Japanese Psychological Research
2002, Volume 44, No. 3, 124–133
Special Issue: Reciprocity between applied and basic studies

Shift of attention in depth in a semi-realistic setting

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Abstract: This research was based on previous research on the useful field of view in real driving, however shift of attention was examined in depth by the use of an improved tunnel simulator. Despite of the importance of this area of research, nothing like this has been performed previously. The subjects' task was judgment of the relative distance of targets (farther, nearer, or the same), in comparison with a fixation point. Reaction times were measured. There were two variables. One was three observing conditions. Subjects moved at apparent speeds of 40 km/h or 80 km/h or were stationary. The second variable was the validity of the precue concerning the location of the appearance of the target relative to the fixation point. There were three conditions, valid, invalid and or neutral. The results clearly showed that reaction times for nearer targets were shorter than those for farther targets in all conditions. This supports a viewer-centered representation of three-dimensional space. Concerning the direction of shift of attention, reaction time for shift of attention from far locations to near locations was shorter than for the opposite. This difference was more remarkable in the moving condition than in the stationary condition. This was called the *rubber band metaphor of attention in locomotion* (asymmetrical viewer-centered mode of shift of attention in depth). These results are ecologically valid. Possible underlying mechanisms are discussed from the viewpoint of distribution of attention resource.

Key words: visual attention, three-dimensional space, asymmetry in depth, shift of attention, cost-benefit method.

The background of the present research is our previous research on eye movements and useful field of view in real driving. It has been shown clearly that with increase in demands, useful field of view becomes narrower and, correspondingly, reaction time for detection of peripherally presented targets becomes longer (Miura, 1986, 1990). But this decrement of peripheral visual performance should not merely be taken as deterioration in acquiring and processing information. When the decrement is observed due to an increase in demands, two active functions are found. One is the deeper processing at each fixation point, which causes the useful field of view to narrow (Miura, 1987). The other is the stronger inclination towards acquiring information in the peripheral visual field (Miura, 1996). Miura (1996) also found these two active functions by examining the rate of increase in the reaction time as a function of the onset eccentricity of targets. Moreover, Miura (1992) demonstrated the product of response eccentricity with reaction time in foveal vision to be constant, indicating the amount of processing resources available to be constant. These active functions found in more demanding situations were called *cognitive momentum* by Miura (1990). It might be said that this cognitive momentum reflects an optimization of the allocation of limited processing resources for coping with greater demands.

Although these findings gave a new perspective to active attention, eye movement study can tell little about attention in three-dimensional space. We would like to know more about the characteristics of three-dimensional useful field of view. But there has been little research on the characteristics of shift of attention in depth and useful field of view in depth (Downing & Pinker, 1985; Gawryszewski, Riggio, Rizzolatti & Umilta, 1987; Andersen, 1990; Miura, Shinohara & Kanda K, 1994a; Iavecchia & Folk, 1995; Kasukawa & Kikuchi, 2001; Kimura & Miura, 2001a).

The purpose of the present research is also practical, that is examining the influence of visual aids such as automobile navigation systems (Miura, Akamatsu, Ishida, Sugano & Yano, 1993; Yano, Takahashi & Sugano, 1994b; Miura & Shinohara, 1998; Miura & Shinohara, 2000) and head-up displays (Wickens & Long, 1995; Tufano, 1997) on driving safety. It is almost self-evident that visual attention deteriorates during observation of a navigation display, because sight lines deviate from the forward environment. Furthermore, the rapid and efficient switching of attention between the forward environment and the inside display of a car is crucial for safety. But this characteristic of attention switching in depth has not yet been investigated.

Based on this background, the purpose of the present research is to examine the characteristics of shift of attention in depth for moving and stationary observers.

Method

Overview

Targets and a fixation point were presented on the central line of sight of subjects in depth direction. Subjects made judgment of relative position of targets to a fixation point, that is, near, far, and the same, under both moving and stationary conditions. Before each trial, a cue was given on the location of appearance of a target relative to the fixation point. A certain percentage of the cues were incorrect. Reaction times for the judgment were measured.

