performance among the four individual conditions, because both Easy and Low condition would generate higher task accuracy than Difficult and High condition. On the other hand, Difficult-High condition would generate the lowest task accuracy. Similarly, Difficult-Low and Easy-High conditions were expected to generate the lowest confidence level and the highest confidence level, respectively. Using MVPA, one decoding model tested high vs. low task accuracy (i.e., Easy-Low vs. Difficult-High) and the other model tested high vs. low confidence level (i.e., Easy-High vs. Difficult-Low) (High accuracy: HA; Moderate accuracy: MA; Low accuracy: LA; High confidence: HC; Moderate confidence: MC; Low confidence: LC). Texts highlighted with blue color indicate high and low task performance and with yellow color indicate high and low confidence level.

To perform the MVPA analysis, I generated a separate GLM with regressors for the four individual conditions (e.g., Difficult-High, Difficult-Low, Easy-High, and Easy-Low) estimated separately for each run. For the MVPA model training and testing, leave-one-run-out method was used where the beta values of five runs were fed into the training model and then the data of the remaining one run was used for the testing the model. This procedure requires training to be done on very few datapoints (just five sets of samples from each of the four conditions) but each individual sample has a relatively low level of noise. In the Discussion, I return to this issue and discuss other ways in which the MVPA analyses could be performed.

The first decoding model trained beta values of the ROIs to test high vs. low task performance with moderate confidence level (i.e., Easy-Low vs. Difficult-High), and the second decoding model trained and tested the distinction between high vs. low confidence level with moderate task accuracy (i.e., Easy-High vs. Difficult-Low). For model training and testing, leave-one-run-out cross-classification method was used. For the classification, support vector machine was used. Individual-level decoding accuracies of the model were averaged across the subjects to report the group-level decoding accuracy. The MVPA analysis was performed using The Decoding Toolbox (TDT) (Hebart et al., 2015).

The initial plan for the data analysis included functional connectivity analysis between the regions revealed in the GLM and visual cortex. The aim for the connectivity analysis was to investigate how the pattern of functional connectivity of the brain regions changes between the decision and confidence processes. However, the GLM analysis could not find strong association between the activated brain regions and the decision and confidence processes. The MVPA analysis also did not show meaningful result. Therefore, I could not find reliable regions associated selectively with objective and subjective performance and consequently could not perform connectivity analyses on these regions.

3.8 Exploratory fMRI analyses

In the behavioral analysis, the task accuracy between Difficult-High and Difficult-Low conditions was higher in Difficult-Low condition, while the confidence level was slightly lower in Difficult-Low condition (see Behavioral results). As an exploratory analysis, I generated a separate model for contrast tests between Difficult-High and Difficult-Low conditions. The model included regressors for Difficult-High and Difficult-Low conditions, and the trials for the rest conditions (i.e., Easy-High and Easy-Low conditions) were put into a single regressor. The model also included the between-block regressor, as well as six head movements, four tissues, and a constant term per run. Two contrast tests (Difficult-High > Difficult-Low and Difficult-Low > Difficult-High) were performed, and statistical maps of individual subjects were used for the second-level analysis. The statistical map was thresholded with $p < .001$ (uncorrected) and voxel size ≥ 80 for display.

CHAPTER 4. BEHAVIORAL RESULTS

4.1 Accuracy and confidence results

The behavioral responses for the task performance were slightly different from the expectation. When planning for the experiment, I expected to observe the highest task performance in Easy-Low condition and the second highest task accuracy in Easy-High condition (**Table 2**). However, the result revealed that Easy-Low condition showed the highest task accuracy (M= 86.9%, SD = 6.6), which was followed by Easy-High condition (M = 83.9%, SD = 7.7) (**Figure 11**). On the other hand, Difficult-Low and Difficult-High conditions were expected to generate similar task accuracy. Nevertheless, the observed data showed higher task performance in Difficult-Low condition (M = 70.8%, SD = 6.2) compared to Difficult-High condition (M = 68.2%, SD = 6.8; t(49) =-3.17, p = .0026). Beyond examining the individual conditions, I also examined the two experimental factors. The result showed higher task accuracy in Easy condition (M = 85.4%, SD = 6.7) than Difficult condition (M = 69.5%, SD = 5.9; t(49) = -34.75, $p = 3.51 \times 10^{-36}$), as expected. Moreover, Low condition (M = 78.9%, SD = 5.9) also showed higher task accuracy than High condition (M = 76.1%, SD = 6.9; t(49) = -4.57, $p = 3.34 \times 10^{-5}$) (**Figure 12**). An ANOVA test found that both task difficulty (F(1,196) = 272.01, $p = 6.73 \times 10^{-39}$) and the number of presented dots (F(1, 196) = 8.2, p = .0046) affected the task accuracy, but there was no interaction between the two factors (F(1,196) = .04, p = .836).

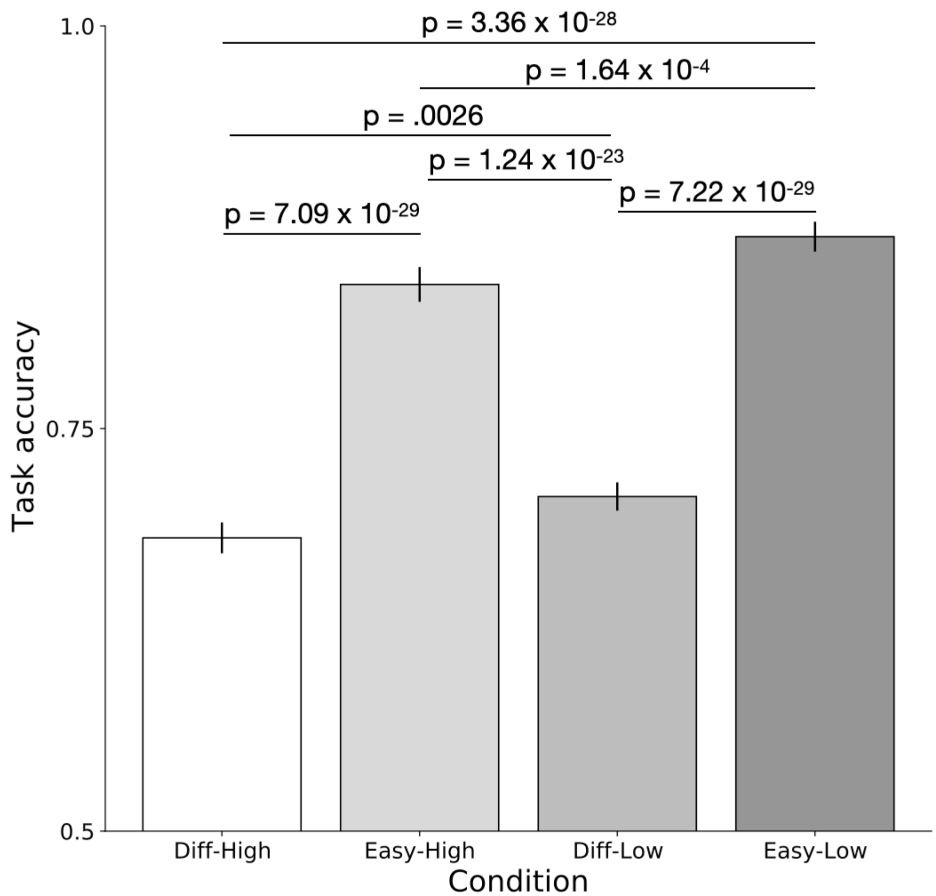

Figure 11. Task performance in the four individual conditions. Difficult-High condition (M = 68.2%, SD = 6.8) showed lower task accuracy than Difficult-Low condition (M = 70.8%, SD = 6.2; t(49) = -3.17, p = .0026). The difference in task performance was greater between Easy-High and Easy-Low conditions. Easy-Low condition generated higher task performance (M = 86.9%, SD = 6.6) than Easy-High condition (M = 83.9%, SD = 7.7; t(49) = -4.08, $p = 1.64 \times 10^{-4}$). Two-sample t-tests were performed and the error bars indicate standard errors.

