Perceptual judgment of stimulus depth during fixation and saccadic eye movement

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Perceptual judgment of stimulus depth during fixation and saccadic eye movement

Directed by Professor Jong Bok Lee

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It has been a long way since I first visited Eye Movement & Vision Lab in Kwanak Mountain in the fall of 2002. At that time, I had vague idea of perceptual neuroscience. Though it is still true of vagueness, I feel like a bit acquainted with the terminology of the business.

I thank Professor Choongkil Lee for generous guidance, critical comments, enormous patience, and, especially, specific questions to enlighten my intellect when I was in the midst of confusion. But, above all, he set an example of professor to me just by showing the way he is.

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<ABSTRACT>

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It has been known that spatial perception undergoes systematic changes during a short time window (about 100ms) prior to a saccadic eye movement. A notable example is saccadic compression in which perceived location of stimuli that are presented immediately before saccades are shifted toward the location of saccadic target. These experiments and related models have dealt with stimulus presented in two-dimension, and, to my knowledge, no study examined the third dimension, the depth. In two experiments, I examined whether similar perceptual distortions occur for perception of stimulus depth at the time of saccadic eye movements. In experiment I, I measured the perceptual judgment of stimulus depth in saccadic and steady fixation conditions. The results showed that (1) saccade caused stimulus depth was shifted toward the fixation point, (2) presence of reference at the horopter also caused shift toward the fixation, (3) in saccadic condition, sensitivity was inversely proportional to the strength of compression, and (4) the perceptual shift was a general phenomenon in this short term memory task. In experiment II, by adopting 2-alternative forced choice task, I found that the compression was not an artifact. These results indicated that the perceived location of presaccadic target is mislocalized toward the fixation point in three-dimension, extending previously-known two-dimensional compression of space.

Key words: depth perception, spatial map, saccadic compression

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I. INTRODUCTION

A. Saccade, spatial constancy, and spatial remapping

Saccades are the fastest of known eye movement, as fast about 800 degrees per second and most prompt that the latency in normal person is 200ms[1].

When we make saccades, retinal image abruptly changes as visual direction changes but we know it certain that it was the eye that moved, not the environment. From here, an interesting perceptual problem arises; how do we know the changes of retinal image are caused by eye movement and not by the movement of external world?

Helmholtz believed that this constancy of perceived position was maintained during and after saccade, because both extraretinal information (the effort of will) and retinal information (sensed but not perceived image motion) were used to recalibrate the direction of gaze[2]. Later, the concept of the effort of will was further evolved as efference copy[3] or corollary discharge[4]. Recent researchers view that in brain there is spatial map or internal representation of space and when we determined to make saccades, the efferent signal not only goes to ocular motor system but also to reference frame of spatial map to slide as visual direction moves respectively. And the process is called as spatial remapping[5].

B. 2-dimensional perceptual distortions in perisaccadic periods

Since the remapping is not the consequence of saccadic eye movement rather of the effort of will (in terms of Helmholtz) to make saccades, it can be experimentally detectable before the initiation of actual eye movement because the latency of saccade is about 200ms. Various experiments in complete dark condition showed that objects presented before or during the early phase of the saccades are misperceived in the direction of the eye movement[6, 7, 8, 9, 10, 11]. But, interestingly in slightly illuminated conditions, the perceived positions of objects were compressed toward the saccade target[10, 12, 13].

The phenomenon of perisaccadic compression is not only limited to saccadic direction. Kaiser and Lappe[14] showed perisaccadic mislocalization also occurs in direction orthogonal to saccade. Cho and Lee[15] reported post saccadic (not presaccadic) expansion of visual space in the direction orthogonal to saccade. Furthermore, Morrone, Ross and Burr[16] reported that even perceived times were compressed when presented perisaccadically and even reversed. They suggested that the very similar time courses of spatial and temporal compression suggest that both are mediated by a common neural mechanism.

C. Presumed retinotopy of 2- dimensional space map

There have been models to explain this perisaccadic compression and all of them are based on the assumption of retinotopic arrangement of space map.

In the occipital lobe, the primate brain contains re-representation of the retinal images laid out in topological maps, called retinotopic maps[17]. In recent years fMRI studies have shown topographic representations outside of occipital regions, in temporal[18], parietal [19, 20], and frontal cortex [21].

Morrone, Ross, and Burr[22] presented a model to simulate the compression during saccades. The model based on two assumptions: (1) a shift in the assumed external reference point for the center of the fovea and (2) retinal eccentricities are liable to a horizontal compression. Niemeier et al.[23, 24] proposed optimal transsaccadic integration model based on Baysian probability that the brain uses noisy eye-position signals in interpreting retinal information with prior probability of implausibility of sudden jumps during saccades to calculate perceived locations. But, their model only predicts the compression in the direction of saccade but not the compression orthogonal to it. All above models consider the efference copy of saccade as the cause of compression. Recently, Hamker et al.[25] constructed computational model based on the assumption that oculomotor feedback of saccade onto the corresponding receptive field that alters the two-dimensional receptive field structure at an intermediate level of the cortical hierarchy so that the estimated positions in visual space are mislocalized. In this model the efference copy or oculomotor feedback is not in one-dimension but in two-dimension, thus it is capable of explaining compression orthogonal to the direction of saccade.

D. Depth and perisaccadic perceptual distortion

But all above experiments deal with one-dimensional or two-dimensional phenomena and all models are based on retinotopic arrangement of visual space map. One of the reasons for this can be that retinotopic organization of space map is more intuitive and experimentally easier to verify. But, in real life, dimension of depth is as critical as two-dimensional visual scenes as it exemplifies when we make reaching and grasping for an object or navigating through a field. For this reason, the presence of space map for depth dimension is mandatory.

The location of higher depth perception processing is thought to be in middle temporal area (MT), medial superior temporal area (MST) and lateral intraparietal area (LIP)[26] as other space perceptual functions but their functional arrangement as depth map is not yet studied contrary to the their known retinotopic arrangement[27, 28]. If the similar compression or other perceptual distortions in two-dimension appear in depth perception, we can infer the functional arrangement of depth map could be similar to two-dimensional map, although the explanation of saccadic compression based on retinotopic arrangement of space map is not fully established.

E. The effect of saccadic target or reference

In the pattern of compression, the saccadic target seems to have a special role[10, 29]. In the study of Lappe et al., compression of flash positions toward the target is only seen when visual references are present after the saccade. They think that immediately after saccade the visual system searches for the saccade target and the presence of visual reference allows evaluation of the previously stored position of the target. In this process of localizing objects relative to saccadic target, the error is reflected as compression[10] and they suggested that perisaccadic compression relies on an encoding of relative spatial locations of objects rather than on localizations in egocentric space[30].

Another phenomenon known about perceptual compression of 2-dimensional space is related to fixation itself. Several studies have shown that subjects mislocalized the positions of targets during steady eye fixation in the manner of compression[30, 31, 32].

E. The purpose of this study

This study is composed with two successive experiments.

In experiment I, (1) I tested whether presaccadic compression occurs in depth dimension and (2) what effects of the presence of saccadic target or a reference has on the compression.

The current models of space map are heavily dependent on 2-dimensional retinotopic arrangement and perceptual distortions around saccade and fixation are interpreted on such models. If similar phenomena are found in depth perception, these results can lead us to the insight of the functional organization of depth map in brain which has not yet been studied. The design of the experiment is 2 by 2 design, a combination of ‘no saccade’ and ‘saccade’ with ‘no center reference’ and ‘center reference’. This makes 4 sets of experiment.

In experiment II, to answer the general compression found in experiment I which incurred a suspicion about the validity of experimental method, I adopted 2-alternative forced choice method and showed general compression in depth is not an artifact of experimental method.

II. EXPERIMENT I:
PERCEPTUAL JUDGMENT OF STIMULUS DEPTH DURING FIXATION AND SACCADIC EYE MOVMENT

1. Materials and Methods

A. Subjects

Four male subjects (aged 26-37) participated in the experiment. All four subjects were naïve to the experiment. Stereoacuity was measured with Titmus Stereo Test and all four subjects showed normal stereoacuity of 40 seconds of arc. From all, written consents were obtained.

B. Apparatus

Subjects were seated in a dimly lighted room. Heads of the subjects were fixed on chin rest at 60 cm from the display. Visual stimuli were presented on a 21-inch flat CRT monitor (Sony GDM-W900) with a spatial resolution of 800 × 600 pixels at a refresh rate of 100 Hz. The edge and the surface of monitor were visible to subjects and they were well aware of the distance to the monitor plane. The horizontal position of the right eye was monitored with an infra-red reflection method (IRIS, Skalar Medical), sampled at 500 Hz with a 16-bit resolution. Stimuli generation, timely presentation of stimuli and probes, for response registering were controlled and executed by a graphical programming language LabVIEW™7.0 (National Instrument).