Subjects

Four male undergraduate students of Osaka University participated as subjects. All subjects were members of an ice hockey club, and had either normal or corrected-to-normal vision.

Apparatus and presentation of targets

A three-dimensional attention measurement system for moving observers was used (Figure 1). This was an improved system based on a 1/25-scale tunnel simulator 13 m in length. The simulator had miniatures of typical tunnel lights, sidewalls and road surface. The inner size was 33 cm wide and 16 cm high. The apparent size of the inner scenery was reduced to 1/2 scale by a viewing lens, and as a result the scenery viewed was on a 1/50 scale. Under the two moving conditions, each subject sat on the chair of a cart, placed his face to the frame of a viewing lens, and moved into the simulator with the cart. The cart itself was moved by a motor and subjects did not operate the cart. Under stationary conditions, they did not move.

A fixation point was presented 2.5 cm above the road surface at a distance of 1.20 m from the subject. The distance of a virtual image of the fixation point was 2.40 m through the viewing lens, and the image yielded a semi-realistic feeling of distance of 60 m from a subject in calculation. The cart with the chair sat by the subject and the road surface with the fixation point moved together into the simulator (see Figure 1). Subjects were instructed to focus their attention on the fixation point binocularly.

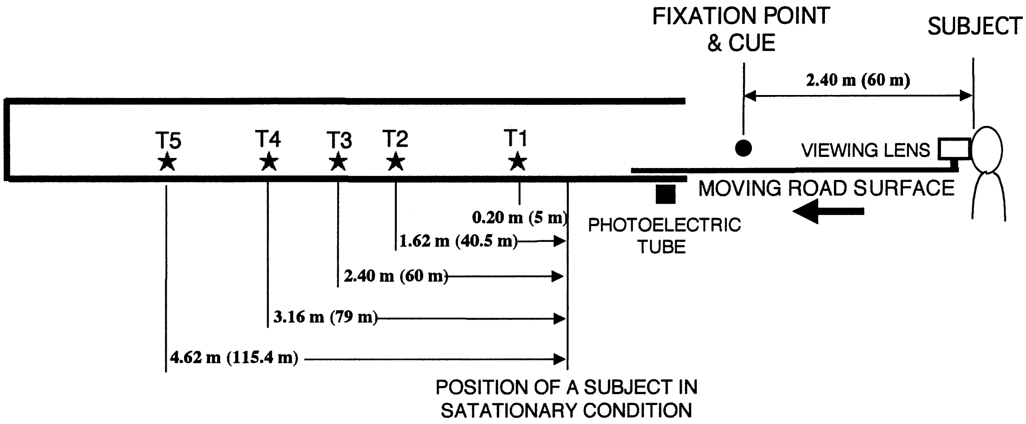

Figure 1. A three-dimensional attention measurement system for moving observers. This is an improved system based on a 1/25 scale tunnel simulator (13 m in real size). The apparent size of inner scenery is reduced to 1/2 scale by a viewing lens, so the apparent scenery is 1/50 scale. Under moving conditions, a subject moved into the simulator together with a cart, road surface and viewing lens. The distances of virtual image of targets are indicated. Numbers in parentheses indicate semi-realistic apparent distances. T = Target.

A target was presented at five possible locations at a height of 3 cm on the central line of sight of subjects. Under both moving and stationary conditions, the distances of the virtual image of the targets were 0.20 m, 1.62 m, 2.40 m, 3.16 m, 4.62 m, yielding a semi-realistic apparent distance of 5 m, 40.5 m, 60 m, 79 m, 115.4 m, respectively. As shown in Figure 1, under stationary conditions, target 3 (T3) was presented at approximately the same location as the fixation point, and distances between targets and a fixation point were the same for target 1 (T1) and target 5 (T5), and for target 2 (T2) and target 4 (T4) in opposite direction (Figure 2). Target 2 (T2) and target 5 (T5) were equivalent in degree of accommodation from a fixation point in diopter. Under moving conditions, the same relationship among targets and a fixation point was accomplished by calculating moving speeds and target distances. Almost all targets in Figure 1 could be both nearer and farther targets under the moving conditions. Presentation of targets and a fixation point was controlled by a microcomputer (Macintosh Classic II), a control device (Science Link, Keisoku-Giken, Tokyo, Japan) and a pair of photoelectric tubes.

