MULTI-DIMENSIONAL STATE SPACE OF PERCEPTION

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Abstract

A typical traditional psychophysics has been concerned with a functional relation between a single sensory dimension and a single physical dimension. However, a perceptual object is usually defined by many perceptual dimensions and related to many physical dimensions. Accordingly a multidimensional state-space model of perception is proposed. The state space of visual perception consists of several dimensions including perceptual dimensions of color, shape, size, as well as spatial dimensions. A point in the state space represents a perceptual object which has some color, size, shape, and is located at a certain point in the visual space of an observer. Different points in the state space correspond to different perceptual objects in some perceptual characteristics and/or in location. Distances between these points correspond to differences in perceptual characteristics and/or perceived spatial separation. Interactions between different points indicate some perceptual phenomena related to these objects, e.g. perceptual grouping, apparent motion, etc.

A typical traditional psychophysics has been concerned with a functional relation between a single sensory dimension and a single physical dimension. However, a perceptual object is usually defined by many perceptual dimensions and related to many physical dimensions. Accordingly we would like to propose a multidimensional state-space model of perception and to discuss its relations to perceptual grouping, apparent motion and some other perceptual phenomena   A "state space" usually represents a space in which the state of a dynamical system is represented as a point, and by the state is meant any well defined condition or property that can be recognized if it occurs again (e.g. Ashby, 1956). In the following, we will explain how this concept of state space can be used to describe the phenomena of perceptual grouping and apparent motion, although our state space approach is still in a preliminary level and can not give clear rules governing the dynamical behavior of perceptual state as in system sciences.

Perceptual State Space Model

The perceptual state space in vision consists of several dimensions including perceptual dimensions of color (hue, brightness, and saturation), shape, size, as well as spatial dimensions (vertical, horizontal and depth). A point in the perceptual state space represents a perceptual object which has a certain color, a certain size and a cetain shape, and is located at a certain point in the visual space of an observer. Different points in the perceptual state space correspond to different perceptual objects in some perceptual characteristics and/or in location. Distances between these points in the perceptual state space correspond to differences in perceptual characteristics and/or perceived spatial separation. Interactions between different points would indicate some perceptual phenomena related with these objects.

In Figure 1, only three perceptual dimensions, hue, shape, and the position in one of the spatial dimensions are shown, and other perceptual dimensions are omitted for the simplicity of the figure. Shape is represented as one dimension in this figure, though it may have three or more dimensions as shown by Oyama, Miyano, & Yamada (2003) , Zusne (1970) and others. Solid symbols indicate red objects and open ones, green objects. Hue is well known to be represented by polar-coordinates, but here it is schematically represented by a linear axe for simplicity. The point **a** corresponds to the red disc on the left side, the point **b** is a red disc on the right side, the point **c** is a green disc on the left side and the point **d** is a red triangle on the left side. Three arrows from **a** to **b**, from **a** to **c**, and from **a** to **d** indicate the spatial separation between the left and the right red discs, the hue difference between the red and green discs, and the shape difference between the red disc and the red triangle, respectively.

The magnitude of differences or dissimilarities in hue, size and/or shape as well as spatial separations between different objects can be represented by distances between them in this perceptual state space, if all dimensions have a common scale. The multi-
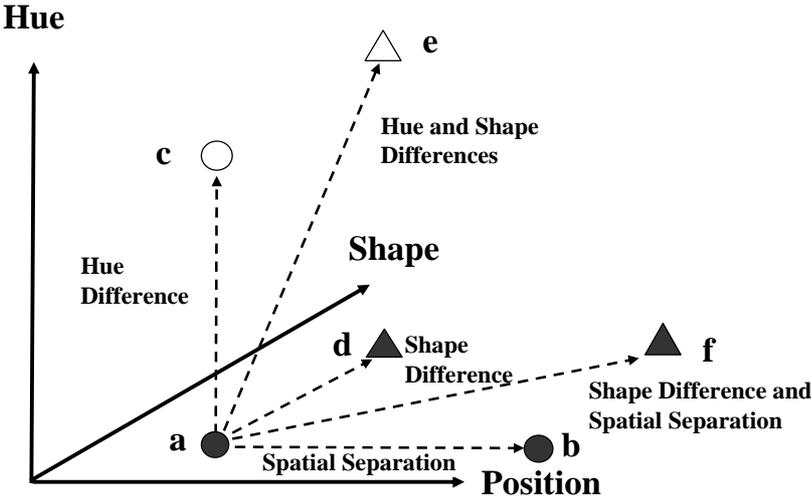

