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Anisotropy of environmental perception caused by spatial changes during locomotion☆

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A R T I C L E I N F O

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A B S T R A C T

Daily perception entails an immediate awareness of the environment surrounding the body. To explore its dynamic nature during locomotion, this study tests the hypothesis that significant changes in spatial volume induce the directional focusing (i.e., anisotropy) of environmental perception. To capture perceptual activity in its natural state, we have attempted an approach using the feeling of visual pressure (i.e., felt presence) caused by the surrounding environment. In the present experiment that uses a virtual reality setup, participants were required to continuously rate their feelings while moving along a virtual outdoor route. Their ratings were analyzed in relation to environmental measurements along the route, such as the visible area of buildings and the horizontal extent of surrounding space. The relationship between the ratings and measurements was explored by using two prediction models: with and without consideration of perceptual anisotropy. The results suggested that a consideration of anisotropy improved the prediction accuracy, thereby supporting our hypothesis.

1. Introduction

1.1. Environmental psychologist's fallacy

Environmental psychology deals with (only a part of) environmental perception in daily life. Early in its history, Ittelson (1976) argued that traditional experimental psychology had exclusively investigated object perception, rather than environmental perception. He wrote that "the environment surrounds, enfolds, engulfs" and "One does not, indeed cannot, observe the environment: one explores it" (p. 149). In other words, he emphasized the daily situation in which people perceive the surrounding environment while actively moving in it. This emphasis still persists today in environmental psychology. For example, a major textbook (Gifford, 2002) begins its chapter on environmental perception with the following quotation:

> We know a great deal about the perception of a one-eyed man with his head in a clamp watching glowing lights in a dark room, but surprisingly little about his perceptual abilities in a real-life situation. (Ross, 1974, p. 9)

In this regard, the following question naturally arises: What theory has been constructed to account for such daily perception? Experimental psychology has repeatedly conducted experiments under closely-controlled conditions to build up a vast amount of knowledge on object perception. As a result, perceptual theories have been developed to explain how sensory stimuli generate the awareness of objects. However, does the same hold true for environmental perception? Or, has environmental psychology developed any perceptual theories to explain how people become aware of their daily environments? On this matter, the textbook (Gifford, 2002) merely cites a few suggestive instances such as the lens model (Brunswik, 1956) and the concept of affordance (Gibson, 1979), and does not provide an original perceptual theory. This implies that environmental psychology has not constructed any specific theories to understand daily environmental perception.

The inability of environmental psychology to construct perceptual theories is attributed to two methodological problems. One is that the experimental conditions are designed without taking into consideration the dynamic nature of environmental perception. Most experiments have presented environments by using static displays (e.g., photographs), which provide experiences that are different from daily perception, as Heft and Nasar (2000) have pointed out (see also Heft, 1983). The other methodological problem is that most of the experiments deal with subjective assessment rather than the perception of environments. The term environmental perception is sometimes used in a broad sense to include subjective assessment (Gifford, 2002, p. 21). However,

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subjective assessment may or not be included in environmental perception depending on how perception is conceptualized. Regardless, the understanding of assessment alone is not enough to elucidate perceptual activities in daily life.

The two methodological problems in studying environmental perception are related to what William James (1890/1950a) referred to as the "psychologist's fallacy" (p. 196). He used this term to describe the confusion between a psychological phenomenon itself and psychologists' understanding about it from their own standpoint. The most general form of this fallacy is the confusion between tacit and explicit knowing, or feeling and thinking (see also James, 1890/1950b, p. 281; Reed, 1990). In the case of daily environmental perception, people are tacitly aware of their immediate surroundings. This awareness enables them to perform various actions in that space (see, e.g., Heft, 1993). They have explicit thoughts about their environment only when it is necessary. As Heft and Poe (2005) have pointed out, when assessing some properties (e.g., complexity) with respect to statically presented environments, participants adopt an "analytical" stance or a detached viewpoint, which they call the "spectator mode" of experiencing environments. Thus, the assessed properties are not an immediate awareness of the environment but concepts abstracted from it; confusing them is a type of psychologist's fallacy (Heft, 2003, in press). The fallacy has prevented environmental psychologists from investigating immediate environmental awareness, thereby preventing them from fully understanding daily environmental perception.

To explain such immediate environmental awareness, James Gibson (1979) developed a groundbreaking theory—the ecological theory. In addition, over the last few decades, Heft (1981, 1996, 1997, 2001) has attempted to apply the perceptual theory to aspects of environmental psychology. We agree with Heft that the ecological approach is an effective way of gaining an appreciation and understanding of daily environmental perception. This study, as well as our previous study (Inagami, Ohno, & Tsujiuchi, 2008), has an overall purpose of examining the validity of the ecological theory on the basis of our original methodology.

1.2. Our methodology and purpose

During daily locomotion, perceivers are constantly aware of the environment that surrounds their bodies. They immediately "feel" the presence of surrounding surfaces (e.g., walls and trees), rather than intellectually understanding the geometrical layout. The feeling changes in accordance with the extent to which the point of observation is spatially enclosed. That is, the feeling is similar to what has been studied as the impression of enclosure, closeness, spaciousness, or openness (as described later). However, we refer to the feeling by using the term "feeling of pressure," which seems to have a more dynamic connotation. Cullen (1971), a keen urban designer, aptly described the experience of walking through townscapes as "a journey through pressures and vacuums" (p. 10). As he suggested, perceivers are immediately aware of the environment, which keeps changing during locomotion, in the form of the feeling of pressure caused by the surrounding surfaces.