Targets were red LED with a diameter of 5 mm and approximately 6.9 cd/m^2 in brightness. The fixation point was a LED with the same size and brightness in red or green, depending on contents of the cue (see below). The brightness of the inside gray wall of the simulator was 230.0 cd/m^2.

Design and procedure

There were two independent variables. One was the observing condition of the subjects: the stationary condition, and the two moving conditions at apparent speeds of 40 km/h and 80 km/h. These three conditions were conducted in separate sessions of 200 trials, and the order of the conditions was counterbalanced among subjects. One session lasted from 30 min to 2.5 h, depending on conditions.

The other variable was validity of cue or expectancy on the appearance locations of the targets, relative to a fixation point. On each trial, subjects fixated on the fixation point, which indicated by color whether a target would be presented nearer to or farther than the fixation point. The green fixation point indicated nearer presentation, the red one indicated farther presentation, and when both green and red fixation points were presented,

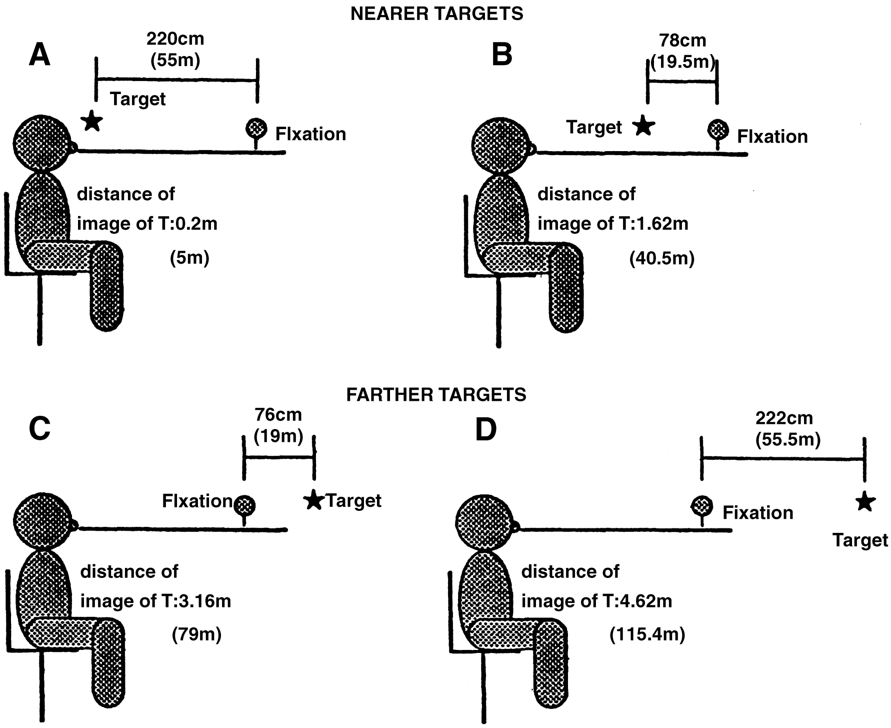

Figure 2. Relative distance between targets and a fixation point. The distances between targets and a fixation point are indicated in virtual distance. Distances of targets from fixation points in (A) and (D), and those in (B) and (C) are corresponding in the opposite direction. Under moving conditions, the same relation among targets and a fixation point is accomplished by calculating moving speeds and target distances. Almost all targets in Figure 1 can be both nearer and farther targets under moving condition. T = Target.

subjects would not know the presentation location in advance. Within each session, 50% of trials were unknown (not cued), called neutral trials. The other 50% of trials were cued. Among cued trials, 80% of trials were cued correctly, called valid cue trials. The other 20% of trials were cued incorrectly, called invalid cue trials. In these trials, targets appeared on one of the other locations, that is if cued as nearer, the target appeared farther away or at the same location in comparison with the fixation point.