C. Visual stimuli

(A) Generation of depth images

To generate depth images, anaglyphic method was used. Subjects wore a red filter in front of the right eye and a green filter in front of the left. On the monitor, the image for the right eye was shown in red and the image for the left was green (Figure 1). For images to be seen by both eyes, luminance adjusted gray image was used. In this experimental setting, 2-pixel crossed disparity matches 4.83 minutes of arc with the depth effect of 5.23mm near while the interocular distance being 60mm.

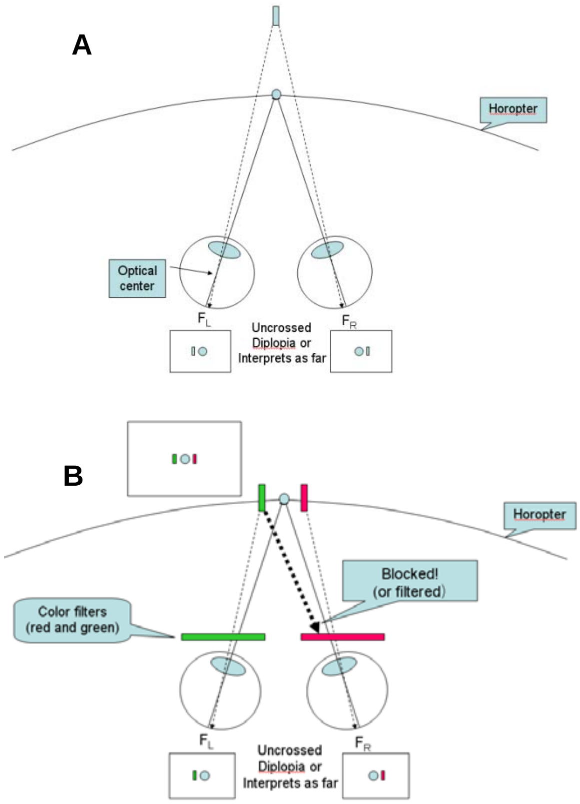

Figure 1. Principle of anaglyphic method

(A) Normal binocular viewing condition. When the subject fixates at an object with binocular viewing, the image of the object falls on each corresponding fovea of both eyes. If another object behind the fixated object appears, the image of new object falls on nasal part of the each retina and it is felt as farther than fixating object. (B) Experimental condition. Subjects wore a red filter in front of the right eye and a green filter in front of the left. Green stimulus does not pass through red filter and red stimulus does not pass through green filter. On the monitor, the image for the right eye was shown in red and the image for the left was green. For images to be seen by both eyes, luminance adjusted gray image was used.

(B) Coding depth

In this experiment, coding depth was done according to 2-pixel unit. In the constraint of pixel based image generation, I have to vary the depth by 2-pixel as one step. Negative sign denotes near (crossed disparity) from the zero disparity (monitor plane) and positive sign denotes far (uncrossed disparity) from zero disparity. If a depth was coded as '-4', it means 8 pixels of crossed disparity and '2' means 4 pixels of uncrossed disparity.

(C) Depth stimuli

In this experiment, I used two vertical lines horizontally 6.7 degrees apart of identical depth were used as single depth stimuli (Figure 2). In detail, a pair of red and green vertical line, each in 2 pixels width and 128 pixels height (5.4 arc minute widths and 5.71 arc degrees in height) was aligned side by side in disparity of each corresponding disparities. And another pair of depth stimuli of identical depth were placed 6.7 degrees horizontally apart. The reason of using two pair of line depth was to induce the sensation of depth plane and not to draw attention out of its center.

(D) Probes

To obtain a response, I used method of adjustment. After a subject having seen the stimulus, probes of same configuration as depth stimuli but in random depth was shown. Then the subject adjusted the depth of probe until it matches remembered depth of the stimulus.

(E) Fixation target, saccadic target, and reference

For fixation target, saccadic target, and center reference, same configuration of cross was used.

Each line has dimension of 4.3mm width and 18mm length. Left of figure 2 shows the center reference with depth stimuli. The reason of seemingly large reference was to induce a sensation of depth plane.

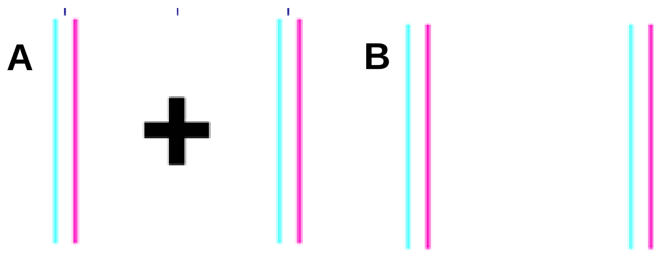

Figure 2. Depth stimulus with and without center reference

(A) Depth stimulus with center reference. (B) Depth stimulus without center reference.

D. Procedure

The design of this experiment is 2 by 2 design, combination of ‘no saccade’ and ‘saccade’ with ‘no center reference’ and ‘center reference’. This makes 4 sets of experiment. The basic procedures are same in all 4 experiments except their particular conditions. The following and the figure 3 are the procedure based on ‘saccade’ and ‘center reference’ condition. In no saccade condition, the subject makes no saccade and maintained fixation at the center. Also, the stimuli and probes are presented at the center. In no center reference condition, the stimuli and the probes are presented with no center references.

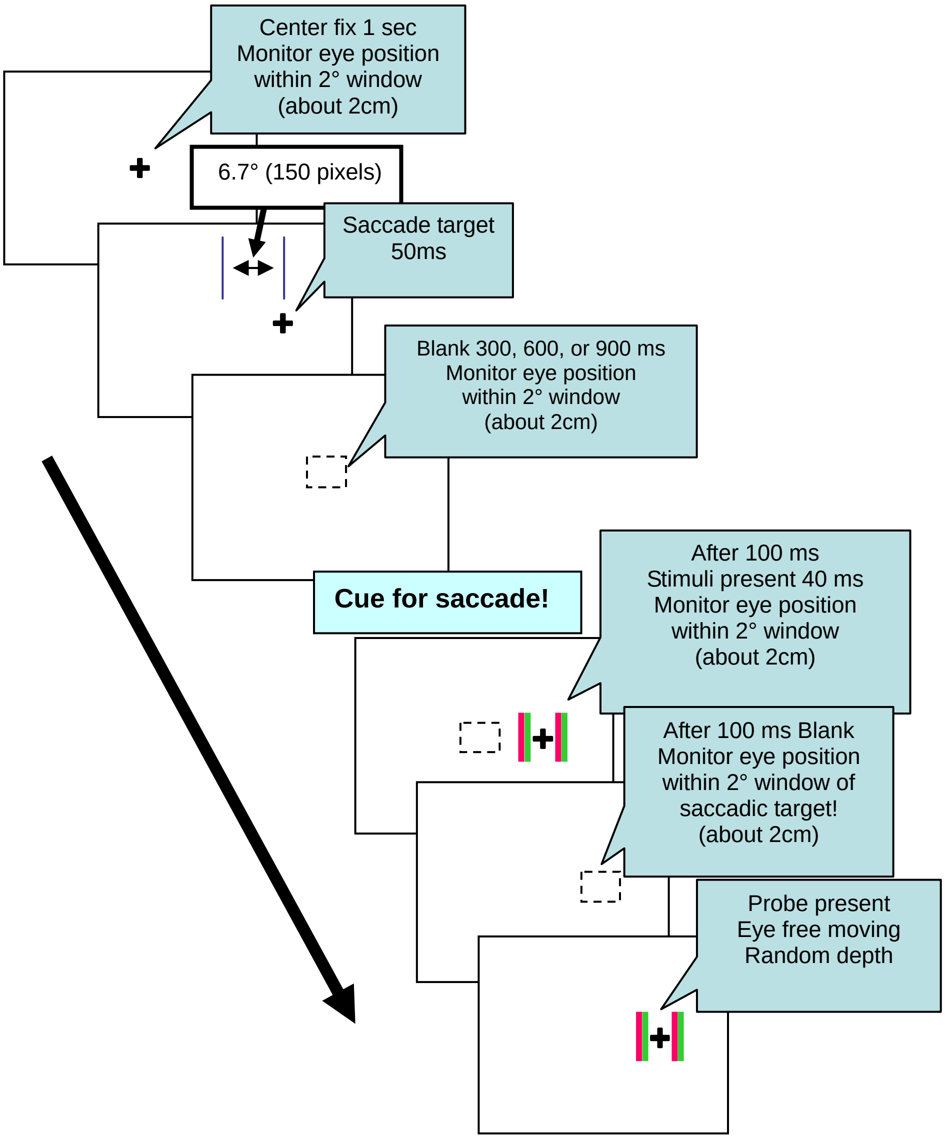

Figure 3. Procedure of experiment in saccade and center reference condition From top to down, frames are arranged in time sequential manner (direction of arrow). For detail, see the text.