Thus far, we have attempted to investigate immediate awareness in environmental perception by creating an original methodology (Inagami et al., 2008; Ohno, Tsujiuchi, & Inagami, 2003). In our experiments, participants rate the feeling of pressure caused by their surrounding environment. The rated value is considered as the integration of the pressures that they feel with respect to their surroundings as a whole, that is, the integration of environmental awareness. While walking along a route, our participants continuously output their feelings using a portable rating device (in the present experiment, by sliding a lever on the device). The data obtained are the rated values that fluctuate as the participants walk along the route. Our methodology assumes that each rated value reflects the participant's environmental awareness at the place. On the basis of this assumption, awareness is explored by analyzing the relationship between the participants' ratings and several measurements of the environmental surfaces (e.g., visible area of buildings) along the route.

It should be noted that when our participants rate their feelings of pressure, they never analyze the environment intellectually. The rating device allows them to output their continuously changing feelings directly or "on line." The rating task is conducted intuitively without the intervention of any cognitive processes such as the estimation of the sizes of visible walls and buildings (cf. Heft, 1993). Accordingly, the feeling of pressure rated in this manner is considered to be a direct response to the surrounding environment. Although the feeling may include such evaluative meanings as fear and discomfort, they are not the results of intellectual assessment with respect to the environment. Viewed in this light, the feeling of pressure in our study is immediate environmental awareness itself rather than something derived from the awareness analytically.

Using this methodology, our previous study (Inagami et al., 2008) investigated the extent to which perceivers are aware of the environment, that is, how much of the surrounding surfaces they perceive, during daily locomotion. In the experiment, the rating data were collected along an outdoor route in our university campus. The data were analyzed in relation to the visible areas of buildings and trees measured along the route. Results of the analysis suggested that their feelings were correlated with the environmental variables measured from a full 360° view. Based on this result, we concluded that perception extends to the environment surrounding the body without being limited to the view ahead.

The present study investigates additional details to explore the dynamic aspect of environmental perception during locomotion. As mentioned above, we have found that perceivers are globally aware of the surrounding surfaces (i.e., buildings and trees). This global awareness is considered to be maintained so that behavior fits the environment. However, from a practical viewpoint, it is not efficient to always remain equally aware of the environment from all directions. A more efficient way is to assign attentional resources as the situation demands, that is, to focus awareness on the direction that requires more information. In this study, we refer to such directional focusing of environmental awareness as "anisotropy." Note that perceptual anisotropy does not necessarily entail gaze behavior. Here, attentional focus means being vividly aware of, rather than scrutinizing, the environment in a particular direction. In this study, we test the hypothesis that significant changes in spatial volume induce the anisotropy of environmental perception, that is, the awareness focuses on the direction in which spatial volume expands or contracts. For the purpose of this study, we used computer graphics (CG) to model a virtual route along which spatial configuration changed significantly. In addition, we employed a virtual reality (VR) setup to create a virtual experience of walking along the route.

1.3. Related studies

Spatial feelings such as pressure have been studied primarily as environmental enclosure. Thiel's (1970) theoretical study proposed a model for enclosure within a room; he assumed that each component (ceiling, wall, and floor) affected enclosure with a ratio of 3:2:1. The validity of this model was supported by later experiments (Dainoff, Sherman, Miskie, & Grovesnor, 1981; Pedersen & Topham, 1990; Thiel, Harrison, & Alden, 1986). Hayward and Franklin (1974) found that enclosure within a room is correlated with the retinal angle (i.e., perspective size) of the room's back wall.

Recently, Stamps (2005a) and Stamps and Smith (2002) investigated enclosure within urban street scenes to clarify several influential factors including the proportion of the view covered by walls. These results indicate that subjective enclosure is closely related to the constituent surfaces of environments.

Interestingly, Stamps and his colleague (Stamps, 2005a, 2005b, 2005c; Stamps & Smith, 2002) discussed the relationship between enclosure and environmental surfaces from a functional perspective. On the basis of the above-cited results, Stamps (2005a) and Stamps and Smith (2002) speculated that enclosure was related to the freedom of movement and prospect, that is, walls were influential because they blocked locomotion and vision. In addition, Stamps (2005b, 2005c) proposed his "permeability theory" and investigated enclosure in relation to several variables that described the visual and locomotive permeability of environmental surfaces. This series of studies is suggestive for our study because it considers subjective enclosure to be functional. Such spatial feeling probably supports various actions, including perceptual activities, in the environment. Viewed in this light, it is reasonable that the feeling of pressure would reflect the configuration of environmental surfaces. This supports the possibility that the feeling can be used for capturing the immediate awareness of environments.

However, the above mentioned experiments presented stimulus environments in a static manner by using drawings, photographs, or CG images. The participants rated the enclosure of directionally restricted scenes by facing them. Due to this experimental situation, the participants could have taken analytical stances such as estimating the size of walls in the scenes. As mentioned previously, our experimental situation is different from these studies in that our participants intuitively rate their feelings caused by the entire surrounding environment. In Gärling's (1969) pioneering research, participants rated openness and closeness on site at several places in a town. Ratings were provided for the place as a whole and for each scene in four different directions. The results indicated that the former ratings were correlated with the average of the latter ratings. This suggests that spatial feelings can reflect the entire surrounding environment in natural situations.