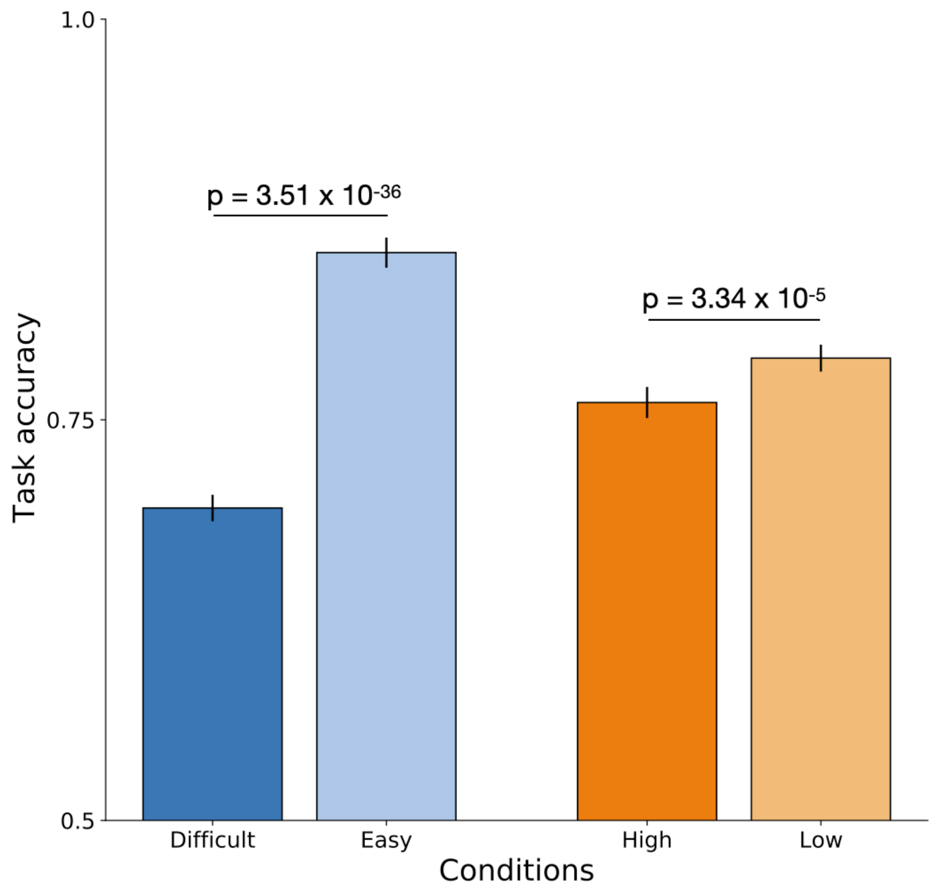

Figure 12. Task performance comparisons between the conditions grouped by experimental factors. Not only Easy condition (M = 85.4%, SD = 6.7) showed higher task condition to Difficult condition (M = 69.5%, SD = 5.9; t(49) = -34.75, p = 3.51 x 10^{-36}), but Low condition (M = 78.9%, SD = 5.9) also showed higher task performance to High condition (M = 76.1%, SD = 6.9; t(49) = -4.57, p = 3.34 x 10^{-5}). Two-sample t-tests were performed and the error bars indicate standard errors.

Not only the task performance, but also the confidence responses were different from the initial expectation. Originally, I assumed that higher confidence level would be observed in Easy condition compared to Difficult condition, and in High condition compared to Low condition (**Table 2**). Hence the expected order of the confidence level was the highest in Easy-High condition, followed by Difficult-High, Easy-Low, and Difficult-Low conditions. However, the real data showed different results from my expectation. The highest confidence level was observed in Easy-Low condition (M = 2.67, SD = .473), and followed by Easy-High (M = 2.61, SD = 4.63), Difficult-High (M = 2.38, SD = .502), and Difficult-Low condition (M = 2.34, SD = .487) (**Figure 13**). When calculated the confidence level by grouping task difficulty, the result revealed that Easy condition (M = 2.64, SD = .462) showed higher confidence level than Difficult condition (M = 2.36, SD = .489; $t(49) = -12.61$, $p = 5.27 \times 10^{-17}$). Importantly, while I expected to find higher confidence level in High condition compared to the Low condition, the effect was not observed. When the data was grouped by the number of dots, it turned out that there was no difference in confidence level between High (M = 2.49, SD = .475) and Low conditions (M = 2.50, SD = .471; $t(49) = -.528$, $p = .6$) (**Figure 14**). An ANOVA test found that only the task difficulty factor had a significant effect on confidence ($F(1, 196) = 17.15$, $p = .0001$). There was no main effect of the number of presented dots ($F(1, 196) = .02$, $p = .8949$) and no interaction between task difficulty and number of presented dots ($F(1, 196) = .53$, $p = .4682$).