The subjects were seated 60cm in front of monitor with their heads restrained on a chin and forehead rest. In each trial, at the center of monitor, a fixation target appeared and the subjects were instructed to fixate at the center of fixation target. The position of right eye was monitored within 2 degree window centered at fixation target for 1 second. Then saccadic target appeared 6.7 degree right of the fixation target for 50ms and disappeared. But, subjects were instructed not to make saccade until an auditory cue was given. After for randomly chosen duration of 300, 600, and 900ms, auditory cue was given. 100ms after the cue, while the eye was still at center, a depth stimulus was presented with center reference for 40ms, its center being at the same 6.7 degree right. 100ms after, the eye position was monitored and if the eye was not within 2 degree window at saccadic target, the trial was discarded. By this method, the minimal eye velocity of a trial is at least 34 degree/second. Then a probe of random depth was shown and the subject adjusted the probe depth with mouse wheel until it matches with remembered depth of stimulus (Figure 3). One session comprised of 150 trials and between sessions, 5 to 10 minutes rest was taken by the subjects. No more than 3 sessions of experiments were done on the same day.

E. Data adjustment for interpersonal comparison

Naturally, all psychophysical data contain certain amount of interpersonal variability. There are variations surely originated from firm perceptual deviations, but also mere dispersions from individual difference of sensitivity as well. To adjust them, I divided the each data by the standard deviation of each subject’s particular experimental conditions and I put ‘adjusted’ in front of the headings. This procedure is similar to standardizing in statistics except subtracting their means.

Thus, we get

Adjusted Response =

Response / SD of each subject's particular experimental condition

F. Adjusted compression index

To evaluate compression, I devised compression index. First, we get deviation from stimulus by subtracting stimulus from response. Since I knew the center of compression would be near zero disparity plane (monitor plane) from the pilot study, the sign of deviation reverses across the zero plane. The value of deviation for near stimuli would be positive and for far stimuli would be negative if compression occurred as expected. To convert these deviation values for representing compression, I multiply them by direction adjuster as for near stimuli, –1 and for far stimuli, 1. The more negative value means more compression and positive value means rather expansion and the following is its formula form

Compression Index = [Response – Stimulus] × direction adjuster

After dividing them by the standard deviation of each subject's particular experimental conditions, we get adjusted compression index. In formula form, it is written as,

Adjusted Compression Index

= [Response – Stimulus] × direction adjuster

/ SD of each subject's particular experimental condition

2. Results

Data of 2959 valid trials were collected for analysis. For each subject, basically 6 sessions, or 900 trials of experiments were administered and about 20 percent of trials were aborted trials.

A. Generalized compression of the responses

One unexpected result was generalized compression of the responses. Though our purpose was to investigate the compression while in 'saccade' or 'center reference condition', there also were compressions in 'no saccade' and 'no center reference' condition. Table 1 shows means and standard errors of responses of each condition. The mean of 'no saccade' and 'no center reference' condition is -0.9244 and its standard error are 0.0370.

Table 1. Means and standard errors of adjusted compression index of each condition (SE: standard error)

Saccadic condition	Center ref. condition	Number of trials	Mean of Adjusted Compression Index	SE of Adjusted Compression Index
No Saccade	No center ref.	859	-0.9244	0.0370
	Center ref.	703	-0.8701	0.0405
Saccade	No center ref.	693	-1.1778	0.0400
	Center ref.	704	-1.5995	0.0434

B. The effect of saccade on compression

Figure 4 shows adjusted compression index comparing 'no saccade' and 'saccade' condition within each subjects. Data were plotted with standard error bars. In x-axis, 0 denotes 'no saccade' and '1' denotes 'saccade' condition. . All subjects showed tendency of compression in 'saccade' condition and they were statistically significant (p value < 0,005 *) except in subject T (p value = 0.3246).

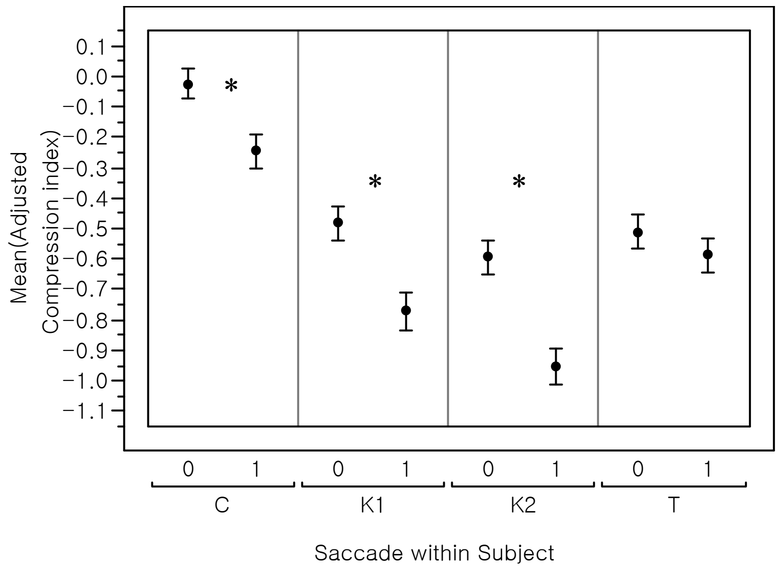

Figure 4. Adjusted compression index comparing ‘no saccade’ and ‘saccade’ condition within each subjects

Data were plotted with standard error bars. In x-axis, 0 denotes ‘no saccade’ and ‘1’ denotes ‘saccade’ condition. All subjects showed tendency of compression in saccade condition and they were statistically significant (p value < 0,005 *) except in subject T (p value = 0.3246).

C. The effect of center reference on compression

Figure 5 shows adjusted compression index comparing ‘no center reference’ and ‘reference’ condition within each subjects. Data were plotted with standard error bars. In x-axis, 0 denotes ‘no center reference’ and ‘1’ denotes ‘center reference’ condition. All subjects showed tendency of compression in ‘center reference’ condition and they significant (p value < 0,002 *) except in subject C (p value = 0.7753).

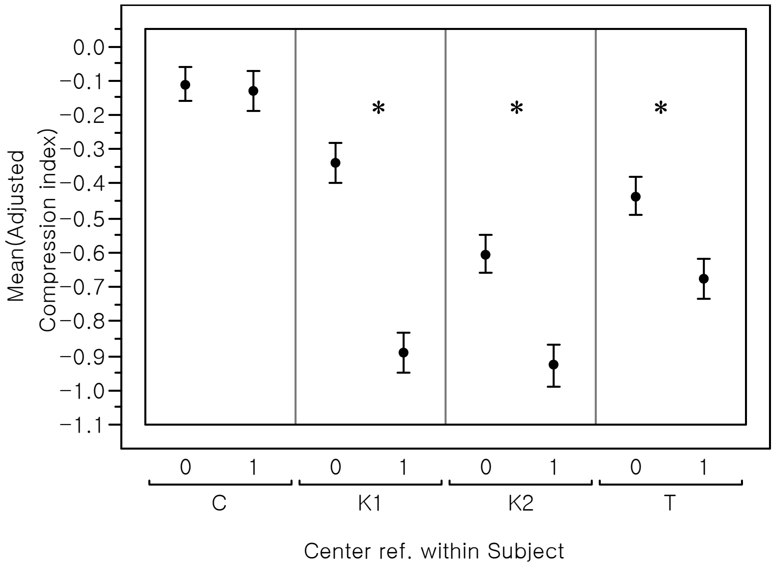

Figure 5. Adjusted compression index comparing ‘no center reference’ and ‘reference’ condition within each subjects
Data were plotted with standard error bars. In x-axis, 0 denotes ‘no center reference’ and ‘1’ denotes ‘center reference’ condition. All subjects showed tendency of compression in ‘center reference’ condition and they were statistically significant (p value < 0,002 *) except in subject C (p value = 0.7753).

D. Multiple linear regression analysis of adjusted compression index against subject, stimulus depth, saccade, and center reference

To investigate the effect of saccade and center reference while controlling other variables, I ran a multiple linear regression analysis. The dependent variable was adjusted compression index and the independent variables were subject, stimulus depth, saccade, and center reference. The model is written as following

Adjusted compression index =

intercept + β1 × subject + β2 × stimulus depth + β3 × saccade [0, 1] + β4 × center ref. [0, 1]

The parameter estimates for saccade was –0.1067 and for center reference was –0.1364. As noted earlier, negative values means compression. And they were both independently significant (p value < 0.0001*).