Wiener et al. (Wiener & Franz, 2005; Wiener et al., 2007) used a VR setup to conduct rating experiments in a situation wherein participants were allowed to move around freely. The participants rated several properties including spaciousness with respect to different-shaped indoor spaces. The spatial forms were quantitatively described by a method called "isovist." The isovist of a particular observation point is defined as the planar shape of the surrounding space that is visible from there, which is quantified by using various measures such as its area and perimeter (Benedikt, 1979; Benedikt & Burnham, 1985). Wiener et al. found that rated spaciousness was correlated with the area of an isovist. However, the rating task was performed after exploring each space for a while, i.e., with respect to the entire experience of the space that had been integrated through exploration. Our study, on the contrary, concerns the constantly changing experiences of the surrounding environment before integration. As mentioned earlier, the purpose of our study is to investigate the awareness of surrounding surfaces during locomotion by using continuously rated feelings of pressure, and test the hypothesis that significant changes in spatial volume induce the anisotropy of environmental awareness.

2. Method

2.1. Experiment

2.1.1. Participants

Eighteen graduate and undergraduate students (7 females and 11 males) participated in our experiment. They were all naïve to the purpose of this study. All participants, except those who had volunteered, were compensated.

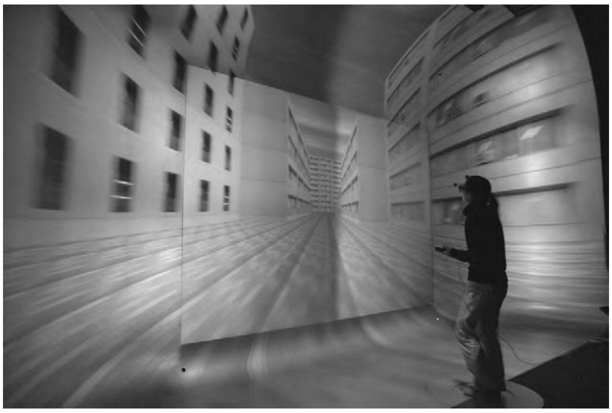

Fig. 1. Snapshot of the rating experiment conducted using a virtual reality setup.

2.1.2. Experimental route

The experimental route was modeled in a virtual space by using CG software (Discreet 3ds Max 4.2). The virtual environment comprised buildings (including walls), ground, and sky, each of which was textured with photographs (see, e.g., Fig. 1). The experimental route was 795 m long and included several characteristic places in terms of spatial configuration, as illustrated in Fig. 2. In such places, spatial volume significantly changed in specific directions as the viewpoint moved along the route.

2.1.3. Virtual reality setup

In order to create a virtual experience of walking along the route, we employed a multi-projection system "D-vision"[1] for image presentation. As shown in Fig. 1, the system has an immersive screen (6.3 m wide and 4.0 m high), which consists of a flat central part and curved peripheral parts that provide a 180° view angle both horizontally and vertically. On this hybrid screen, the image is projected by using 24 projectors at a resolution of approximately 4000 $\times$ 4000 pixels. In addition, the system offers stereo (i.e., three-dimensional) viewing through polarized glasses. In the virtual space, the viewpoint is at the level of 1.5 m above the ground.

Further, D-vision is equipped with a locomotion interface that enables one to walk around in virtual environments by stepping on it. In this experiment, however, we set the viewpoint to follow a predetermined path along the route. At the corners, the path smoothly curved along a circular arc with a radius of 7.0 m. The direction of view was fixed in the traveling direction. By constraining the participants' behavior in this manner, they could be made to experience an identical environment along the route (i.e., the scenes projected on the screen were identical for all participants); moreover, they could concentrate only on the rating task.

Another behavioral constraint was set in that the viewpoint automatically proceeded to the end at a constant speed of 3.0 m/s,[2] once the interface sensed the participants' steps. However, we instructed the participants to continue walking and not stop on the route; this was to ensure that they would not notice they were

[1] This system was developed by the Sato-Koike group at the Precision and Intelligence Laboratory, Tokyo Institute of Technology. For more details, visit the website http://sklab-www.pi.titech.ac.jp/.

[2] This speed is more than twice the walking speed of normal adults. This is due to the fact that locomotion is generally experienced as being duller in a virtual space.