Fig. 1. A schematic representation of the perceptual state space. Only three related coordinates (horizontal position, hue and shape) are shown in this figure for simplicity. Solid symbols indicate red objects and open ones, green objects. Arrows represent perceptual differences and/or separations between objects.

regression formulae which will be shown later on the basis of experimental data will give us a basis for estimating such a common scale among different perceptual dimensions. The obtained regression coefficient of each perceptual dimension will represent its relative value of dissimilarity as compared with a spatial separation measured in degree of the visual angle (the standard scale). If two objects are different in more than two perceptual dimensions, for example hue and shape, as a red disc and a green triangle, the combined dissimilarity is represented in such as the arrow from the solid disc **a** to the open triangle **e** in Figure 1. And if two objects are different in more than two perceptual dimensions, for example shape and spatial position, as a red disc and a red triangle on different positions, the combined dissimilarity and separation is represented in such as the arrow from the solid disc **a** to the solid triangle **f** in Figure 1.

An experimental situation of perceptual grouping can be represented by arrows in the perceptual state space like Figure 1. In this perceptual state space with the calibrated, adjusted common scale for every dimension, the length of each arrow shows the degree of dissimilarity and separation or the difficulty of perceptual grouping between the two different objects represented by the head and end of the arrow, respectively. The shortest arrow indicates the perceptual grouping which should occur most frequently. In this model, the spatial separation and the dissimilarities in hue, size and shape, and then the proximity and similarities are treated in the same way. *Thus the proximity factor and the similarity factor are synthesized or unified as a single factor, ie. the proximity in the perceptual state space.*

Displacement from one point to another in this perceptual state space corresponds to a perceptual motion, if the direction of the displacement is related with the dimensions of the visual space. Such displacement may also correspond to a perceptual change in hue, size or shape, if the direction of displacement in the perceptual state space is related with dimensions of hue, size or shape. Thus perceptual *motions* in the visual space and perceptual *changes* in hue, size and shape are represented in the same way in this perceptual state space, except that the related dimensions are different between perceptual motions and other changes. If a displacement is related with both the dimensions of the visual space and other perceptual dimensions of hue, size and/or shape as arrows like that one from **a** to **f** in Figure 1, perceptual motion and change(s) will occur in the same time.

Application to the Experimental Situations

The experimental situation of perceptual grouping shown by Figure 2 is represented in the perceptual state space model as shown in Figure 3, where the dimensions of the horizontal and vertical spatial positions and that of the hue of an object are represented, while the other perceptual dimensions are omitted for simplicity of the figure. The point **g**, indicate a red disc in the stimulus pattern, while points **h** and **i** show red and green discs located in different positions in the same stimulus pattern, the right and lower points, respectively. In the perceptual state space shown in Figure 3, arrows show possible grouping between two objects and the vertical separation between the points **g** and **i** is smaller than the horizontal separation between the points **g** and **h**, but the points **g** and **i** are located in different depths.
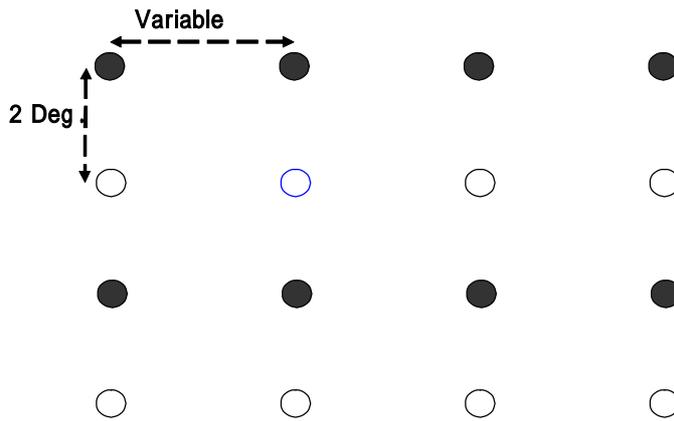
Fig. 2. The stimulus pattern used in Oyama, Simizu & Tozawa (1999) experiment of perceptual grouping. Solid and open symbols represent red and green objects respectively.