E. The standard deviation as an index of sensitivity and its relation to compression

The reason why I introduced the concept of 'adjustment' is to adjust interpersonal and interconditional variations of responses. By dividing the variables with standard deviation of each subject's particular experimental condition, the ranges or in other words, sharpness of interpersonal and interconditional variation are normalized. In this sense, the standard deviation of each subject's particular experimental condition can be viewed as an index of sensitivity. For example, if a standard deviation of particular subject's experimental condition is smaller than others, we can say that the responses are more consistent and narrower in range than others, regardless of their correctness. So, if we take out the 'adjustment' from adjusted compression index, namely not dividing the variable by standard deviation of each subject's particular experimental condition, we get just compression index and can investigate compression under the influence of various native sensitivity conditions. In this scheme, only the relation between standard deviations of particular experimental condition as a representation of sensitivity and compressions can be investigated.

Thus, I did simple linear regression analysis on compression index and standard deviation of subject's particular experimental conditions as an index of sensitivity. In this analysis, various experimental conditions such as subject variability, saccade, center reference, and stimulus depth are treated just as simple different experimental conditions. Figure 6 is the result of regression and the slope is –0.6248. Negative value of slope means as standard deviation increases (in other sense, sensitivity decreases), compression gets stronger. From this analysis, we can conclude the compression is stronger when the sensitivity of the experiment is lower.

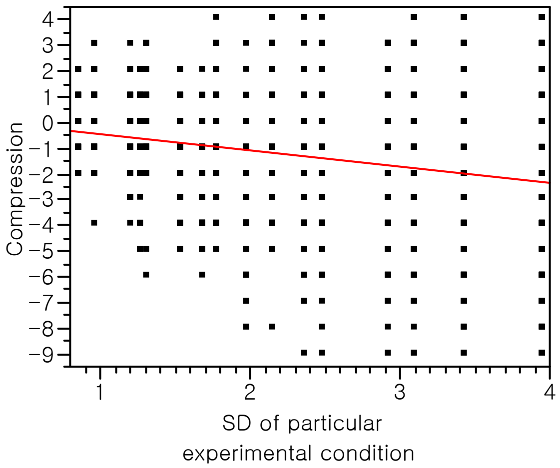

Figure 6. Simple linear regression analysis of compressions against standard deviations of particular experimental condition

The slope is –0.6248 (p value < 0.0001*). Negative value of slope means as standard deviation (in other sense, sensitivity of the particular experiment) increases, compression gets stronger. The regression line was significant in ANOVA (p value < 0.0001*). I also ran multiple linear regression analysis the standard deviation of particular experimental condition with subject, saccade, center reference, stimulus depth variables and obtained same result (p value < 0.0001*).

F. Effect of saccade and center reference on the standard deviation: Sensitivity comparison of saccade and center reference condition

In previous section 4 I showed that the saccadic condition and the presence of center reference causes compression, and from the result of section 5, lower sensitivity yields more compression.

But, although the center reference condition does induce compression, the presence of center reference seemed to make the task easier to the subjects meaning narrower standard deviation. I ran a multiple linear regression on standard deviation of particular experimental conditions against saccadic condition and center reference condition. Following is the model.

Standard deviation of subject's particular experimental condition

$$= \text{intercept} + \beta 1 \times \text{saccade } [0, 1] + \beta 2 \times \text{center ref. } [0, 1]$$

Parameter estimate for saccadic condition (β1) was 0.1472 meaning widening of standard deviations and for center reference condition (β2) was –0.2794 meaning narrowing of standard deviations. All the two estimates were statistically significant and the p value for ANOVA for the fit was significant also (p value <0.001*).

The result is confusing that saccade widens standard deviation and center reference narrows the standard deviation while both conditions showed compressions. The difference of sensitivity may reflect different mechanism of compression.

3. Discussion of Experiment I

A. Result summary of experiment I

The results of this experiment were that depth judgment appears (1) compressed when the stimulus is presented in presaccadic period and (2) compressed when the stimulus is presented with center reference. Three other by-products were (3) presaccadic compression is inversely related to sensitivity of the stimuli or experimental conditions, (4) while both saccade and presence of center reference induces compression, the sensitivity of center reference condition was narrower than saccadic condition and (5) compression of depth judgment is general even without center reference and saccade.

B. The mechanism of saccadic compression: Uncertainty?

(A) Uncertainty from noisy efference copy

The mechanism of saccadic compression is not clear yet. But most researchers agree that extraretinal signal or efference copy is not as precise as visual information[22, 23, 24]. Niemeier et al. have proposed a hypothesis based on a Bayesian probability that perceived target motion results from an optimal integration of sensory input, efference copy, and a prior expectation of object stability. A prediction of post-saccadic target location from a spatial remapping of the presaccadic input is imprecise because of imprecision of efference copy or variability in motor execution. With these uncertainty, brain relies on the prior expectation that target is stationary and calculates optimal position of post-saccadic target location[, 23, 24].

(B) Uncertainty from saccadic suppression

But there is another possible source of uncertainty associated with saccades and it is known as saccadic suppression. The most striking demonstration of saccadic suppression is the fact that we do not perceive the fast changes of scene that are induced by the retinal image shift when saccade occurs. Near the time of saccade, it is shown that the luminance threshold to detect an object is increased by about 0.6 log units[33]. Saccadic suppression is not restricted to just the time of the eye movement. It starts before the eye moves, has its maximum at saccade onset and disappears directly after the saccade is finished[34]. This temporal characteristic is very similar to that of saccadic compression. There is other report that support the decrease of sensitivity associated saccade leads stronger compression. They concluded that the similarity of contrast dependence and time course suggest that saccadic compression is related to saccadic suppression[35].

Because the uncertainty yields random error in responses, the standard deviation can be the measure of uncertainty and it is inversely proportional to the sensitivity of psychometric experiment. If the experimental task were easy for the subject, the standard deviation of response would be narrow. If difficult, the standard deviation would be wide. In the analysis of compression index and standard deviation of particular experimental condition, I have shown that as the standard deviation increases, in other word the sensitivity decreases, the compression increases. And in subsequent multiple linear regression analysis on standard deviation of particular experimental condition against saccadic condition and center reference condition, the saccade caused increase of the standard deviation while center reference caused decrease.

C. The call for depth dimensional map

The principal difference in this experiment from previous experiments is that we are dealing with dimension of depth. Most of previous models are based on the imprecise efference copy which has one-horizontal dimension[22, 23, 24]. And its uncertainty inducing effect should be limited to direction of saccades, in other words, the efference copy is direction specific. But, there are reports support that saccadic compression occurs orthogonal to saccadic direction[14,15]. From the result of this depth dimension experiment, I suspect that the dimensionless uncertainty caused by saccadic suppression may have role in perisaccadic compression as well as efference copy of saccade. It may be that the saccade temporarily causes uncertainty in some part of neural system by increasing their sensory threshold. Recently, Morrone, Ross and Burr[16] reported that even perceived times were compressed when presented perisaccadically. The perception of time has no relevance to the metric of space perception. And this bears implication that compressions are not dimension specific.

D. Compression in presence of center reference

For the compression in the presence of center reference needs different interpretation. While presence of center reference increased sensitivity of depth perception as its decrease standard deviation, it showed compression of perceived depth. It is natural that in localization task, the performance improves when the stimuli were presented with reference. But, in view of above scheme, less compression has to be found.

There are numerous reports that observers showed systematic tendency to mislocalized targets towards a stable frame of reference[30, 31, 32]. In the experiments of Sheth and Shimojo, the subjects had to locate a briefly flashed target while they are fixating. The authors suggested that the fixation is but one example of a frame of reference. They assumed that coding of stimulus position with respect to distance from the reference and the distance from the reference induces noise in localization judgment. For the neurophysiologic basis for the mislocalization, they assumed in given cortical area, the landmark and the briefly presented target cause two non-overlapping groups of cells to fire and after turned off, the activity of the cells die down while the activity of neighboring cells recovers. Thus, the peak of activity corresponding to the target will shift in time to lie closer to the landmark[32].

In our experiment, the center reference can be viewed as a salient frame of reference and presence of center reference though not actually a saccadic target in stimulation of depth. Our result can be a depth dimensional version of above experiment. In above context, compression without center reference and without saccade can be explained, too. As the center reference functions as overt attention plane, the fixation point or the monitor plane may have worked as covert attention plane for the distance to the monitor was obvious to the subject and the monitor frame was visible during the experiment.

E. Neuroanatomic correlation of depth perception and possibility of its spatiotopic arrangement.

The pathway for depth perception especially from binocular disparity is believed to be starting from disparity sensitive neurons in visual cortex. They are found in V1 and also in the extrastriate areas V2 and V3. Many direction-selective cells in MT respond best to stimuli at specific distances, either at the plane of fixation or nearer or farther than the plane. Some cells in MST, the next step in the parietal pathway, fire in response to combinations of disparity and direction of motion[36]. In fact, this experiment is not about the depth representation on lower visual information processing hierarchy. The process of this experiment deals with spatial map, or in other words working memory of space.