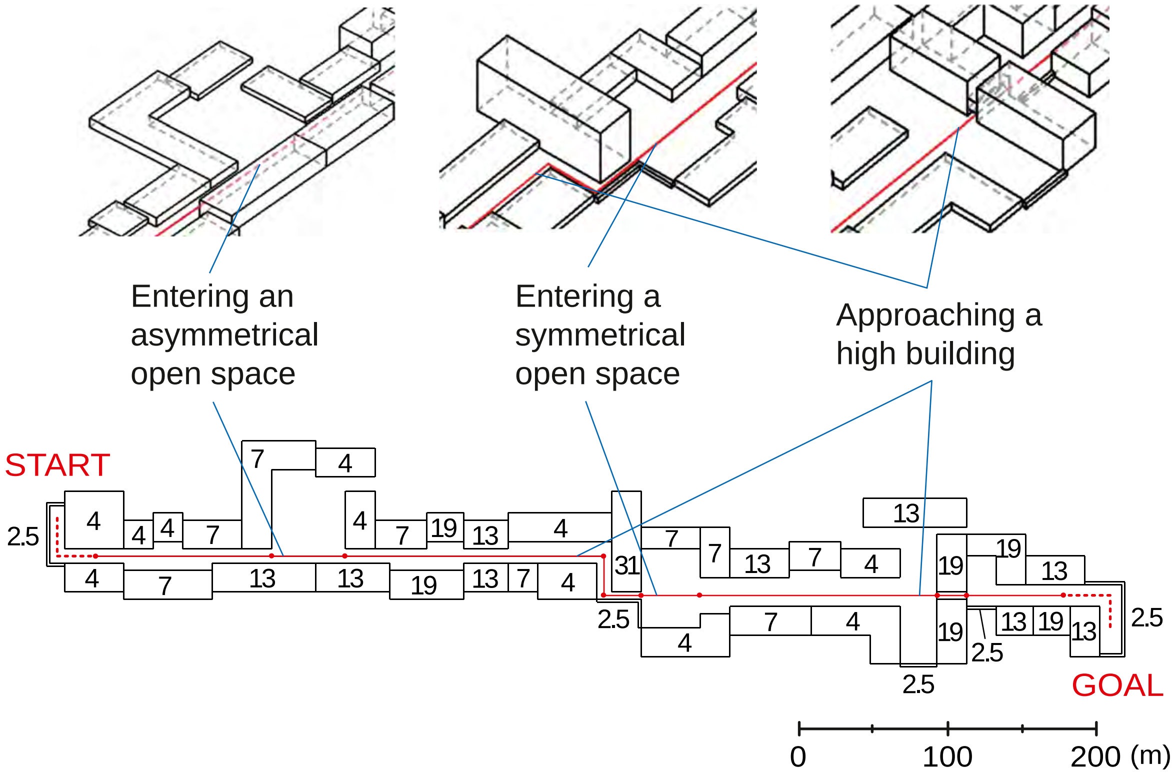

Fig. 2. Experimental route in the virtual environment created by using computer graphics. The dashed lines in the plan view indicate the sections that were not used for data analysis. The numbers on (or near) the buildings and walls indicate their heights in meters.

proceeding automatically. This was done so that a virtual experience of walking could be created by the participants themselves.

2.1.4. *Rating device*

We used a portable rating device developed by our research group (Ohno et al., 2003) after making some minor modifications. This device allows participants to rate their feelings continuously while walking in both virtual and real environments. As shown in Fig. 3, their continuously changing feelings are outputted by sliding the lever in their hand up or down. The rating data are recorded on a laptop (IBM ThinkPad X31) via a data-collecting PC card (KEYENCE NR110), which continually captures the data at the rate of five times per second.

Fig. 3. Continuous rating device to output participants' feelings of pressure.

2.1.5. *Procedure*

All participants provided their informed consent in advance and were tested individually. First, they received an explanation of the experiment. We instructed them to rate their feelings of pressure intuitively while imagining that they were walking in the virtual environment. In addition, we asked them to operate the rating device as subtly as possible in such a way that the lever position always corresponded to the pressure that they were feeling. Thereafter, without performing the rating task, the participants walked through the virtual route once. This was aimed at allowing them to know the range of the feeling of pressure caused by the environment along the route. In this manner, the participants, during the rating session, could output the variations in their feelings without exceeding the slidable range of the rating lever. We had instructed them that it was not necessary to use the whole range of the lever, and we had not specified any standard position for operating it.

2.2. *Environmental measurement*

We quantitatively described the environment along the route by using a method developed by our research group (Ohno, 1991). This method views the environment around a viewpoint as a spherical surface consisting of several environmental components (e.g., buildings, trees, ground, and sky) and measures each visible area as a ratio of solid angle. In addition, the average distance to the surroundings is measured as the spatial volume. By measuring these variables at multiple viewpoints along a path, the environment along the path is described as variations in the variables. This measurement is conducted with the help of our original computer program, based on the environmental data created using computer-aided design (CAD) software (for details on the program