      The three-dimensional separation, measured with city-block or Euclidian metrics as will be discussed later, between **g** and **h** can be matched to that between the points **g** and **i** in this perceptual state space. In that occasion, the probabilities of occurrence will be
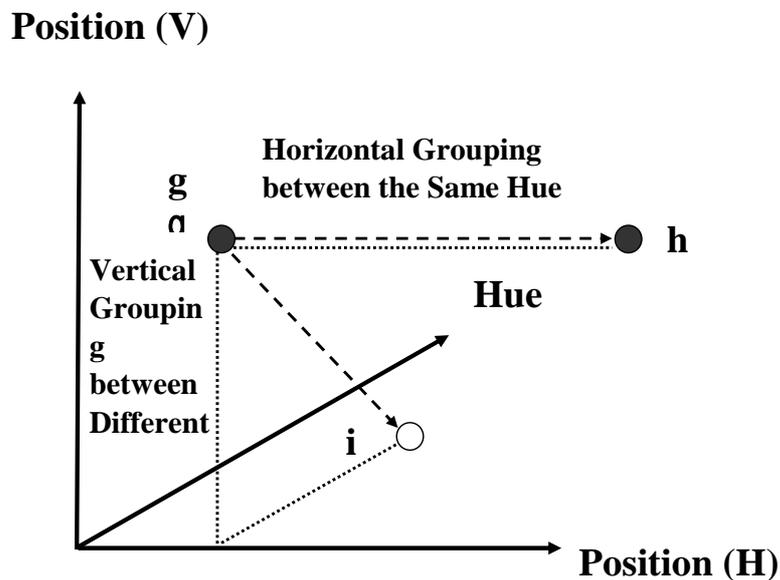

Fig. 3. A schematic representation of the perceptual state indicating the experimental situations shown in Figures 2 and 4. Only three related coordinates (horizontal and vertical positions and hue) are shown in this figure for simplicity. Solid symbols indicate red objects and an open one, a green object. Arrows represent possible perceptual groupings, apparent motions, or perceptual changes between these objects. Dotted lines indicate city-block distances and broken lines, Euclidean distances.