Duhamel and his colleagues devised experiments to test whether LIP neurons have visual receptive fields which –like classical receptive fields throughout the visual system-are tied to retinal co-ordinates. Thus, whenever a stimulus is flashed in the part of the visual field with constitutes a neuron’s receptive field, it fires, regardless of where the eyes are looking and they found that the visual receptive fields of some LIP neurons appeared to shift just before saccade, from their normal retinal location to th0e location the receptive field would occupy after the saccade[37]. In recent study using functional MRI, strong spatiotopic activity in parietal and frontal cortex was invoked by directed attention[38]. But only the two-dimensional arrangement of field was investigated and no studies were carried out on the depth dimension yet.

In this experiment, I showed the similar phenomena of saccadic compression and compression with presence of reference seen in 2-dimension. I believe this result give us the insight that the functional organization of depth map may have similar arrangement to two-dimensional map.

4. Summary and Conclusions of Experiment I

We designed experiments to investigate the perceptual judgment of depth stimulus in saccadic and fixation condition. I found that (1) saccade causes compression of space toward fixation point, (2) presence of reference at the horopter also caused shift toward the fixation, also caused compression, (3) in saccadic condition, decreased sensitivity was related the strength of compression, and (4) the compression was a general phenomenon in this short term memory task. These are the well-known phenomena in the two-dimension based studies and much of them are explained by the arrangement of two-dimensional space map models. From the similarity between two-dimensional results and our findings, we can infer the similar functional arrangement of depth coding exists.

III. EXPERIMENT II:

COMPRESSION OF DEPTH ON SPATIAL MEMORY

1. Introduction of experiment II

In the previous experiment, one interesting phenomenon was exposed. It was general compression towards fixation point regardless of the experimental conditions. For this unexpected result, a question arose within our group that the general compression toward center might not be caused from firm perception per se but from the method that the subject adjusts the probes to match previous stimuli. What we thought was while adjusting probes, the probes itself acted as a new stimulus that the originally memorized depth location would be violated, thus in the midst of confusion the subject might hit the midway between the real stimuli and the fixation point. One other question about the method was related to ceiling effect or range effect. When extreme value of stimulus was presented, the limited range of cursor might restrict the responses causing the result to be seemingly compressed. The similar consideration was addressed in other studies, too[39].

To overcome these problems, I adopted 2-alternative forced choice method. In brief, after presenting depth stimulus, a probe near the depth of stimulus is shown. Then the subject decides whether the probe was in front of or behind of the stimulus. By repeating this procedure systematically, one can infer the perceived depth of stimuli or in psychophysical term, point of subjective equality (PSE). By this see and decide method, we can evade problem of adjusting the cursors. Moreover, even if the ceiling effect interferes in the veridical perception of depth, it interferes in the perception of both the stimuli and the probes equally. So, the inferred PSE's will reflect the real perceived depth of stimuli, thus circumventing the ceiling effect.

Among other interesting phenomena, the effect of center reference drew our attention. With center reference in the zero disparity plane, the compression was more prominent and slight repulsion of responses from ego was seen when compared to no center reference condition. These results imply that the presence of reference may have an effect in depth localization. And also, in experiment I, center of compression was fixation point in both ‘center reference’ and ‘no center reference’. For the ‘center reference’ conditions, the presence of center reference might have acted as a compression center but this can not explain the compression in ‘no center reference’ condition. I designed these subsequent experiments with 3 different depth references.

Our experiment is not a study of the immediate perception of depth, rather is a study of memorized stimulus depth, or short term depth memory. The characteristics of this experiment were discussed and investigated in the study of Sheth and Shimojo[32].

Those results were not related to saccade as shown by multiple regression analysis. So these subsequent experiments were done without eye monitoring.

2. Methods of experiment II

A. Subjects

Two male subjects (CJ, 25 years old, K, 26 years old) and two female subjects (J, 24 years old, C, 29 years old) participated in the experiment. All four subjects were naïve to the experiment. Stereoacuity was measured with Titmus Stereo Test and all four subjects showed normal stereoacuity of 40 seconds of arc. From all, written consents were obtained.

B. Apparatus

Subjects were seated in a dimly lighted room. Heads of the subjects were fixed on chin rest with a band around their heads at 60 cm from the display. Visual stimuli were presented on a 17-inch TFT-LCD display (Samsung SyncMaster Magic CX702B) with a spatial resolution of 800 × 600 pixels at a refresh rate of 60 Hz. The edge and the surface of monitor were plainly visible to subjects and they were well aware of the distance to the monitor plane. Stimuli generation, timely presentation of stimuli and probes for 2-alternative forced choice, and response registering were controlled and executed by a graphical programming language LabVIEW^{TM}7.0 (National Instrument). Eye positions were not monitored though the subjects were instructed to fixate at center reference line as possible.

C. Visual stimuli

(A) Generation of depth images

To generate depth images, same method as the main experiment (anaglyphic method) was used. Subjects wore a red filter in front of the right eye and a green filter in front of the left. On the monitor, the image for the right eye was shown in red and the image for the left was green. For images to be seen by both eyes, luminance adjusted gray image was used. In this experimental setting, 2-pixel crossed disparity matches 4.83 minutes of arc with the depth effect of 5.23mm near while the interocular distance being 60mm.

(B) Coding depth

Same as the experiment I.

(C) Reference, Stimuli, and Probe

Visual stimuli consisted of two components, reference and depth stimulus. (Figure 7)

(D) Reference

The reference consisted of 3 horizontally arranged vertical lines at the vertical center of the monitor (in vertical middle of the each figures in figure 1. except reference at zero but only one line). In detail, the dimension of each vertical line was 2.42 minutes of arc (1 pixel) in width and 51.62 minutes of arc (20 pixels) in height and they were arranged 24.20 minutes of arc (10 pixels) horizontally apart.

To investigate the effect of reference location on depth judgments, the experiment was designed with 3 different reference depths; near, far and zero disparity (i.e. on the monitor). Disparity for near was 6 pixels of crossed disparity (in this experiment, it is coded as '-3'.) and for far was 6 pixels of uncrossed disparity (in this experiment, it is coded as '3'.). In addition, to investigate the effect of the strength of reference, I included one reference line condition at zero disparity. This was based on the assumption that the space coding intensity can be varied by overall stimulus intensity in additive manner.

(E) Depth stimuli

For the depth stimulus, two vertical lines of identical depth were shown, one above the reference and another below (Figure 7). The dimension of depth stimulus line was 2.42 minutes of arc (1 pixel) in width and 64.54 minutes of arc (25 pixels) in height. The reference and depth stimulus was vertically separated by 12.90 minutes of arc (5 pixels). The reason for placing two identical depth stimuli above and below is not to attract 2-dimensional attention out of center reference.

Five depth stimuli were investigated, two for near, one for zero disparity, another two for far. The near depth stimuli were '-4' and '-2' (8 pixels and 4 pixels of crossed disparity respectively). The far depth stimuli were '2' and '4' (4 pixels and 8 pixels of uncrossed disparity respectively).

(F) Probes

The configuration of probe is basically same as stimulus, two depth lines above and below the center reference. To draw a psychometric function of a given stimulus, 7 depths adjacent to the depth and including its own are probed. From the pilot experiment, the range of probe depth was predetermined so that most of point of subjective equality (PSE) falls within the 4 center probe location ranges.