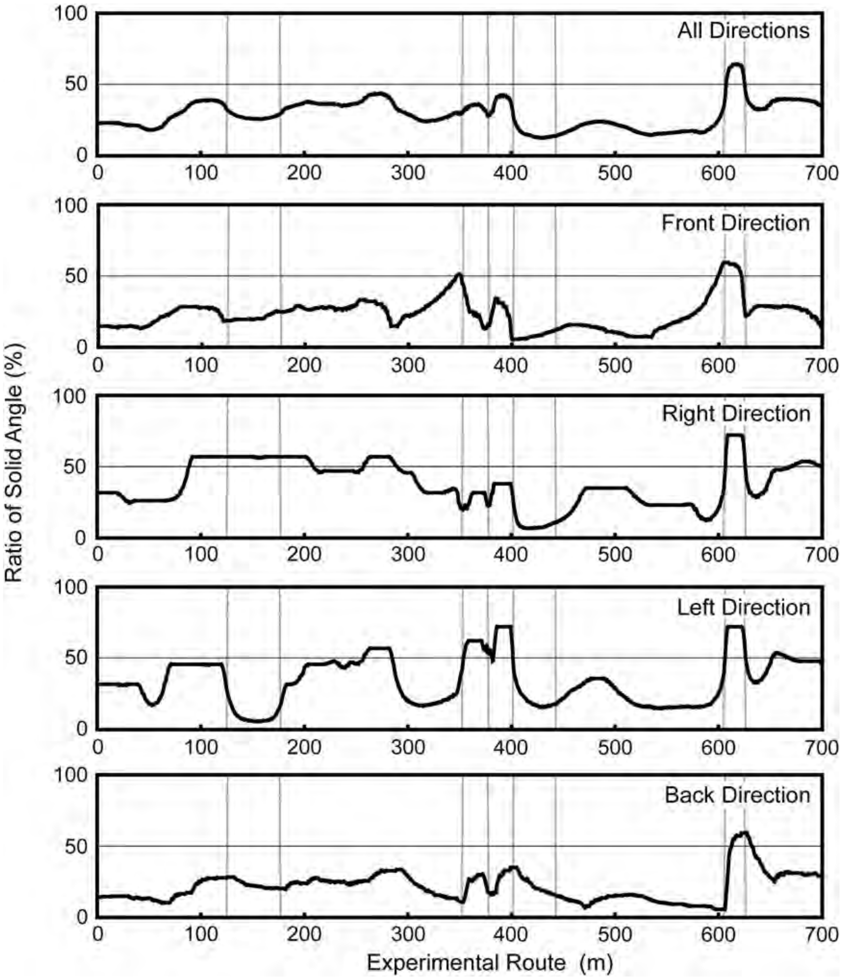

Fig. 4. Examples of environmental measurements along the route: visible area of buildings measured from all directions together and separately from each of the four directions. The vertical lines in the graphs correspond to the dotted lines along the route in Fig. 2.

see Ohno, 1991). The program repeats the measurement at set intervals along a given path. At each measuring point, the surrounding environment is assessed by 1944 scanning lines (72 horizontally $\times$ 27 vertically). The measurement is limited to a 72-m radius at each measuring point.

In the present study, the measurement was conducted at 795 points at 1.0-m intervals along the route. We adopted two kinds of measurements for the environmental variables. One was the visible area of buildings, which was considered to describe the amount of surrounding surfaces. This variable was found to correlate with participants' feelings of pressure in our previous study (Inagami et al., 2008). The other was the average of the horizontal distances to the surroundings, which we referred to as the "spatial extent." This variable describes the horizontal volume of surrounding space. The two variables were calculated in the following two ways: (1) together in all directions and (2) separately in the front, right, left, and back directions (see, e.g., Fig. 4). In the latter case, the surrounding environment was divided into quarters with the traveling direction as the center of the front part.

2.3. Data treatment

We employed a 700-m section in the middle of the route for analysis by removing the beginning and end sections, which were approximately 50 m each (see Fig. 2). Since the data rated by the participants were recorded in time series, we converted them such that they represented the measuring points of the environmental variables. In other words, we chose 700 pieces of rating data in such a way that each piece approximately corresponded to 700 points at 1.0-m intervals along the route. Moreover, the rating data were standardized to z-scores for each participant, because the correspondence between the feeling and response (lever position) would possibly differ from one participant to another. Thereafter, the rating data at each point along the route were averaged across all participants.[3] The resultant average variation in their ratings was used for the analysis below as the observed values of the feeling of pressure.

3. Analysis and results

3.1. Model without consideration of anisotropy

To explore the relationship between the participants' feelings of pressure and the surrounding environment, we first attempted the application of the following linear model:

$$F = \alpha + \beta B_{\mathrm{a}} + \varepsilon, \tag{1}$$

[3] The ratings were judged to be highly consistent among the 18 participants, considering that the intraclass correlation coefficient was calculated to be .97.

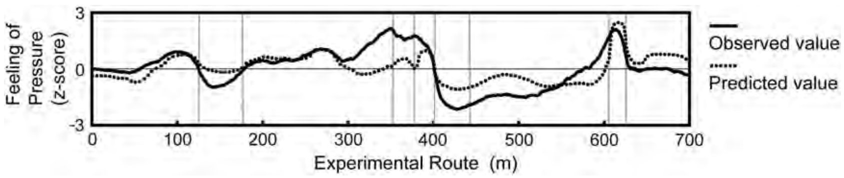

Fig. 5. Prediction of the feeling of pressure along the route by using a model without considering perceptual anisotropy. The vertical lines in the graph correspond to the dotted lines along the route in Fig. 2.

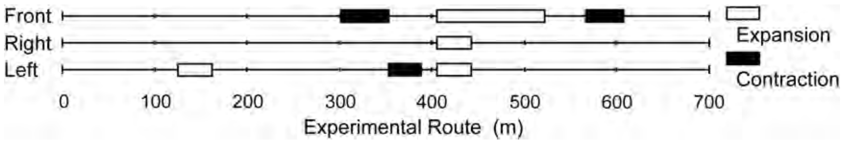

Fig. 6. Changes in the spatial volume in each direction at the places where large prediction errors are observed.

where F is the feeling of pressure, B_a is the visible area of buildings measured from all directions, α and β are the parameters, and ε is the error term. This model implies that the feeling corresponds to the amount of surrounding surfaces measured from a full 360° view. Accordingly, this model assumes that humans are equally aware of the environment in all directions; in other words, it does not consider perceptual anisotropy. Based on a simple regression analysis, α and β were estimated to be -1.96 and .07, respectively ($p < .01$ in both cases).[4] The resultant coefficient of determination was .45. Fig. 5 illustrates the variations in the observed and predicted values along the route, which show that there are large prediction errors at several places. The errors indicate that the participants' feelings did not correspond to the 360° environmental measurements, and therefore the participants were anisotropically aware of the surrounding environment.