The task of the subjects was to judge the relative distance of targets – farther, nearer, or the same – in comparison with a fixation point. Reaction times were measured. A target appeared immediately after the disappearance of the cueing fixation point, and the target disappeared with the subjects' response. The response was a three-alternative forced choice. Response keys were attached to left and right handgrips in front of subjects. Keys for far and near responses were on the right hand grip, and a key for the same response was on the left handgrip. After each response, feedback was given orally as to reaction time and correctness.

Under moving conditions, the sequence of presentation in each trial was as follows. The subject was given a verbal ready signal at the starting location and the cart movement started. When the cart passed a pair of photoelectric cubes, the cueing fixation point was presented. The presentation duration ranged from 1.85 s to 13.5 s, depending on the moving speed and distance of the target. At the moment of disappearance of the fixation point, a target was presented. After response, feedback was given, and then the cart was returned to the starting location. Under the stationary condition, the presentation duration of the cueing fixation point was from 1.8 s to 2.0 s.

Results

Percentages of the rates of correct responses were 81.8, 85.5, and 89.5, under 40 km/h (lower speed) conditions, 80 km/h (higher speed) conditions, and stationary conditions, respectively. The correct responses were analyzed and reaction times of less than 100 ms or more than 1000 ms were discarded, because the former was considered an anticipatory response without judgment and the latter that a target appeared when subject was distracted.

First, the effects of target location, expectancy and moving conditions are examined independently. Then, the integrated effects will be discussed.

Effect of target location relative to fixation point

Figure 3 shows the mean reaction time as a function of target location relative to the fixation point under all observing conditions. The mean reaction time was shorter for nearer targets than for farther targets. Reaction times for the same distance targets were longest. This indicates that judging the same distance was most difficult in the present experiment. A one-way analysis of variance showed that the effect of relative location was significant ($F_{2,902} = 52.45$, $p < 0.0001$), and Scheffe's test showed significant differences in reaction time between "near" and "the same", and between "near" and "far" ($p < 0.05$), and no significant difference between "the same" and "far".

Asymmetry of reaction time in depth should be noted. That is, reaction time is shorter for nearer targets than farther ones, where brightness and relative distance from the fixation point are the same. This supports "viewer centered representation of three-dimensional space" (Andersen, 1990).

Effect of expectancy for appearance of a target in depth

Figure 4 shows the mean effect of validity of expectancy (cue) under all observing conditions. Reaction time was shortest in valid cases. A one-way analysis of variance showed that the effect of validity of expectancy is significant ($F_{2,1776} = 82.3$, $p < 0.0001$), and Scheffe's test showed significant differences between valid and invalid cases ($p < 0.05$), and between valid and neutral cases ($p < 0.05$), and no significant difference between invalid and neutral cases.

Thus, the effect of validity of expectancy in depth under both moving and stationary

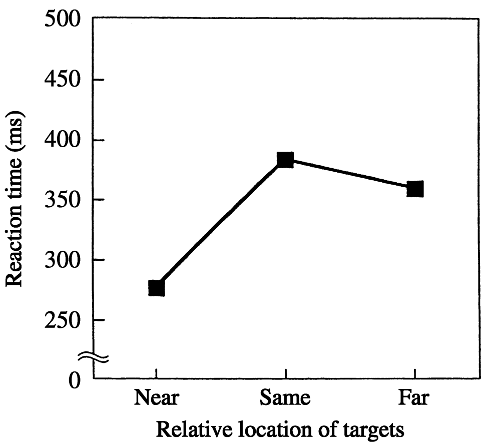

Figure 3. Effect of location of targets relative to a fixation point.

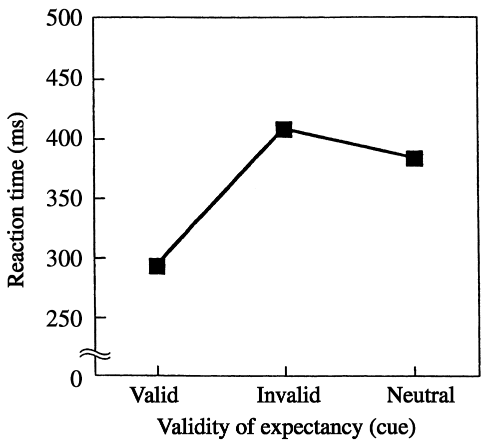

Figure 4. Effect of validity of expectancy. This effect is more remarkable in depth than in two-dimensional space.