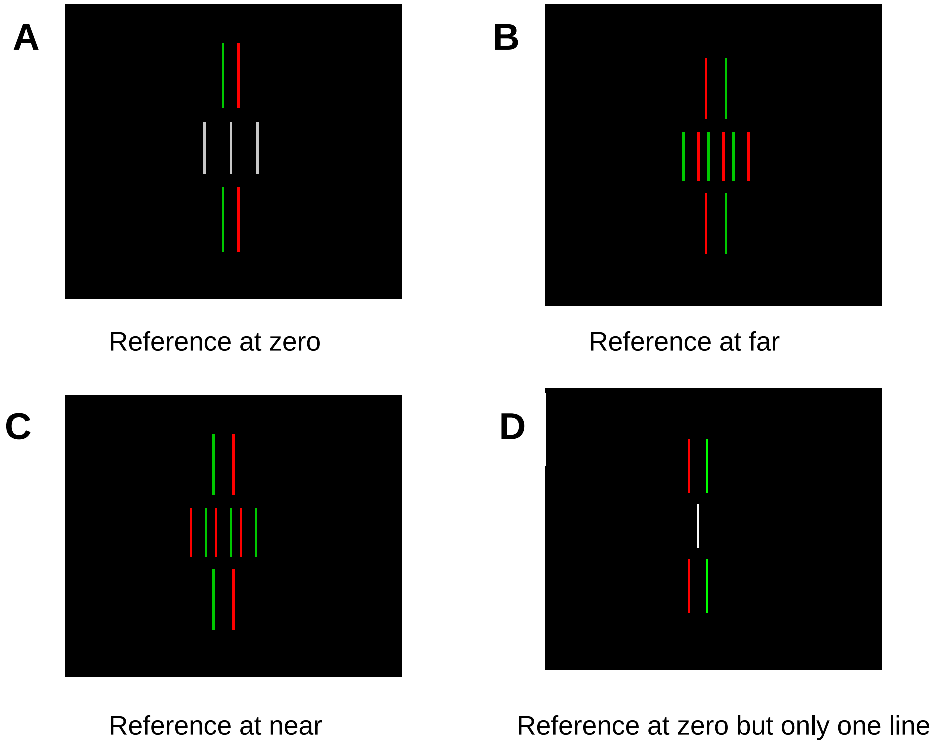

Figure 7. Four types of references with depth stimuli
(A) Reference at zero disparity in vertical middle with depth stimuli above and below. (B) Reference at far with depth stimuli. Note that references are arranged in 6 pixels of uncrossed disparity when viewing with red filter in right eye and green filter in left. (C) Reference at near in 6 pixels of crossed disparity with depth stimuli. (D) Reference at zero but only one line. Image used for probing was in basically same configuration with same reference.

D. 2-alternative forced choice (2-AFC) and psychometric function

For estimation of depth judgment, 2-alternative forced choice (2-AFC) procedure was used.

To explain briefly, after a stimulus presentation, a probe appears. Then the subject is forced to make a choice whether the probe was nearer or farther than the stimulus. If the probe seemed definitely nearer than the stimulus, the probability for near response goes high up to 100% and for far response down near to 0%. If the probe gets closer to the stimulus, the subject has to guess and the probability for far increases until it approaches to the chance level of 50%. After some number of trials, the ratios of far response were obtained for each probe depth to a given stimulus. They are plotted and a psychometric function was fitted with Weibul function[40]. Two parameters were extracted from the fitted curve. One is point of subjective equality (PSE) where the ratio for near takes 50%, which corresponds to perceived depth of the given stimulus. The other is slope of the curve at the PSE, which corresponds to the depth sensitivity of the given stimulus (i.e. if the slope is steeper, the depth difference is more easily discriminated). Figure 2 is an example of psychometric function fitting. The depth stimulus was at the depth of 3. Plotted dots correspond to the ratios of far response at the given probe depth. For example, at the probe depth of 3 the subject responded 0% far. In other words, the subject responded 100% near. At probe depth of 6, the subject responded 40% far. After fitting the curve, we get PSE of 5.685. This means that the subject judged the stimulus shown at depth of 3 as being at 5.685 of depth.

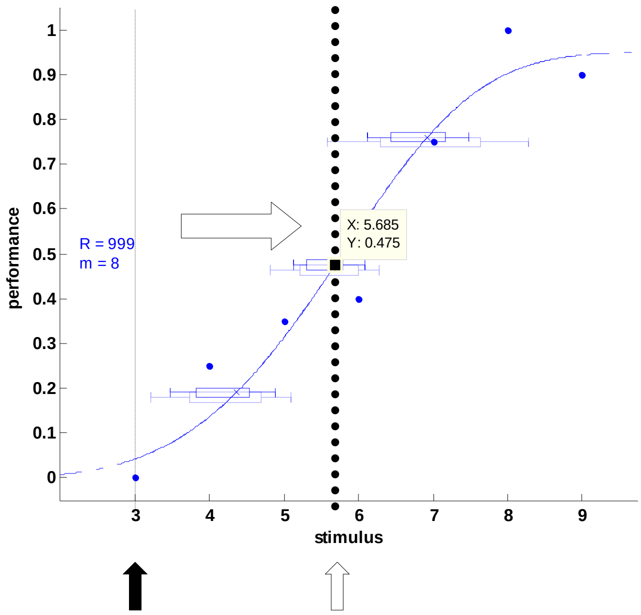

Figure 8. An example of psychometric function fitting

The actual stimulus was presented at location 3 (Filled arrow). Probes were presented at 3, 4, 5, 6, 7, 8, and 9 for 20 times each. Plotted dots are the ratio of near responses. For example, at probe depth 3 the ratio of near was 0.This means that the subject responded the stimulus was never felt nearer than the probe although it was the same location as the stimulus in all 20 probe trials. At probe depth of 6, the subject responded 40% far. With the same manner, each ratio at each probe location was determined and psychometric function in this experiment, Weibul function, was fitted. After fitting the curve, we get PSE of 5.685 (empty arrow). This means that the subject judged the stimulus shown at depth of 3 as being at 5.685 of depth (large empty arrow).

E. Procedures

As explained above, there are 4 experimental conditions. One, 3 reference line at fixation point, two, 3 reference line at near, three, 3 reference line at far, and four, one reference line at fixation point. All the experimental procedures were basically same.

Subjects were seated in a dimly lighted room. After, heads of the subjects were fixed on chin rest with a band around their heads at 60 cm from the display, they were instructed to maintain fixation at the center of the reference. In each trial, a stimulus with reference was presented for 500ms followed by only reference shown for 500ms. Then a probe with reference for 2-AFC was shown for 500ms, again followed by only reference. Then the subject was forced to make a choice whether the probe was nearer or farther than the stimulus by pressing an arrow key on a computer keyboard. In each depth stimulus, 7 varying depth probes were tested 20 trials for each stimulus depth.

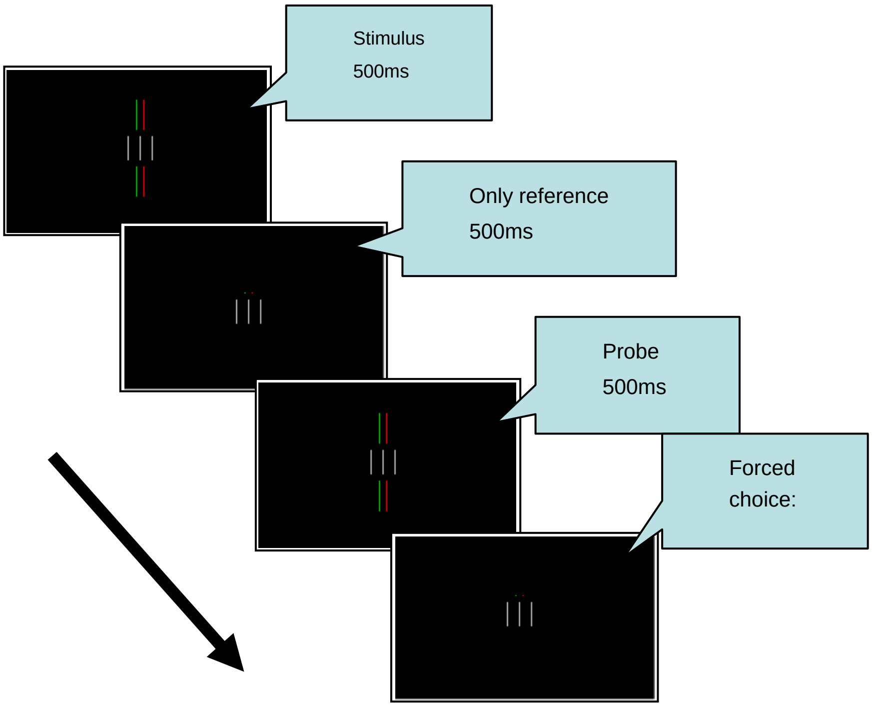

Figure 9. Procedure of Experiment II

At first, a stimulus with reference was shown for 500ms. Next, only reference was shown for another 500ms. Then after a probe with the same reference was shown for 500ms. Finally, only reference was shown and the subject was forced to make a choice.

F. Data adjustment for interpersonal comparison

Data adjustment was done in similar manner to the experiment I. In his experiment PSE was main variable. Thus, we get

Adjusted PSE =

PSE / SD of each subject's particular experimental condition

G. Adjusted compression index

The same concept was applied in calculating adjusted compression index, too. In formula form, it is written as,

Adjusted Compression Index = [PSE – Stimulus] × direction adjuster
/ SD of each subject's particular experimental condition

3. Results of experiment II

A. Overall data descriptions

Figure 10 shows all subject' PSE's (not 'adjusted') against stimulus depth in each experimental condition. All data point indicated the compression though there were subject variabilities. Results of subject C were plotted as blue line with diamond dot, result of subject J as orange line with square dot, result of subject CJ as yellow line with triangle dot, and result of subject K as bright blue with cross. The veridical line stands for a line where the dots should be placed if the PSE's were veridical. In the conditions of reference at zero and reference at zero but one line, the results of all subjects were above the veridical line when the stimulus was near and below when the stimulus was far, which mean compression. For the zero disparity stimuli, PSE's were not equal to zero implying that there could be overall push or pull of PSE's. Also, there were subject variabilities, especially for subject CJ who showed nearly veridical PSE's. For reference at near condition, subject J showed rather expansions on far 2 stimulus but after offsetting PSE of zero disparity stimulus being above zero as center of PSE's, we can infer the compression still implied in. There are 3 other points that seemed to be outliers, -4 stimulus of subject C in reference at near and 2 and 4 stimuli of subject K in reference at far. Their slopes were under 0.1, which is below 5% lower quantile of slope distribution meaning that the subject showed very low discriminability thus the validity of psychometric function questionable. They were excluded from subsequent analyses.