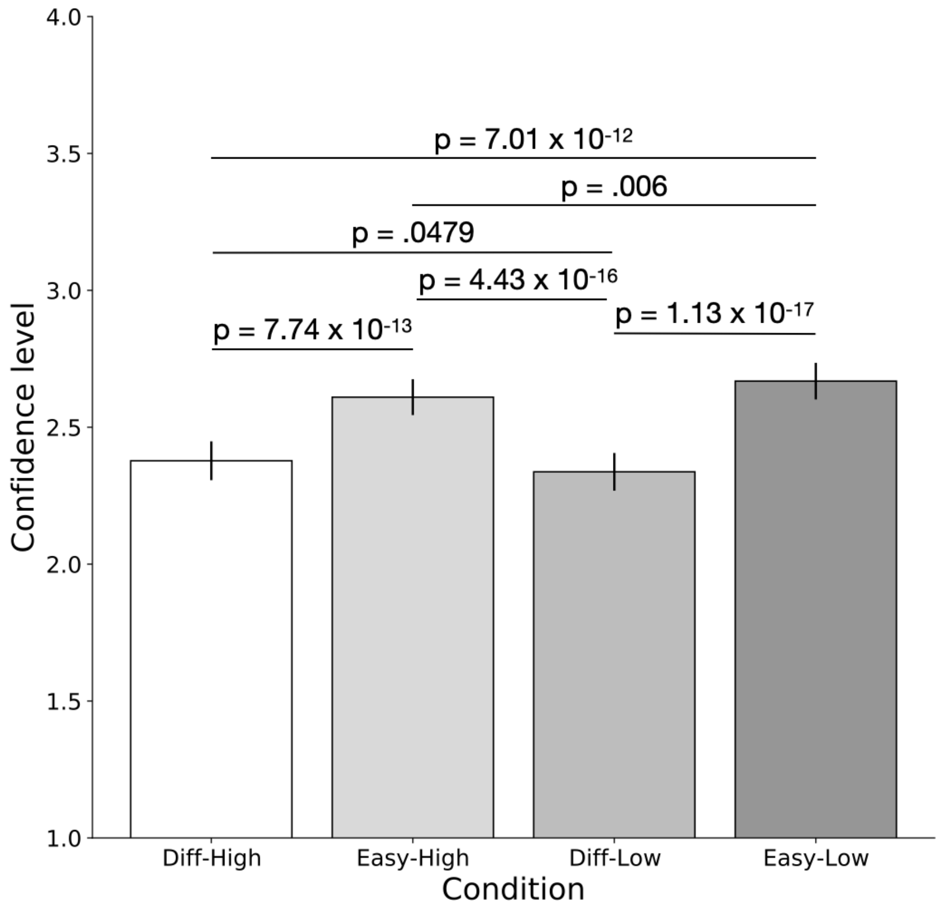

Figure 13. Confidence in the four individual conditions. Easy-Low (M = 2.67, SD = .473) condition showed the highest confidence level, which was followed by Easy-High (M = 2.61, SD = .463), Difficult-High (M = 2.38, SD = .502), and Difficult-Low (M = 2.34, SD = .487) conditions. In Easy condition, the number of dots presented affected confidence level (i.e., higher confidence level in Easy-Low condition compared to Easy-High condition: t(49) = -2.89, *p* = .006). Meanwhile, the confidence level *was marginally affected* by the number of dots within Difficult condition (i.e., Difficult-High vs. Difficult-Easy: t(49) = 2.03, *p* = .0479). Two-sample t-tests were performed and the error bars indicate standard errors.

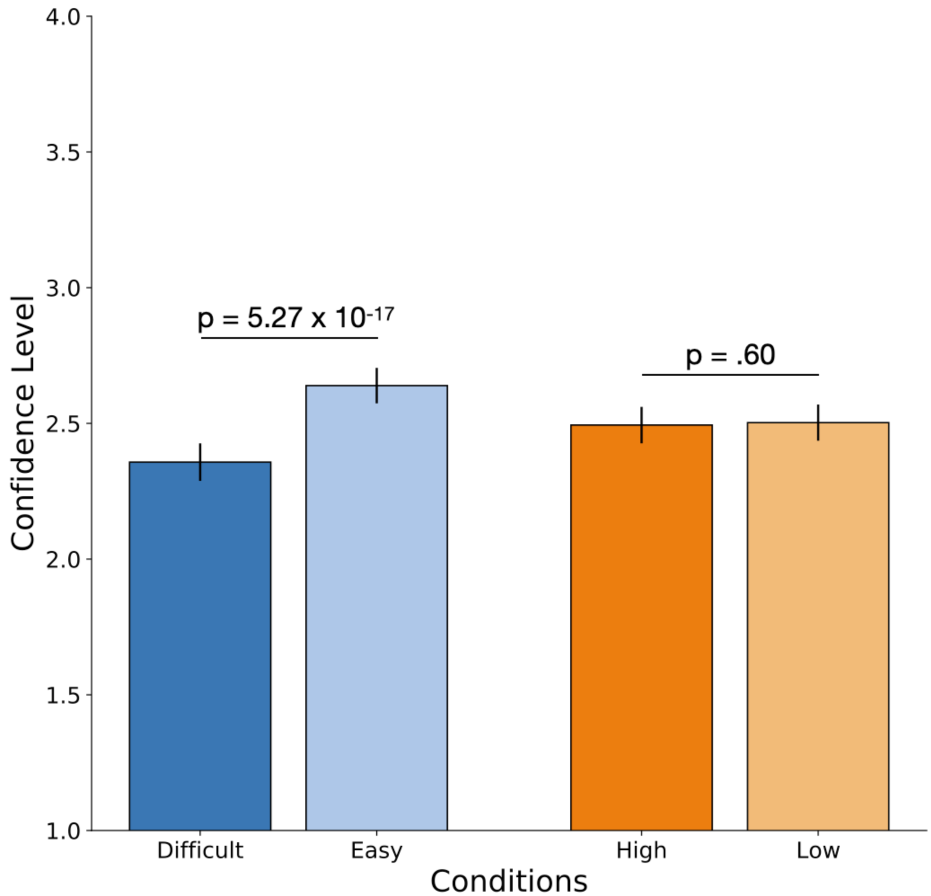

Figure 14. Confidence comparisons between the conditions grouped experimental factors. Easy condition (M = 2.64, SD = .462) showed higher confidence level than Difficult condition (M = 2.36, SD = .489; t(49) = -12.61, $p = 5.27 \times 10^{-17}$). Meanwhile, High (M = 2.49, SD = .475) and Low (M = 2.50, SD = .471) conditions did not show difference in confidence level (t(49) = -.528, $p = .60$). Two-sample t-tests were performed and the error bars indicate standard errors.

High and Low conditions failed to show dissociated task performance and confidence level, different from what was originally expected. Meanwhile, I observed a weak dissociation effect between Difficult-High and Difficult-Low conditions. Difficult-High condition showed significantly higher task accuracy (M = 68.2%, SD = 6.8) than Difficult-Low condition (M = 70.8%, SD = 6.2; t(49) = -3.17, *p* = .003) (**Figure 15A**). However, the confidence level of Difficult-Low condition (M = 2.34, SD = .487) was slightly higher than Difficult-High condition (M = 2.38, SD = .502; t(49) = 2.03, *p* = .0479) (**Figure 15B**). The result might reveal some interesting findings in the neural data considering the low p-value.