To examine the spatial configurations of the places where the large prediction errors were observed, we applied discriminant analyses through the following steps. First, we selected the places where large prediction errors had occurred by using the 50% prediction intervals that had been calculated in the regression analysis. In other words, we defined the places of large error as the sections where the observed values were beyond the prediction intervals. Next, we (subjectively) classified the spatial configurations of the selected places as "expansion" or "contraction" in the front, right, and/or left directions, as shown in Fig. 6 (see also Fig. 2). Thereafter, we performed discriminant analyses on the basis of objectively measured data to distinguish the places that demonstrated the spatial changes from the other parts on the route. The visible area of buildings and the spatial extent, both of which were measured from each direction, were employed as explanatory variables. Considering that the former comprises the solid angles of wall surfaces, its value (inversely) indexes the longitudinal and latitudinal volume of surrounding space; on the other hand, the latter describes the horizontal volume as mentioned above. By combining the two kinds of variables, three-dimensional spatial volumes can be represented with respect to each direction.

The results of the discriminant analyses are illustrated in Fig. 7. Its left panel shows the analysis of the spatial volume in the front direction. The scatter plot indicates the relationship between the two explanatory variables. Each data point of the plot represents one of the 700 measuring points on the route. The three types of symbols of the data points correspond to the classifications of spatial changes illustrated in Fig. 6 (i.e., expansion, contraction, and others). This discriminant analysis estimated the two linear functions that best separate the three classes. The two lines on the graph indicate the resultant discriminant functions. Likewise, the right panel in Fig. 7 shows the analysis of the spatial volumes in the right and left directions. The two directions were analyzed together as the "side" direction, considering the symmetry. Accordingly, the scatter plot consists of twice as many data points as that in the front direction (i.e., the left panel). The hit ratios of the discriminant analyses of the front and side directions were 83.6% and 83.7%, respectively. Each discriminant function was judged to be valid by tests based on the Wilks' Λ statistics ($p < .01$ in all cases).[5]

These results suggest that the participants were anisotropically aware of the environment at the places where the surrounding space expanded or contracted in some direction. This finding is consistent with our hypothesis that significant changes in spatial volume induce perceptual anisotropy. In addition, supposing that the hypothesis is true, the participants' awareness may be considered to have focused on the directions in which the spatial changes occurred and, as a result, their feelings of pressure reflected the environment in certain specific directions.

3.2. Model with consideration of anisotropy

On the basis of the analyses described above, we next modified the model (Eq. (1)) in order to develop one that included the consideration of the anisotropy of environmental perception. In this new model, anisotropy is expressed using a weighted mean of the visible areas of buildings measured from each direction as follows:

$$F = \alpha + \beta \frac{W_f B_f + W_r B_r + W_l B_l + B_b}{W_f + W_r + W_l + 1} + \varepsilon, \tag{2}$$

where F is the feeling of pressure; B_f, B_r, B_l, and B_b are the visible areas of buildings measured from the front, right, left, and back directions, respectively; W_f, W_r, and W_l are the weights of the front, right, and left directions, respectively; α and β are the parameters; and ε is the error term. Each weight can take a value from one to infinity, and expresses the extent to which awareness is focused on the environment in a particular direction. In other words, the heavier the weight of a direction, the more is the feeling of pressure

[4] Note that these statistical tests confirm that each parameter is different from zero, contributing to a raise in prediction accuracy. Hence, strictly speaking, their results do not ensure the validity of the model.

[5] Based on these results, we decided to use linear discriminant analyses, although the results of Box's M tests rejected the homogeneity of the variance-covariance matrices (at a significance level of .01).