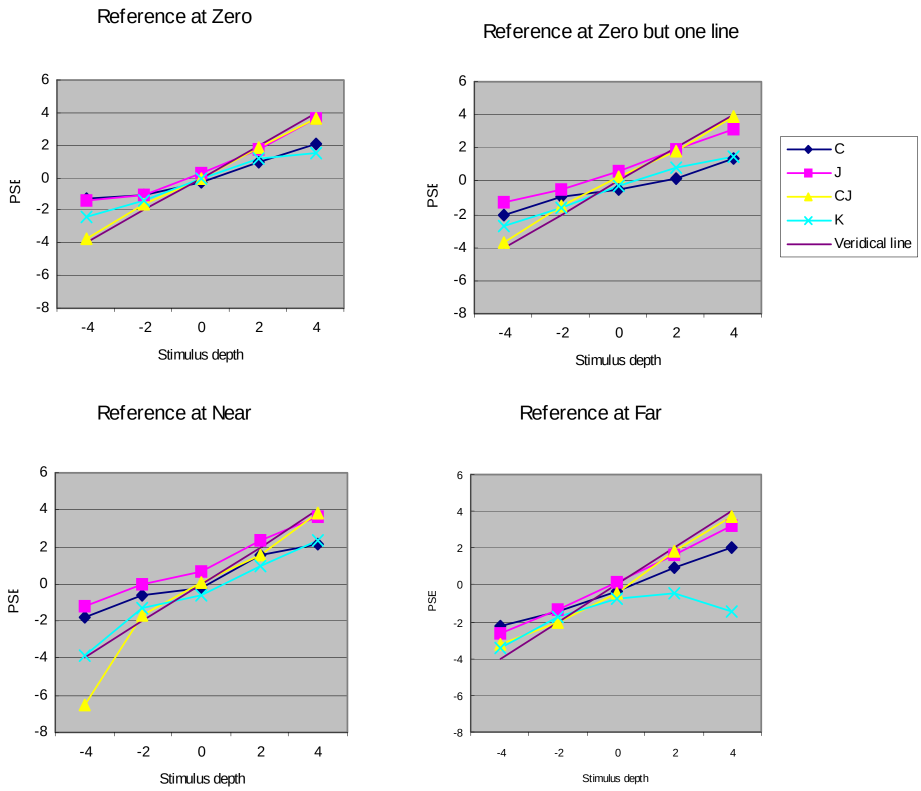

Figure 10. All subjects' PSE (not adjusted) against stimulus depth in each experimental condition.

Results of subject C were plotted as blue line with diamond dot, result of subject J as orange line with square dot, result of subject CJ as yellow line with triangle dot, and result of subject K as bright blue with cross. The veridical line stands for a line where the dots should be placed if the PSE's were veridical. For detailed descriptions, see the text.

B. Adjusted compression index and effect of reference depth on compression

(A) Adjusted compression indices of each experimental condition

Figure 11 shows the adjusted compression indices of each experimental condition. The data were plotted with box and whisker. Across the experimental conditions, almost all data points were under 0, which means compression. Wider dispersions were seen in –4 and 4 stimulus depths compared to –2 and 2 stimulus.

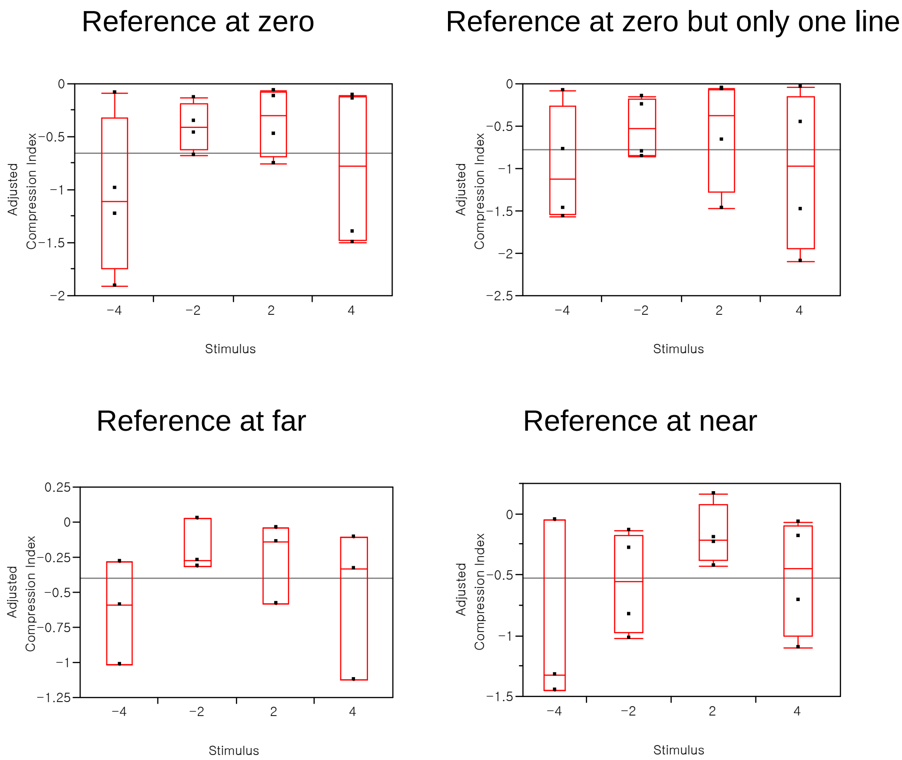

Figure 11. Adjusted compression indices of each experimental condition Each PSE were converted to adjusted PSE for interpersonal comparison. Across the experimental conditions, almost all data points were under 0, which means compression. Wider dispersions were seen in –4 and 4 stimulus depths compared to –2 and 2 stimulus.

(B) Multiple linear regression analysis

To investigate the effect of reference depth on compression statistically while controlling other variables, I did multiple linear regression analysis. The dependent variable was adjusted compression index and independent variables taken into the model were reference depth, stimulus depth, and subject. For analysis, data of ‘reference at zero’ and ‘reference at zero but only one line’ were put together since preliminary analysis showed no significant difference of compression between the two. The model can be written as

Adjusted compression index =
intercept + $\beta 1 \times$ reference depth [-3, 0, 3] + $\beta 2 \times$ stimulus depth + $\beta 3 \times$ subject

The effect of near compared with zero disparity was not significant (p value: 0.1162) but the effect of far compared to zero was significant (p value: 0.0461^{*}). The parameter estimate ($\beta 1=0.3030$) being positive means there were less compressions in ‘reference at far’ condition than in ‘reference at zero’ conditions.

C. Effect of reference on general depth localization

(A) One-way ANOVA

Besides the effect of reference depth on compression, I examined its effect on general depth localizations. Figure 6 is a result of one-way ANOVA of adjusted PSE against each reference depth group. On x-axis, ‘-3’ stands for reference at near, ‘0’ stands for sum of reference at zero and reference at zero but only one line, and ‘3’ stands for reference at far. X-axis was set to be proportional to the each group size. Although the result showed no statistical significance (p value: 0.6442), there seems to be a tendency that as reference depth gets farther, the mean of PSE gets nearer.

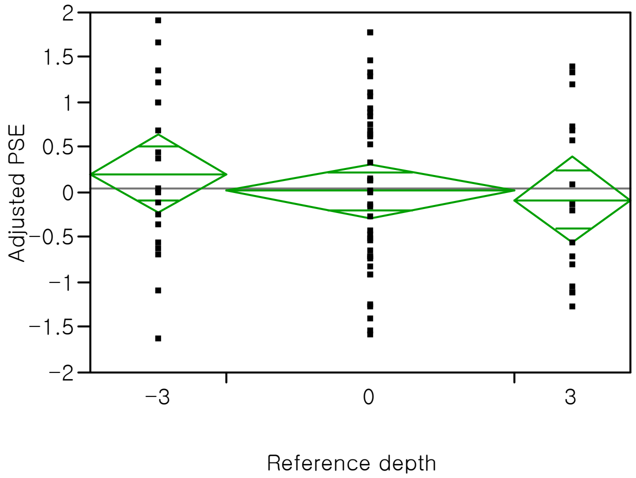

Figure 12. Effect of reference on general depth localization by one-way ANOVA

On x-axis, '-3' stands for reference at near, '0' stands for sum of reference at zero and reference at zero but only one line, and '3' stands for reference at far. X-axis was set to be proportional to the each group size. The line across each diamond represents the group mean. The vertical span of each diamond represents the 95% confidence interval for each group.