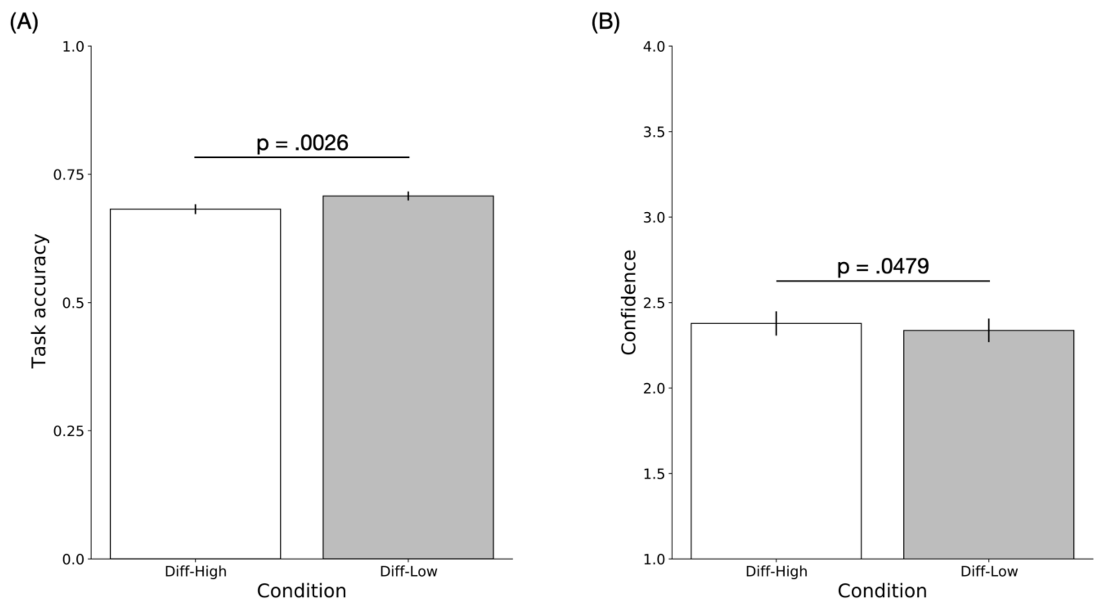

Figure 15. Weak dissociation effect was found between Difficult-High and Difficult-Low conditions. (A) Task accuracy was higher in Difficult-Low condition (M = 70.8%, SD = 6.2) than Difficult-High condition (M = 68.2%, SD = 6.8; t(49) = -3.17, *p* = .0026). (B) Meanwhile, confidence level was lower in Difficult-Low condition (M = 2.34, SD = .487*;* Difficult-High: M = 2.38, SD = .502; t(49) = 2.03, *p* = .0479). Two-sample t-tests were performed and the error bars indicate standard errors.

4.2 Response times for decision making and confidence rating were distinguished between Difficult and Easy conditions, but not between High and Low conditions

The effect of each experimental factor on decision and confidence RT were examined. Decision RT was significantly higher in Difficult condition (M = .767 sec, SD = .196) than Easy condition (M = .673 sec, SD = .175; $t(49) = 3.05$, $p = 4.48 \times 10^{-13}$) (**Figure 16**). Decision RT of High and Low conditions were not significantly different (High condition: M = .722 sec, SD = .189; Low condition: M = .718 sec, SD = .180; $t(49) = 1.13$, $p = .586$).

For confidence RT, Difficult condition (M = .415 sec, SD = .124) showed longer RT than Easy condition (M = .401 sec, SD = .109; $t(49) = 3.05$, $p = .004$) (**Figure 17**), which indicates that task difficult affected RT in evaluating confidence as well. On the other hand, High and Low conditions did not show any difference in confidence RT (High condition: M = .410 sec, SD = .120; Low condition: M = .406 sec, SD = .112; $t(49) = 1.13$, $p = .265$), similar to what was observed in decision RT.

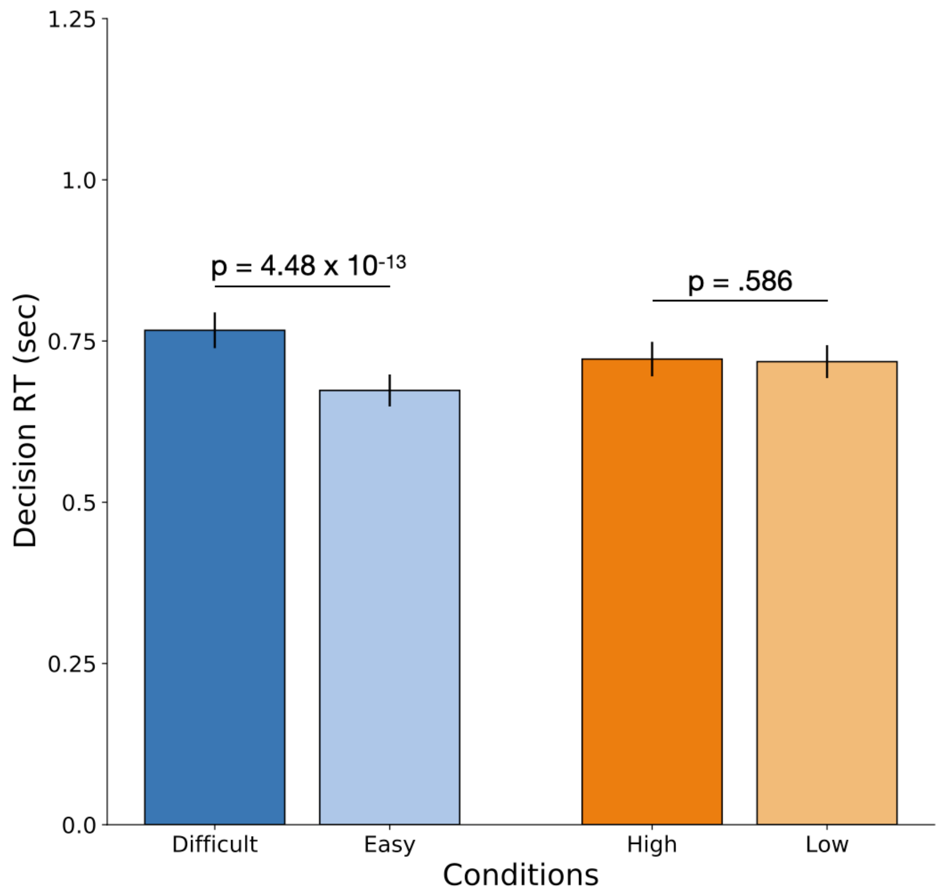

Figure 16. Decision RT comparisons grouped by experimental factors. Difficult condition (M = .767 sec, SD = .196) showed higher decision RT than Easy condition (M = .673 sec, SD = .175; t(49) = 3.05, $p = 4.48 \times 10^{-13}$). Meanwhile High and Low conditions did not show differences in decision RT (High condition: M = .722 sec, SD = .189; Low condition: M = .718 sec, SD = .180; t(49) = 1.13, p = .586). Two sample t-test were conducted for the statistical analysis. Error bars indicate standard errors.