1st Frame

Variable

2 Deg Duration = 100 ms

2nd Frame

ISI = 100 ms

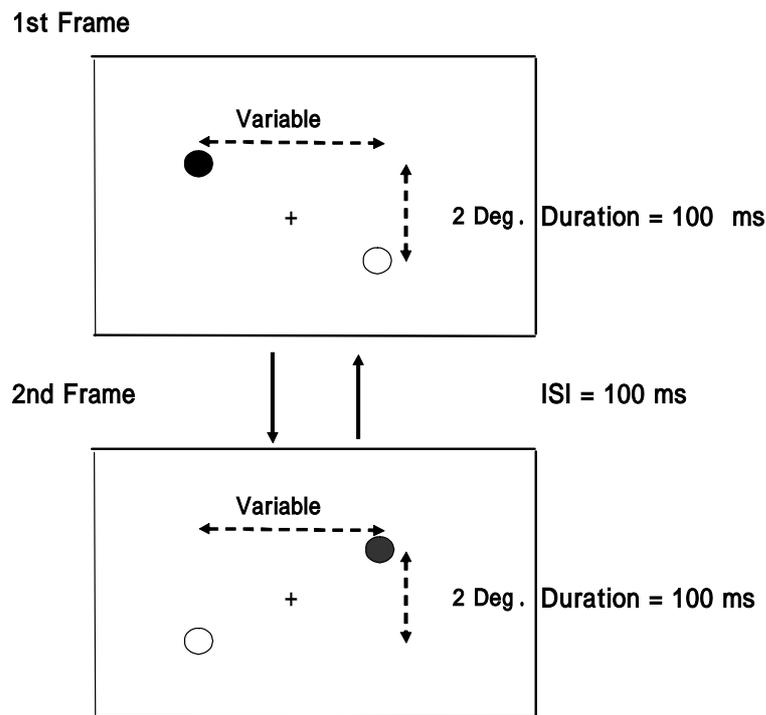Variable

2 Deg Duration = 100 ms

Fig. 4. The stimulus pattern used in Oyama, Simizu & Tozawa (1999) experiment of apparent motion. Solid symbols indicate red objects and an open one, a green object.

matched between the two possible groupings, a grouping of **g** and **h** and another grouping of **g** and **i**. For this prediction, the distance scaling should be calibrated and adjusted to be common in its function across the spatial dimensions and the hue dimension in the perceptual state space, as discussed before. These relations should also be held across other dimensions such as brightness, size and shape which were omitted in the figure for simplicity.

The experimental situation of apparent motion shown in Figure 4 can also be represented in the perceptual state space in the same way as in perceptual grouping. In that case, arrows represent possible apparent motions and/or perceptual changes of one object from the first frame of stimulus pattern to either object in the second frame in Figure 4, when these frames are succesively presented with some suitable inter-stimulus interval (ISI). The perceptual state space model shown in Figure 3 can also be used to predict which of these possible percepts occurs most frequently in a given ambiguous stimulus situation, if the relative lengths can be compared among the arrows. The perceptual motion or change represented by the shortest arrow is expected to occur most frequently, according to the minimum principle or the principle of "least amount of change" (Hochberg, 1957; Johansson, 1958; Koffka, 1935). For this comparison between arrow lengths, a common distance scale should be defined across different dimensions, spatial position, hue, size, shape and *etc.*, as discussed before.

To examine more systematically these variations among perceptual dimensions in the effects of dissimilarities or differences on the matched separations, we conducted multiple linear regression analyses on the data obtained by Oyama, Simizu & Tozawa (1999) on perceptual grouping and apparent motion.

The obtained regression formulae were as follows:

$$X = 2.04\,D + 0.43\,H + 0.20\,B + 0.39\,S + 0.36\,SH \quad (1),$$

$$X = 2.29\,D + 0.23\,H + 0.05\,B + 0.16\,S + 0.11\,SH \quad (2),$$

where X represented the matched horizontal separation in visual angle, and D, H, B, S and SH indicated the vertical separation, hue, brightness, size, and shape, respectively. The values of these variables are 1 if the respective differences exist, and 0 if no difference exists. The value of D is always 1, because the constant vertical separation always exists. Formulae (1) and (2) indicate the results of regression analyses applied to the experimental results of perceptual grouping and apparent motion, respectively. These regression formulae are very effective as shown by such high coefficients of determination (adjusted R^2) as .830 and .967, respectively.

It should be noted that the linear combinations of effects of perceptual differences in different dimensions shown in formulae (1) and (2) revealed that the city-block distances (the sum of distances along each dimension as shown by dotted lines in Figure 3) rather than Euclidean distances (broken lines) determine probabilities of occurrence of perceptual grouping, apparent motion, and/or perceptual changes. We also tried to apply the Euclidean metrics to the same results, and obtained very slightly lower coefficients of determination (.829 and .961 for grouping and apparent motion, respectively) as compared with the city-block metrics.

More experimental analyses are needed to examine which kind of metric is the most suitable for the distance representing perceptual differences in this state space.

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