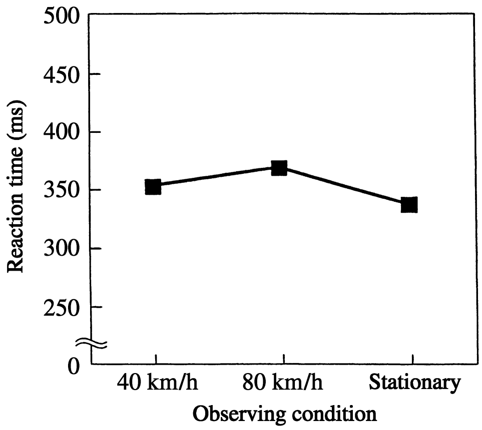

Figure 5. Effect of observing condition. No difference is found among observing conditions, but significant differences are found in relation with validity of expectancy.

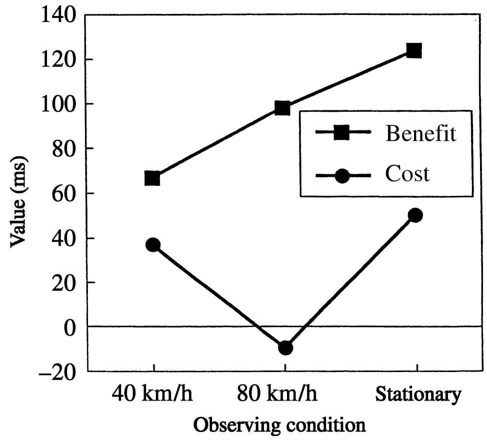

Figure 6. Relation between cost-benefit and moving condition. Attention operates to unexpected events more efficiently in the moving situations than in the stationary situation, and in the higher speed condition than in the lower speed condition.

conditions was confirmed. The magnitude of the effect should be noticed. The difference of 121 ms in reaction time between valid cases (290 ms) and invalid ones (411 ms) in the present experiment is much larger than the difference of 70 ms found in an experiment in two-dimensional space by Posner, Nissen, and Ogden (1978) (reaction times of 235 ms and 305 ms in valid and invalid cases, respectively). This demonstrated that the effect of expectancy of spatial location is greater in three-dimensional space than in two-dimensional space.

Effect of moving condition

As shown in Figure 5, the moving condition had no significant effect on reaction time. However, a thorough examination of the moving condition in relation to validity of expectancy and relative location of targets, revealed the profound implications that follow.

Discussion: Mode of shift of attention

It was shown that reaction time is shorter for nearer targets than for farther targets. Concerning the effect of the validity of expectancy, the effect was confirmed in depth under the moving condition, and it was shown that the magnitude of the effect here is more remarkable than in two-dimensional space under the stationary condition. But no significant effect of the moving condition on reaction time was found. The relationship among these variables should be discussed.

Relation between cost-benefit and the moving condition

Figure 6 shows values of cost and benefit as a function of the moving condition. "Cost" indicates the loss of efficiency of attention caused by invalid expectancy, that is the difference in mean reaction time between invalid cases (in which a target appears in the opposite direction to expectancy) and neutral cases (in which subjects have no particular expectancy regarding the direction of target appearance). "Benefit" indicates gain of efficiency of attention caused by valid expectancy, that is, the difference in reaction times between a valid case (in which a target appears in an expected direction) and a neutral case. One-way analyses of variance showed that the effect of the moving condition was significant ($F_{2,571} = 15.08$, $p < 0.0001$)

for benefit, but that the effect was not significant for cost ($F_{2,132} = 0.68$).