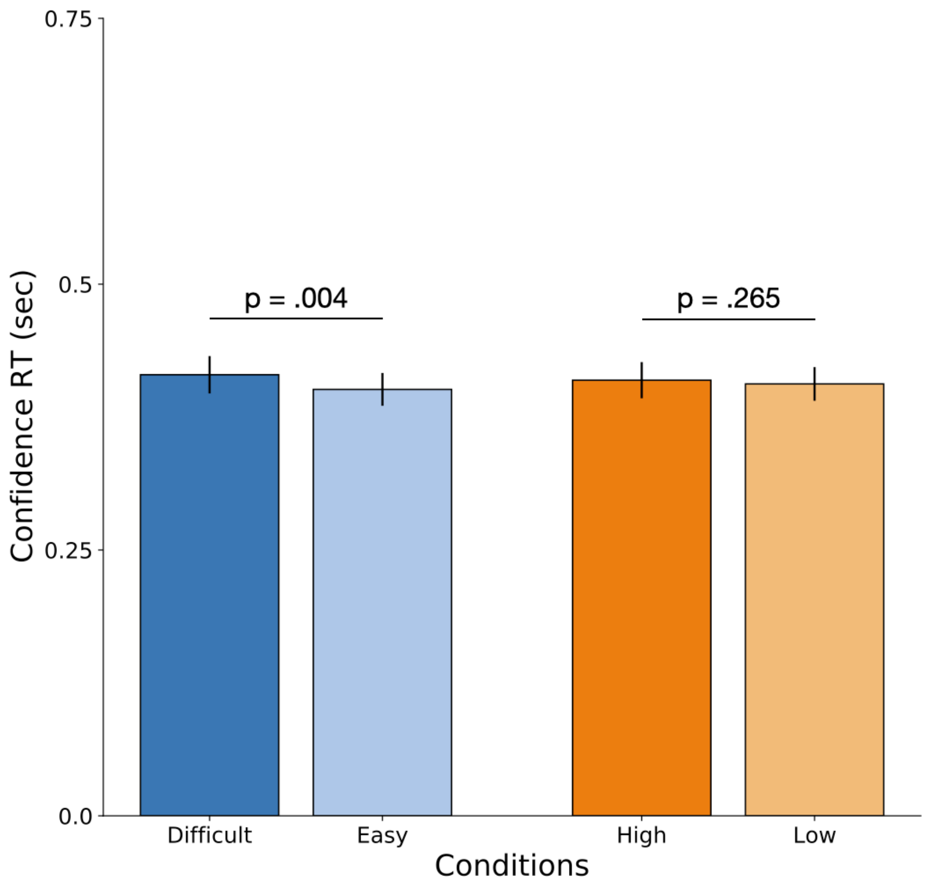

Figure 17. Confidence RT comparisons grouped by experimental factors. Subjects spent more time to answer the confidence level in Difficult condition (M = .415 sec, SD = .124) compared to Easy condition (M = .401 sec, SD = .109; t(49) = 3.05, *p* = .004). On the other hand, the number of dots did not influence in confidence RT (High condition: M = .410 sec, SD = .120; Low condition: M = .406 sec, SD = .112; t(49) = 1.13, *p* = .265).

CHAPTER 5. PLANNED AND EXPLORATORY NEUROIMAGING ANALYSES

5.1 Contrast tests revealed several regions activated more for Easy and Low conditions compared to Difficult and High conditions, respectively

Two sets of contrast tests were conducted from the generated GLMs. The first set compared Difficult and Easy conditions. The Difficult > Easy contrast did not reveal any activated regions. However, the Easy > Difficult contrast test revealed multiple regions. The activated regions included left middle frontal gyrus (MFG), superior parietal lobule (SPL), right occipital and cerebellum regions, and bilateral post-central gyrus (**Figure 18**, **Table 3**).

The second set of analyses compared High and Low conditions each other. High condition did not show any clusters activated higher than Low condition (i.e., High > Low contrast). Meanwhile, Low condition revealed greater activation in middle cingulate gyrus and right SPL region than High condition (i.e., Low > High contrast) (**Figure 19**, **Table 3**).

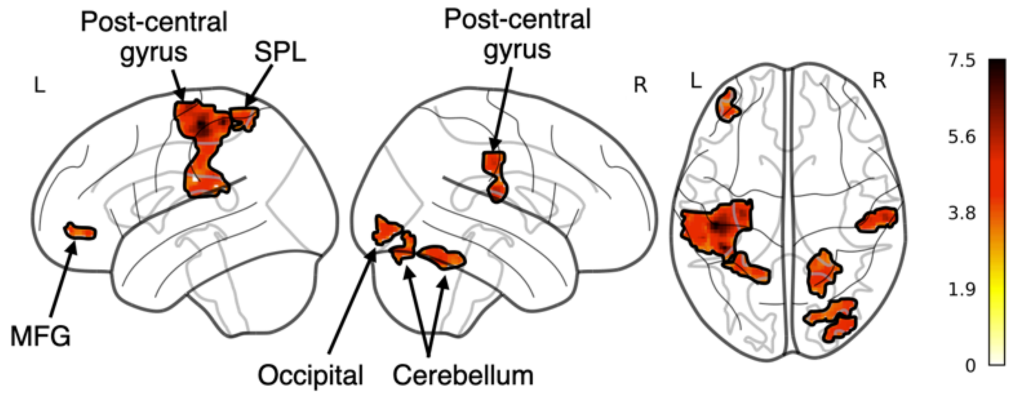

Figure 18. Brain regions activated higher for Easy condition compared to Difficult condition. While there was no region activated meaningfully in Difficult > Easy contrast test, Easy > Difficult test revealed multiple regions in the brain, especially in posterior part of the brain. Colors indicate t values. MFG, middle frontal gyrus; SPL, superior parietal lobe.

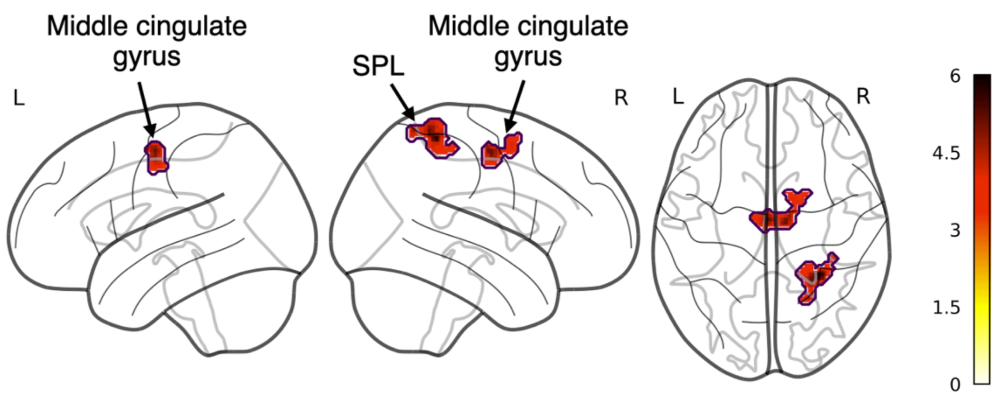

Figure 19. Brain regions activated greater for Low condition compared to High condition. High > Low contrast test did not reveal any clusters that were activated higher for High condition compared to Low condition. Meanwhile, Low > High contrast test revealed activation in middle cingulate gyrus and right SPL. Colors indicate t-values. SPL, superior parietal lobe.

Table 3. Coordinates of peak activity for regions revealed in Easy > Difficult and Low > High contrast test. (Top) Activated clusters detected in Easy > Difficult contrast test and (Bottom) in Low > High contrast test. Difficult > Easy and High > Low contrast tests did not reveal any regions meaningfully activated. Cluster-level Bonferroni-corrected p-values are shown on the rightmost column.