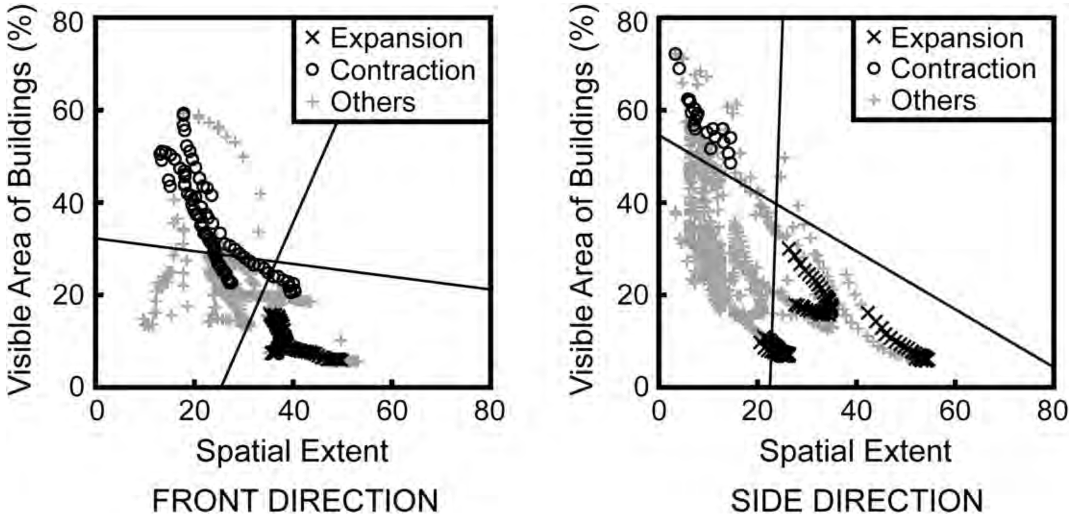

Fig. 7. Prediction of the spatial expansion and contraction that induce perceptual anisotropy by using discriminant analyses based on the environmental measurements. The left and right panels present the resultant discriminant functions with respect to the front direction and the side (right and left) direction, respectively. The functions are expressed as follows: front expansion: $0.09\ B_f - 0.22\ S_f + 5.49 = 0$; front contraction: $-0.16\ B_f - 0.02\ S_f + 5.09 = 0$; side expansion: $0.01\ B_s - 0.35\ S_s + 7.80 = 0$; side contraction: $-0.13\ B_s - 0.08\ S_s + 7.08 = 0$, where B is the visible area of buildings, S is the spatial extent, and the identifiers $_f$ and $_s$ denote variables that were measured from the front and side directions, respectively.

influenced by the visible area of buildings measured in that direction. On the other hand, when all the weights are equal to one, Eq. (2) corresponds to Eq. (1). This implies that in such a situation there is no perceptual anisotropy; that is, the entire surrounding environment equally influences the feeling of pressure.

To set the weights of the model in line with our hypothesis, we applied the results of the above mentioned discriminant analyses with a modification. In the analyses, the places of spatial expansion and contraction were distinguished from the other parts on the route, with respect to the front, right, and left directions (see Fig. 7). In other words, the analyses judged whether or not each point on the route belonged to the classes of the spatial changes. In the present analyses, however, we estimated the probabilities of belonging to either the expansion class or the contraction class with respect to each direction. The probabilities were considered to index the significance of the changes in spatial volume. Accordingly, assuming that significant spatial changes induce perceptual anisotropy, the probabilities were considered to indicate the extent to which awareness focuses on the environment in each direction. Considering this, we expressed the weights of the model as follows:

$$\left.\begin{aligned} W_f &= \gamma_f^{P_f} \\ W_r &= \gamma_r^{P_r} \\ W_l &= \gamma_l^{P_l}, \end{aligned}\right\} \tag{3}$$

where P_f, P_r, and P_l are the probabilities of belonging to the classes of significant spatial changes with respect to the front, right, and left directions, respectively, and γ_f, γ_r, and γ_l are the parameters. The probabilities range from zero to one. When they are all zero, all the weights become one, and Equation (2) corresponds to Equation (1), which implies that there is no perceptual anisotropy. We also set the condition that $\gamma_r = \gamma_l$ by considering the symmetry.

The model was fitted to the observed values using the least squares method with repeated calculations. The parameters α, β, γ_f, and γ_r $(= \gamma_l)$ were estimated to be −1.98, .08, 330.36, and 15.90, respectively ($p < .01$ in all cases).[6] Fig. 8 illustrates the variations in the observed and predicted values along the route, which shows that the two variations fit well compared with those in Fig. 5. The resultant coefficient of determination was .77, indicating that consideration of perceptual anisotropy improved the prediction accuracy in comparison to the previous model.

4. Discussion

The results obtained support our hypothesis that significant changes in spatial volume induce the anisotropy of environmental perception. The model that took perceptual anisotropy into consideration, as compared to the one that did not, provided a better fit to the rated feelings of pressure. However, it will be unfair to merely compare the coefficients of determination of the two models, because the addition of any explanatory variable necessarily raises the index value. Thus, to discuss the validity of the modified model, it is essential to examine the estimated values of each parameter. As shown above, parameters α and β were each estimated to nearly identical values between the two models (α: −1.96 and −1.98, β: .07 and .08), suggesting that the improvement of fit is primarily due to the consideration of anisotropy (see Equations (1) and (2)). The estimated γ_f (330.36) and γ_r ($=\gamma_l$, 15.90) were both greater than one. This means that, with respect to each direction, the higher the probability of anisotropy P, the heavier is weight W (see Eq. (3)). Therefore, the estimated values are consistent with our hypothesis. Considering that the probabilities of anisotropy were predicted based on the objective environmental measurements, it is safe to state that the results obtained support our hypothesis.

The relationship between spatial changes and perceptual anisotropy is reasonable from a functional standpoint. As mentioned earlier, Stamps and his colleague (Stamps & Smith, 2002; Stamps, 2005a, 2005b, 2005c) discussed the function of subjective enclosure in relation to the freedom of movement and prospect. According to them, spatial feeling is evolutionarily significant in that it allows animals to remain aware of the potential danger of hidden enemies as well as barriers in the way of escaping from predators. In our view, the anisotropy of environmental perception, which was captured as the feeling of pressure, also has an important role in our daily lives. The contraction of spatial volume signifies approaching environmental surfaces that block

[6] As mentioned earlier, these statistical tests confirm that each parameter is different from zero.