Comparison between the moving and the stationary conditions. Mean value of benefit in the two moving conditions was 83 ms and the value in the stationary condition was 124 ms. Benefit was larger in the stationary condition than moving ones. Mean value of cost in the two moving conditions was 14 ms and the value in stationary condition was 50 ms.

Based on the above results, attention can operate more rapidly to expected events in the stationary condition than in the moving conditions; on the other hand, the switching of attention to unexpected events might be more efficient in the moving condition than in the stationary condition. This implies that observers rely much more on their expectancy in the stationary condition than in moving conditions. On the other hand, observers in the moving condition do not rely on their expectancy as much, but ascertain an event itself, so they might be able to cope with unexpected events more efficiently. In the moving conditions, a kind of ecologically valid mechanism of attention seems to operate; attention can operate more rapidly to unexpected events in favor of safety.

Comparison within moving conditions. As shown in Figure 6, benefit is larger and cost is smaller in the higher speed condition than in the lower speed condition. That is, in the higher speed condition, valid expectancy has more remarkable benefit and invalid expectancy can be switched more rapidly than in the lower speed condition. So, in a higher speed situation attention can operate more efficiently in favor of security. This can be also a kind of ecologically valid mechanism of attention.

Characteristics of switching of attention in depth

Figures 7 and 8 show reaction time as a function of validity of expectancy and contents of cue in low speed and high speed conditions, respectively. Figure 9 shows the same result in the stationary condition. The cases of invalid cue are noteworthy in order to examine switching of attention. When an invalid cue is given, observers have to switch attention in the opposite direction in depth immediately after the appearance of a target. If the content of the cue is "far," observers have to switch attention from "far" to "near," and if it is "near," they have to switch attention from "near" to "far". It should be noticed that the distance of shift of attention is the same in both switching of attention from "far" to "near" and "near" to "far."

As shown in Figures 7–9, reaction time for attention switching from far locations to near locations was shorter than for attention switching from near locations to far locations. The difference was larger in the moving condition than in the stationary condition. The differences in these reaction times were significant in the low speed condition ($F_{1,42} = 10.62$, $p < 0.0022$), and in the high speed condition ($F_{1,43} = 6.93$, $p < 0.01$), but the difference was not significant in the stationary condition. Thus, asymmetry of switching of attention in depth was found in the moving condition but not in the stationary condition. This discrepancy between moving and stationary conditions derived mainly from the reaction time in switching from far locations to near locations. As shown in Figures 7 and 8, in both the moving conditions reaction times for attention switching from far locations to near locations were shorter even than in the neutral case. On the other hand, in the stationary condition the reaction time with the attention switching was longer than the neutral case. Therefore, attention switching from far locations to near locations is much more efficient in the moving condition than in the stationary condition. In the moving situation, attention operates more efficiently to cope with unexpected close events. This suggests that attention resources may be distributed more densely in a near area relative to a fixation point in the moving condition than in the stationary condition. These are new findings of the ecologically valid distribution of attention resource for security. This also suggests an asymmetrical shape of the three-dimensional useful field of view.

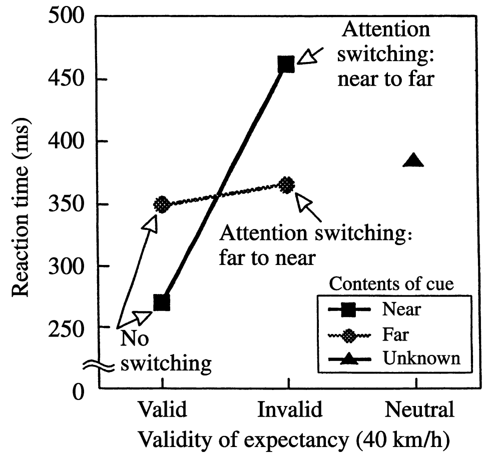

Figure 7. Relations between validity and contents of expectancy in the low speed condition. The invalid case is noteworthy.