Easy > Difficult contrast

	Side	x	y	z	p_FWE
Post-central gyrus	L	-44	-23	60	<.001
Post-central gyrus	R	62	-20	18	<.001
SPL	L	-18	-52	62	0.001
MFG	L	-38	44	-6	0.024
Cerebellum	R	24	-52	-22	<.001
Cerebellum	R	36	-80	-18	0.001
Occipital	R	38	-86	-4	0.001

Low > High contrast

	Side	x	y	z	p_FWE
SPL	R	38	-44	62	<.001
Middle cingulate gyrus	-	0	-10	52	<.001

The initial hypothesis assumed that if a same region is activated for both Difficult vs. Easy and High vs. Low contrast tests, it would be possible to associate the region with a specific level (i.e., high or low) of task performance or confidence responses. Unfortunately, the two sets of contrast tests did not show any regions activated together. Behaviorally, Easy and Low conditions both show higher task accuracy than Difficult and High conditions. If Low condition had generated lower confidence level than High condition as expected, then it would have been possible at least what each activated cluster is associated with. However, the experiment did not successfully dissociate the decision and confidence responses. Considering all these results, it is hard to connect the activated regions with a cognitive process.

5.2 Multi-voxel patterns of the ROIs were not able to distinguish high and low objective task performance or confidence level

MVPA analysis was planned in anticipation of finding whether any of the ROIs (i.e., activated regions revealed in univariate GLM analyses) can distinguish different levels of task accuracy or confidence. Initially, I had planned to compare Easy-Low and Difficult-High conditions, which were expected to show the highest and the lowest task accuracy while the two conditions were assumed to generate moderate level of confidence. In addition, I also planned to compare Easy-High and Difficult-Low conditions assuming that those conditions would generate the highest and the lowest confidence levels, while moderate level of task performance (**Figure 10**).

Unfortunately, the behavioral responses showed different results from the expectation. Although Easy-Low and Difficult-High conditions individually showed the highest and the lowest task accuracy (**Figure 11**), Easy-Low condition also generated the highest confidence level, while the highest confidence level was expected with Easy-High condition (**Figure 13**).

Nevertheless, I examined whether any of the ROIs can distinguish Difficult-High and Easy-Low, and Difficult-Low and Easy-High conditions. I kept the classifications between the two sets of conditions because the conditions are paired orthogonally. Specifically, for example, Difficult-High and Easy-Low conditions do not share the same levels of the two factors.

The classification test of Difficult-High and Easy-Low conditions was accessed in the nine ROIs detected in previous GLM analyses. However, none of the ROIs showed meaningful distinction result of the two conditions (**Table 4**). Similarly, in the other classification test, the distinction between Difficult-Low and Easy-High conditions was accessed in all ROIs. Unfortunately, none of the nine ROIs succeeded in distinguishing the two conditions as well (**Table 5**).

Table 4. None of the regions revealed in the contrast tests could distinguish Difficult-High and Easy-Low conditions. Classification for Difficult-High and Easy-Low conditions was performed on each activated cluster revealed in the two GLM analyses (i.e., Easy > Difficult and Low > High). First seven regions were detected from Easy > Difficult contrast, while the last two regions were found in Low > High contrast. None of the region successfully distinguished the two conditions. Uncorrected p-values are shown under p_unc. column. Family-wise-correct p-values across multiple regions are listed under p_FWE column.

Difficult-High vs. Easy-Low

		x	y	z	t-value	p_unc.	p_FWE
Easy > Difficult	Post-central gyrus	-44	-23	60	1.82	0.08	0.68
	Post-central gyrus	62	-20	18	1.88	0.67	>1
	SPL	-18	-52	62	-1.28	0.21	>1
	MFG	-38	44	-6	0.22	0.83	>1
	Cerebellum	24	-52	-22	-0.26	0.79	>1
	Cerebellum	36	-80	-18	0.71	0.48	>1
	Occipital	38	-86	-4	1.43	0.16	>1
Low > High	SPL	38	-44	62	-0.65	0.52	>1
	Middle cingulate	0	-10	52	-0.44	0.66	>1

Table 5. None of the regions revealed in the contrast test could distinguish Difficult-Low and Easy-High conditions. Classification for Difficult-Low and Easy-High conditions was performed on each activated cluster revealed in the previous two GLM analyses. None of the region successfully distinguished the two conditions. Uncorrected p-values are shown under p_unc. column. Family-wise-correct p-values across multiple regions are listed under p_FWE column.

Difficult-Low vs. Easy-High

		x	y	z	t-value	p_unc.	p_FWE
Easy > Difficult	Post-central gyrus	-44	-23	60	1.19	0.24	>1
	Post-central gyrus	62	-20	18	1.25	0.22	>1
	SPL	-18	-52	62	-0.22	0.83	>1
	MFG	-38	44	-6	0.23	0.82	>1
	Cerebellum	24	-52	-22	-0.52	0.61	>1
	Cerebellum	36	-80	-18	-0.74	0.46	>1
	Occipital	38	-86	-4	-0.37	0.71	>1
Low > High	SPL	38	-44	62	-0.10	0.31	>1
	Middle cingulate	0	-10	52	-0.96	0.34	>1

5.3 Right superior parietal lobe and left middle temporal gyrus were activated for higher objective task accuracy

High and Low conditions did not generate strong dissociation effect between task accuracy and confidence level as planned. Moreover, the original hypothesis was that if same regions were activated for both Difficult vs. Easy contrast and High vs. Low contrast, then the region represents an overlapping feature of a cognitive process (e.g., high task performance, low confidence level, or etc.). However, completely different patterns of activation in the brain were observed in the two contrast tests. In addition, none of the regions successfully classify two orthogonal conditions in MVPA analyses (i.e., Difficult-High vs. Easy-Low, and Difficult-Low vs. Easy-High). Unsuccessful dissociation in behavioral responses for decision and confidence made it hard to suppose what caused the brain regions to be activated.

While the experimental factors did not dissociate decision and confidence successfully, part of the four individual conditions showed weak dissociation effect. Difficult-Low condition showed higher task accuracy (M = 70.8%, SD = 6.2) than Difficult-High condition (M = 68.2%, SD = 6.8; t(49) = -3.17, p = .003) (**Figure 11**), while the confidence level was lower in Difficult-Low condition (M = 2.34, SD = .487; Difficult-High: M = 2.38, SD = .502; p = .0479, t(49) = 2.03) (**Figure 13**). Given the result, I decided that it is worth probing the two conditions more.

To investigate and compare the neural activity of Difficult-High and Difficult-Low conditions, a separate GLM was created. The GLM contained regressors for Difficult-High and Difficult-Low conditions, and the trials for the other conditions (i.e., Easy-High and Easy-Low) were modeled in a same regressor. Two contrast tests were conducted. First, regions activated higher for Difficult-High condition than Difficult-Low condition were examined (i.e., Difficult-High > Difficult-Low). However, the test did not reveal any meaningfully activated regions. Also, the regions activated higher for Difficult-Low condition compared to Difficult-High condition was looked into (i.e., Difficult-Low > Difficult-High). The test revealed Right SPL and left middle temporal gyrus (MTG) were activated higher for Difficult-Low condition.