(B) Multiple linear regression analysis

To control other variables and investigate the effect of reference depth in adjusted PSE, I ran a multiple linear regression analysis. The dependent variable was adjusted PSE and the independent variables were reference depth, stimulus depth, and subject. The model can be written as

Adjusted PSE =

intercept + β1 × reference depth [-3, 0, 3] + β2 × stimulus depth + β3 × subject

The effect of reference depth was significant (p value = 0.0001*) and the parameter value was negative meaning the reference depth gets farther, the mean of PSE gets nearer

4. Discussion of experiment II

A. The reason for experiment II: Compression, an artifact?

In experiment I, a question arose that the general compression toward center might not be caused from the actual perception but from the method that the subject adjusts the cursors to match previous stimuli.

Two possible sources of error were addressed. One is while adjusting probes, the probes itself acted as a new stimulus that the originally memorized depth location would be violated, thus in the midst of confusion the subject might hit the midway between the real stimuli and the fixation point. The other was about the method was related to ceiling effect or range effect. When extreme value of stimulus was presented, the limited range of cursor might restrict the responses causing the result to be seemingly compressed.

B. Adopting 2-alternative forced choice method and the results

To overcome these problems, I employed 2-alternative forced choice method and it showed that the compression was not the artifact of experimental method. In each trials, the subject made simple judgment whether later probe was in front or behind of the previous stimuli. Thus, there were no chances of interference of a memorized depth of stimuli. About the ceiling effects, from the pilot study, the depths of probes to drive PSE were chosen and generated to place the PSE within the 4 center probe location of 7 steps so to place the

PSE near the center of the profile of psychometric function. All data point indicated the compression though there were subject variabilities.

C. Supremacy of disparity zero? : Effect of reference in other depth plane

In experiment I, center of compression was fixation point in both ‘center reference’ and ‘no center reference’. For the ‘center reference’ conditions, the presence of center reference might have acted as a compression center but this can not explain the compression in ‘no center reference’ condition. In experiment II, I placed reference in near (-3) and far (3) out of monitor plane or disparity zero plane. The effect of near compared with zero disparity was not significant (p value: 0.1162) but the effect of far compared to zero was significant (p value: 0.0461[*]). The parameter estimate ($\beta 1=0.3030$) being positive means that there were less compressions in ‘reference at far’ condition than in ‘reference at zero’ conditions. But the center for compression seemed not much varied from monitor plane or disparity zero plane and this may be the subjects already new the monitor distance or the disparity zero has some perceptual supremacy even in other depth conditions.

For the position of adjusted PSE, the effect of reference depth was significant (p value = 0.0001*) and the parameter value was negative meaning the reference depth gets farther, the mean of PSE gets nearer. This result means somewhat perplexing, that if the center of compression is the salient landmark as mentioned in the study of Sheth and Shimojo (2.5 section of their experiment), the mean of PSE should be deviated toward the reference. But, in their experiments, the fixation point and a vertical line was continuously in presence through out the experiment[25]. In our experiment, the second covert landmark, monitor plane or disparity zero plane, was not seen during the experiment. The invisible landmark, monitor plane or disparity zero plane, may have projected negative deflection on the depth map thus yielding reversed result.

5. Summary and Conclusions of Experiment II

We employed 2-alternative forced choice method. All data point indicated the compression though there were subject variabilities.

The effect of near compared with zero disparity was not significant (p value: 0.1162) but the effect of far compared to zero was significant (p value: 0.0461*). The parameter estimate ($\beta 1=0.3030$) being positive means there were less compressions in 'reference at far' condition than in 'reference at zero' conditions. The effect of reference depth was significant (p value = 0.0001*) and the parameter value was negative meaning the reference depth gets farther, the mean of PSE gets nearer. But the center for compression seemed not much varied from monitor plane or disparity zero plane and this may be the subjects already knew the monitor distance or the disparity zero plane has some perceptual supremacy over other depth conditions.

III. GENERAL SUMMARY AND DISCUSSION

In experiment I, I found that (1) saccade causes compression of space toward fixation point, (2) presence of reference at the horopter also caused shift toward the fixation also caused compression, (3) in saccadic condition, decreased sensitivity was related the strength of compression, and (4) the compression was a general phenomenon in this short term memory task.

In experiment II, by adopting 2-alternative forced choice method, I showed that the general compression in not an artifact of experimental methods but a real phenomenon.

The similar phenomena are well-known in the 2-dimension based studies and much of them are explained by the arrangement of two-dimensional space map models. From the similarity between two-dimensional results and our findings, we can infer the similar functional arrangement of depth coding exists.

Then, a fundamental question arises. Why the functional arrangement of depth map should take similar arrangement as 2-dimentional retinotopic spatial map? In higher areas, visual areas are smaller and receptive fields of neurons are larger[41, 42]. With a small cortical area containing somewhat noisy single units, one might think that the spatial coding would be inaccurate and ineffective. But, if those broadly tuned receivers are orderly (or spatiotopically) arranged, the overall response rapidly becomes almost linear in a very smooth and robust fashion[43]. Another explanation can be come from wiring optimization principles. Because of spatial correlations in the external world, the early stages of the visual system combine information coming from the adjacent points in the visual field. To minimize the wiring length, neurons with adjacent receptive fields should be placed as close to each other as possible[44]. This is exactly what an ordered retinotopic map accomplished and the same principles can be applied to depth map, too.

IV. CONCLUSION

Recent researches found that in very short time window (about100ms) prior to a saccade, systematic distortions of space perception occur. One of them is saccadic compression that perceived locations of stimuli are compressed toward saccadic target. It is considered as consequences of uncertainty of eye movement signal while updating the spatial map of the brain. But, these experiments and models have been only dealing with two-dimensional phenomena and map and yet there is no experiment mentioning the third dimension of space, depth. I designed experiments to investigate the perceptual judgment of depth stimulus in saccadic and fixation condition. I found that (1) saccade causes compression of space toward fixation point, (2) presence of reference at the horopter also caused shift toward the fixation also caused compression, (3) in saccadic condition, decreased sensitivity was related the strength of compression, and (4) the compression was a general phenomenon in this short term memory task. These are the well-known phenomena in the two-dimension based studies and much of them are explained by the arrangement of two-dimensional space map models. From the similarities between two-dimensional results and findings from this study, one can infer the spatiotopic arrangement of depth map.

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< ABSTRACT(IN KOREAN)>

안구신속운동조건과 주시조건에서
깊이자극에 대한 지각적 판단에 관한 연구

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최근의 연구들은 신속안구운동 약 100ms 직전 체계적인 공간지각의 왜곡들이 일어남을 보고하고 있다. 신속안구운동에 의한 지각공간의 축소는 이 왜곡들의 하나로서, 신속운동직전 보여진 시자극들이 신속운동의 목표점으로 이동하는 것으로 왜곡되어 지각되는 것이다. 이 현상은 안구운동시 일어나는 공간지각의 재편과정에 관여하는 안구운동신호의 통합이 부정확한 것에서 기인하는 것으로 생각되고 있다. 대체로, 안구운동에 즈음한 지각의 왜곡 현상은 2차원지각에 한정되어 왔으며 깊이지각에 대한 연구는 드물다. 실험 I에서 저자는 안구신속운동조건과 안구고정조건에서 깊이자극에 대한 지각에 대한 실험을 하여 다음과 같은 결과를 얻었다. (1) 안구신속운동은 자극의 깊이가, 망막시차가 없는 응시점으로 왜곡되어 지각되었다. (2) 영시차 평면에 참조자극이 동시에 존재하면, 영시차 평면으로 자극의 깊이가 왜곡되어 지각되었다 (3) 실험조건의 민감도가 감소할수록 응시점으로 왜곡되는 정도는 강하였다. (4) 응시점을 향한 깊이지각의 왜곡은 일반적인 현상이었다. 실험 II 에서는 2-alternative forced choice방법을 통해 깊이지각의 왜곡이 실험방법의 오류에 의한 것이 아니라는 것을 보였다. 이러한 현상들은 2차원 공간지각에서 잘 알려진 지각공간의 축소 현상과 흡사하여, 3차원적 공간의 지각도 마찬가지로 응시점으로 축소되어 지각됨을 시사한다.

핵심되는 말 : 신속안구운동, 깊이지각의 축소, 공간지도