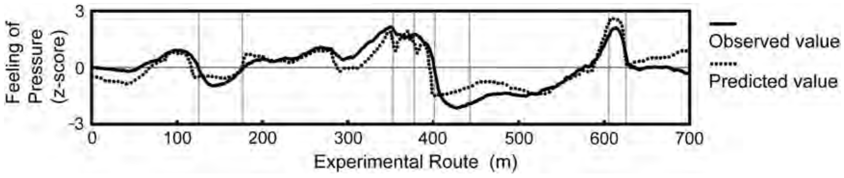

Fig. 8. Prediction of the feeling of pressure along the route by using a model considering perceptual anisotropy. The vertical lines in the graph correspond to the dotted lines along the route in Fig. 2.

locomotion. By focusing perception toward such direction, people can move around the environment smoothly. In addition, when spatial expansion occurs, the previously occluded environment becomes visible. The perceptual focus in the direction serves as an alert to new information including potential dangers. Viewed in this light, our hypothesis is consistent with the functions of environmental perception in daily, adapted activities.

The present experiment, however, also presented a result that was not in accordance with our previous study (Inagami et al., 2008). In the present experiment, the participants' ratings significantly reflected the environment in front of them, as suggested by the fact that the estimated γ_f was much larger than γ_r and γ_l. This indicates the possibility that their perception was limited to the view on the screen, or in other words, they were not aware of the surrounding virtual environment that extended beyond the screen. To examine this possibility, we investigated the relationship between the participants' ratings and the visible area of buildings on the screen. A simple regression analysis was performed using the measurement of a 180° front view as an explanatory variable, that is, by replacing the B_a in Equation (1) with the front measurement. The resultant coefficient of determination was .60, which is higher than that of Equation (1) (.45). Note that this result does not disprove the present hypothesis, because the modified model (Eq. (2)) provided an even higher coefficient of determination (.77). However, the result is contrary to that obtained in our previous study, which showed that participants' awareness extended to the surrounding environment without being limited to the view ahead.

The cause of the inconsistency between the present and previous results is the difference in the experimental condition. As mentioned earlier, whereas the previous experiment (Inagami et al., 2008) was conducted on a real outdoor route, the present experiment used a VR setup. Although the immersive screen provided a 180° field of view, it was not sufficient for the creation of such extensive awareness as actual environmental perception. One of the main causes of this is the application of the passive locomotion mode, in which the viewpoint automatically moves with the view fixed in the traveling direction. Considering this, the inconsistency may be attributed to a sort of artifact that resulted from the present experimental setting, and therefore does not disprove the previous conclusion that awareness extends to the entire surrounding environment. Rather, the fact that the present VR setup could not create such extensive awareness seems to imply an essential feature of actual environmental perception.

The difference between the real and virtual experiences suggests the importance of what is called "embodiment," or "situatedness," for the understanding of environmental perception. The importance of this concept has been discussed in different areas concerning human cognition (e.g., Clark, 1999; May, 2003). In the area of robotics, Brooks (1991) emphasized that agents (i.e., perceivers) experience the world directly with their body situated in it. To put it briefly, embodiment means the immediate link between perceivers and the environment surrounding their body. Under the present experimental condition, the participants could not be completely embodied in the virtual environment, and therefore could not be aware of the surrounding surfaces that virtually extended beyond the screen. As mentioned above, the passive locomotion mode could not provide such an embodied experience as actual environmental perception. This suggests that the emergence of embodiment essentially requires that perceivers interact with the surrounding environment through exploratory actions. Accordingly, embodiment based on such dynamic interaction is considered to be intrinsic to the perceptual activities that are performed in real environments.

Let us then consider the environmental awareness that this study deals with from the viewpoint of embodiment. A perceiver is immediately aware of the surrounding environment in the form of the feeling of pressure. Although the environment continuously changes in accordance with locomotion, the perceiver is always alert to these changes. This awareness is considered to situate the perceiver in the surrounding environment, or in other words, link the two entities as an interactive system. The anisotropy of awareness, as discussed above, has the functional role of supporting the perceiver's locomotion and information detection. In this regard, we speculate that the possibilities of various actions—namely, affordances (Gibson, 1979) —are also perceived as the feeling of pressure. This is consistent with Heft's (1989, 2003) argument that affordances are immediately perceived in the embodied interaction of the perceiver-environment system. The ecological perspective argues that the surrounding environment is filled with a variety of affordances. Given this perspective, the perceptual anisotropy can be considered as the vivid awareness of the affordances that the surrounding environment offers from a particular direction.

In conclusion, the present study, by analyzing the feeling of pressure rated "on line" during locomotion, captured the dynamically changing awareness of its respondents with respect to the surrounding environment. In addition, we discussed the environmental awareness from the perspective of the embodied perceiver-environment system. Gibson (1979) used the term "ecological" in such a holistic sense. Landwehr (1988) critically argued that perception research in environmental psychology was not ecological in that sense. The main cause is that most studies have adopted the static experimental situation in which participants analyze environments from a detached viewpoint, as suggested in Heft (in press) and Heft and Poe (2005). Such a situation may be effective for the study of the subjective assessment of scenes. However, what can be investigated in the situation is only a part of daily environmental perception. For a complete understanding, and for overcoming the "psychologist's fallacy," environmental psychology should not limit its research subjects to suit available methods, but should develop new methodologies to explore perception in its natural state.

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