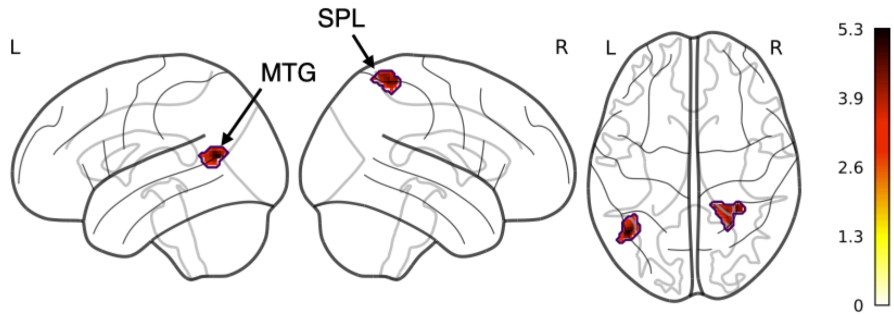

Figure 20. Right SPL and left MTG activated higher for Difficult-Low condition compared to Difficult-High condition. Contrast test on Difficult-High and Difficult-Low conditions were performed given that the two conditions showed weak dissociation effect between task accuracy and confidence level. No regions activated greater for Difficult-High condition compared to Difficult-Low condition. The Difficult-Low > Difficult-High contrast test revealed activated clusters in right SPL and left MTG. Color bars indicate t-values. SPL, superior parietal lobe; MTG, middle temporal gyrus.

Table 6. Peak coordinates of the regions activated higher in Difficult-Low condition than Difficult-High condition. Two clusters, left MTG and right SPL, showed family-wise-error corrected p-values that are lower than the significance level (p = .05).

	Side	x	y	z	p_FWE
MTG	L	-44	-60	14	0.011
SPL	R	24	-48	64	0.002

CHAPTER 6. DISCUSSION

6.1 Summary of the aim and results of the current study

The current study aimed to reveal brain regions associated with decision making and confidence evaluation processes. The two cognitive processes are separable conceptually. However, because of highly covarying responses for decision and confidence, it has been hard to examine whether the two processes are computed using different or same neural circuits.

Previous studies performed in my lab showed possibility of dissociating task accuracy and confidence level using different variances for presenting visual stimuli. Based on the observation, I designed an experiment where subjects were asked to decide the more frequently presented color and then rated their confidence level for the decision. The experiment was a 2 x 2 factorial design, where one factor modulated task difficulty (i.e., Difficult and Easy) and the other factor was related to the total number of colored dots presented (i.e., High and Low).

Initially, I assumed that I would observe dissociated task accuracy and confidence level between High and Low conditions. Once decision and confidence responses were dissociated behaviorally, then by comparing the activated brain regions in Difficult vs. Easy and High vs. Low contrast test, I conjectured that it would be possible to associate activated regions to different cognitive performance. Unfortunately, the behavioral data did not show noticeable dissociation effect in High and Low conditions. The contrast tests revealed multiple brain regions activated greater for Easy condition compared to Difficult condition, and Low compared to High condition. Nevertheless, it was hard to associate those regions to either decision or confidence performance.

The regions detected in the GLM analyses were used in MVPA analysis to check whether any of the area can distinguish either the level of task performance or confidence level. Specifically, distinction between Easy-Low and Difficult-High, and Easy-High and Difficult-Low conditions were tested. The two pairs were selected since the set of conditions were expected to generate the highest and the lowest task accuracy (confidence level) each. However, none of the regions revealed in the GLM analyses distinguished the different level of decision and confidence performances.

While the main conditions were not successful in separating decision and confidence responses, Difficult-High and Difficult-Low conditions showed weak dissociation effect. The higher task accuracy was observed in Difficult-Low condition, while the confidence value was slightly higher in Difficult-High condition. The two conditions were compared using a separate GLM. Difficult-High > Difficult-Low contrast test did not reveal any brain regions significantly activated. On the other hand, right SPL and middle cingulate gyrus were activated higher in Difficult-Low compared to Difficult-High condition.

6.2 Brain regions revealed in the study cannot be associated with particular cognitive functions

In the current study, I supposed that same regions might be activated together for Difficult vs. Easy and High vs. Low contrast tests. If the behavioral responses showed clear dissociation, then those regions could be associated with a shared behavioral feature (e.g., high task performance). Unfortunately, the results did not reveal any overlapping regions activated for different contrast test, as well as the behavioral responses were not separated clearly. Specifically, no brain regions were detected in Difficult > Easy and High > Low contrast tests, and completely different patterns of brain activation were observed in Easy > Difficult and Low > High contrast tests.

With the given results, it is hard to identify the relationship between the activated brain areas with the direction of task accuracy or confidence level. For instance, right SPL and middle cingulate gyrus regions were only observed in Low > High contrast test and not in Easy > Difficult contrast. Considering that Low and High conditions generated similar level of confidence, it could have interpreted as that the two activated regions represent higher task accuracy. However, while Easy condition also generated higher task performance than Difficult condition, none of the two regions appeared in Easy > Difficult contrast. Therefore, we cannot conclude that activations in right SPL and middle cingulate gyrus are associated with high task performance.

6.3 Why were few activity clusters in frontal regions observed?

Previous studies on the subjective aspects of perceptual decision making have frequently reported activations in many frontal regions, including FEF, dlPFC, and aPFC (D. Bang & Fleming, 2018; Cortese et al., 2016; Fleming et al., 2018; Fleming & Dolan, 2012; Frith & Dolan, 1996; Kahnt et al., 2011; Koechlin & Hyafil, 2007; Morales et al., 2018; Rahnev et al., 2016; Shekhar & Rahnev, 2018; Smith & Jonides, 1999; Wokke et al., 2017; Yeon et al., 2020). Different from these previous results, the current study did not observe strong activations in the frontal lobe, and only showed a cluster in left MFG in Easy > Difficult contrast test.

One possible explanation for not seeing large activations in the frontal region could be that the current study compared data where both decision- and confidence-related processes were included in the contrast tests. Whereas in previous studies, they have looked into the frontal regions either by masking the ROIs (D. Bang & Fleming, 2018; Fleming et al., 2018; Rahnev et al., 2016) or by separating the decision and confidence periods (Yeon et al., 2020). Specifically, activation in frontal regions were clearly observed when the decision and confidence related images were contrasted to the baseline, while the activation was reduced when the decision and confidence related data were contrasted directly to each other (Yeon et al., 2020). Because the current study contrasted two sets of data that both contain the decision and confidence processes, the effects could have been canceled out in the result and therefore activations in the frontal region were not observed much.

6.4 Future possible ways to improve performance of the MVPA analysis

The GLM analyses results revealed some brain regions that were activated more in certain conditions compared to others, but the MVPA analyses in these same regions failed to distinguish between the different conditions of the experiment. It has been reported that the two methods are sensitive to different elements (i.e., GLM is more sensitive to the between-subjects variables, while MVPA is more sensitive to the parameters related to the voxel-level variables) (Davis et al., 2014), which could at least partly account for the differences in results between GLM and MVPA observed here.