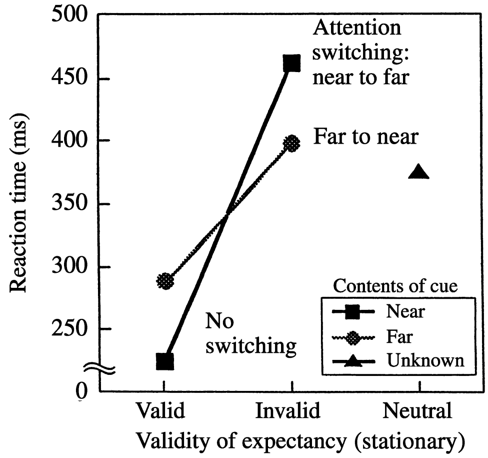

Figure 9. Relation between validity and contents of expectancy in the stationary condition. The invalid case is noteworthy.

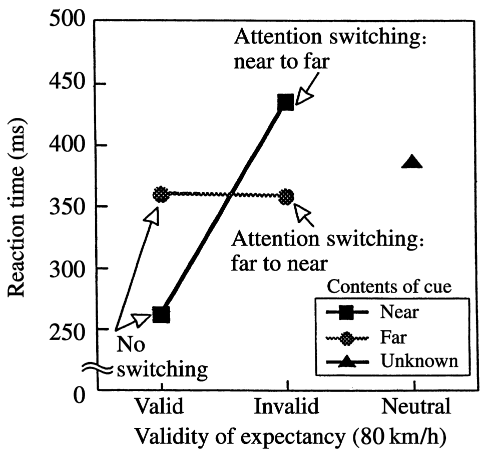

Figure 8. Relation between validity and contents of expectancy in the high speed condition. The invalid case is noteworthy.

Thus far, the present experiment demonstrated an asymmetrical shift of attention in depth in locomotion. We call this the *rubber band metaphor of attention in locomotion*, that is, there is stronger resistance to shift of attention "from near to far" than "from far to near" in observer moving situations.

These results are hard to explain by peripheral factors, such as accommodation and vergence. This is because the overall mean reaction time in the present experiment is shorter than the completion time of accommodation and that of vergence (362 ms). Latency and completion time of accommodation are approximately 300 ms and 900 ms (Westheimer, 1986), and those of vergence are 200 ms and 700 ms (Haber & Hershenson, 1980). Thus, peripheral factors seem difficult to explain the present results.

Conclusions and suggestions

In order to clarify the characteristics of shift of attention in depth for moving observers, a new experimental method was developed and applied. The major results follow

1. Attention operates more efficiently at nearer locations than at farther locations relative to a fixation point;
2. The effect of expectancy is confirmed in depth. This effect is more remarkable in three-dimensional space than in two-dimensional space;
3. Attention operates in unexpected events more efficiently in moving situations than in stationary situations;

4. Attention shifts more efficiently from far locations to near locations than the reverse, especially in moving situations. This was called the *rubber band metaphor of attention in locomotion*.
5. These results suggest that the attention resource is more densely distributed in the near area in moving situations than in stationary situations.

Based on these and related findings, we are performing further research. The first concerned the distribution of the attention resource. The difference in reaction time with attention switching from far locations to near locations and with attention switching to the opposite in Downing and Pinker (1985; p. 177) was 11 ms, and that in Gawryszewski et al. (1987; pp. 21–22) was 27 ms. These studies had only two targets in shorter distances, under the stationary conditions. The difference in the present study was larger, even in the smallest stationary condition (64 ms). Factors examined in relation to distribution of attention resource are the number of targets and fixation points (Kimura, Miura, Usui, & Shinohara, 2001b), the relation between attention and perception of distance of targets (Kimura & Miura, 2001a), and the difficulty of judgments (Kimura, Miura, Doi, & Yamamoto, 2001a). In addition, a more detailed examination of the rubber band metaphor of attention shift should be made. The components of reaction time with attention switching is also under investigation (Kimura & Miura, 2001b). In addition to these, factors that should be examined are the effect of active locomotion on attention in three-dimensional space (for related research see Tipper, Lortie, & Bayli, 1992), and the shape and characteristics of the useful field of view in three-dimensional space under stationary and moving situations.

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(Received Aug. 16, 2001; accepted March 2, 2002)