However, it is also possible that the MVPA analysis lacked sufficient power. Specifically, the current study had relatively small training size (i.e., each training in the leave-one-run-out procedure was conducted on just five samples of each of the four conditions). Although leave-one-run-out cross-validation is widely used (Etzel, 2015; Hebart et al., 2015; Suzuki et al., 2017; Yang et al., 2012), it was reported that having a larger number of shorter runs can improve MVPA performance (Coutanche & Thompson-Schill, 2012). Also, some researchers suggested that because of high collinearity between trials, rather than estimating beta values in a single model (i.e., Least Squares All (LSA) model), estimating the values of each trial separately (i.e., Least Squares Single (LSS) model) is preferred (Mumford et al., 2012, 2014; Turner et al., 2012). Therefore, another way of performing the MVPA analyses would be to train the classifier on the data from each trial separately, thus obtaining many more training samples (though each sample would be of lower quality). Further, this procedure could also be done not on the beta values associated with each run but on the BOLD signal itself after an appropriate shift to account for delays in the hemodynamic responses (Lewis-Peacock et al., 2016; Lewis-Peacock & Norman, 2014). While it is not a priori guaranteed that any specific approach to the MVPA analyses would be better than others, those methods should be considered in future MVPA analysis.

6.5 Possible role for SPL related to task performance and confidence level

Dissociation between task performance and confidence level has been observed beyond perceptual decision-making tasks. Similar effect has been found in memory studies as well, where subjects made decisions based on their recollection (Bona & Silvanto, 2014; Busey et al., 2000; Chua et al., 2004; Moritz et al., 2006; Samaha et al., 2016; Simons et al., 2010). A wealth of memory studies has indicated posterior parietal region to be strongly related with working memory process (Berryhill, 2012; Fleming et al., 2014; McCurdy et al., 2013; Morales et al., 2018). More importantly, it was also suggested that the posterior parietal area is more involved in the confidence level, not the recollection ability per se (Chen et al., 2013; Parvizi & Wagner, 2018; Paulus et al., 2003; Simons et al., 2010). Specifically, Simons and his colleagues (2010) found lesions in bilateral posterior parietal area reduced confidence while the recollection task performance was not affected.

In the current study, right SPL region was revealed both in Low > High and Difficult-Low > Difficult-High contrast tests. Different from previous memory studies where confidence level was positively associated with SPL, Low and High conditions did not show differences in confidence responses and Difficult-Low condition showed lower confidence level than Difficult-High condition. Therefore, the current study result seems to contradict to the findings of previous memory studies. It is currently unclear what the source of this discrepancy is but one possibility is that perception and memory are at least partially mediated by domain-specific mechanisms (Fleming et al., 2014; McCurdy et al., 2013; Morales et al., 2018). Future studies need to investigate this possibility more directly.

6.6 Creating a robust dissociation between accuracy and confidence

The current study aimed to dissociate decision and confidence responses to probe brain regions associated with each process. Even though the experiment was carefully designed after observing the possibility of dissociation between decision and confidence in the pilot experiments, the main experiment was not successful in clearly separating accuracy from confidence. It is possible that not observing the same result could have been due to different circumstances where the pilot experiments and the main experiment were conducted (the pilot tests were performed in the U.S, while the main experiment was conducted in South Korea). It is also possible that the previous results from the lab were partly dependent on the exact combinations of conditions (no pilot test used the exact four conditions from the current experiment) or that the scanner environment somehow influenced participants' responses. However, the exact reason for the lack of sufficiently strong dissociation between accuracy and confidence in the current study remain unclear.

Nevertheless, while the main conditions did not show the dissociation effect as expected, part of the data separated the decision and confidence responses weakly. Specifically, a dissociation was observed between the Difficulty-High and Difficult-Low condition with the former showing significantly lower accuracy but significantly higher confidence than the latter. The dissociation effect in partial data supports that separating decision and confidence responses is possible. Moreover, a recent study demonstrated a "criterion attraction" effect, where people use not identical but not independent criterion for rating confidence when visual stimuli with two standard deviations were presented (Rahnev, 2021). The result showed that the confidence criteria for the two stimuli are "attracted" each other and lead to rate lower confidence level in low-variability condition (or higher confidence level in high-variability condition) while the task performances are matched. Therefore, if task stimuli are properly created, it would be possible to find the brain regions associated separately with decision and confidence processes.

6.7 Why separating decision and confidence responses is important for uncovering the neural substrates of subjective perception?

While the study showed possibility of dissociating decision and confidence responses, the result does not support either separate or unified neural substrates for decision making and confidence evaluation processes. This is because the main conditions of the study did not show dissociated the responses for decision and confidence. Although the partial data demonstrated dissociation in responses (i.e., Difficult-High vs. Difficult-Low), the two conditions alone were not sufficient to indicate whether the two responses are processed using the same neural circuit.

Why separating behavioral responses is critical in investigating neural substrates of covarying cognitive processes? Many human cognitive functions are related to each other, which makes it hard to specify the individual cognitive process. Decision and confidence responses are only one example where two different cognitive processes lead to strongly covarying responses. Other cognitive functions which are not clearly distinct from the decision making process include working memory (Busey et al., 2000; Chua et al., 2004; Hutchinson et al., 2012; Samaha et al., 2016; Simons et al., 2010) and consciousness (Bernacer et al., 2014; Block, 2005, 2007; Shadlen & Kiani, 2011; van Gaal et al., 2012). Because we can interpret and associate neural substrates through behavioral responses, generating conditions where different cognitive processes could be related to different responses is crucial for probing neural substrates related to the cognitive processes.

Nevertheless, dissociating decision and confidence responses might not be the only way to investigate neural responses related to individual cognitive process. Morales and his colleagues (2019) suggested that it would be more feasible to utilize the results of multiple studies rather than attempting to design one "perfect" experiment that eliminates all possible confounds. Specifically, when applied to investigating neural responses for decision and confidence processes, we can create one experiment that features matched task performance, and another experiment that leads to matched confidence level using the same type of stimulus. By comparing the two experiments, it may be possible to uncover the neural responses of individual decision and confidence related processes.

CHAPTER 7. CONCLUSION

Decision and confidence are highly related but conceptually separable processes. Because of the highly correlated two responses, it is difficult to determine whether the two processes are computed using different or the same neural circuits. The present study aimed to reveal brain regions associated with decision and confidence processes. Although the experiment was designed based on the pilot tests where the decision and confidence responses were dissociated, the current study did not generate the same behavioral effect. While the planned GLM analyses revealed multiple activated regions, it is hard to associate the regions with decision or confidence performance. Moreover, none of the activated clusters could distinguish high/low decision or confidence levels. Nevertheless, part of the experiment conditions (i.e., Difficult-High and Difficult-Low) showed weak dissociation effect. Although the current study was not successful to achieve what it aimed initially, it still demonstrated the possibility of dissociating decision and confidence responses. Future studies need to develop stimuli that more robustly dissociate accuracy and confidence to investigate how the brain computes the two highly covarying cognitive processes.

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