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A common auditory-visual space: Evidence for its reality*

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This experiment compares two hypotheses concerning the relation between auditory and visual direction. The first, the "common space" hypothesis, is that both auditory and visual direction are represented on a single underlying direction dimension, so that comparisons between auditory and visual direction may be made directly. The second, the "disjunct space" hypothesis, is that there are two distinct internal dimensions, one for auditory direction and one for visual direction, and that comparison between auditory and visual direction involves a translation between these two dimensions. Both these hypotheses are explicated, using a signal detection theory framework, and evidence is provided for the common space hypothesis.

The aim of the present paper is to explicate a construct implicit in much current research on space perception and its development, namely the notion of a "common auditory-visual space," and to test whether that construct provides an accurate description of the organization of space perception. We will first describe the concept of a common auditory-visual space and then examine what is involved in deciding whether or not there is such a thing.

Consider an experimental S, seated in the dark, presented first with a source of sound, then a source of light, and asked to judge their relative direction. The judgment is, of course, possible, but let us think about what the S who makes the judgment is doing. One possibility is that auditory objects occupy an auditory space, in which they have an auditory direction, and that visual objects occupy a visual space, in which they have a visual direction. If this is the case, then the judgment involves translating auditory direction into visual direction, or visual direction into auditory direction, or both into some modality-independent dimension, in order to compare them. The other possibility is that no translation is required. Instead, both auditory objects and visual objects occupy a common space, in which there is a single dimension, namely direction, which is independent of the modality of the stimuli which have the direction. We will refer to the first alternative as the "disjunct space" hypothesis, and refer to the second as the "common space" hypothesis. The "common space" hypothesis, that is, proposes that auditory and visual directional information leads to directional experience which is independent of modality. The "disjunct space" hypothesis, on the other hand, proposes that auditory directional information leads to auditory directional experience and that visual directional information leads to visual directional experience. Depending upon how auditory and visual directional experiences are compared, there may be directional experience which is independent of modality, as well. If there is only one overall spatial framework, and no separate modality-specific frameworks, then we will refer to that one spatial framework as the "common space." The common space is hypothesized to be common to experiences of different modalities, and we will refer to the dimension of experience common to the modalities as the "common dimension."

The idea of a common space or a common dimension has arisen in a variety of contexts. One such context is the investigation of intersensory facilitation of reaction time. Bernstein and Edelstein (1971), for example, demonstrated that auditory facilitation of the judgment of whether visual stimuli are to the left or right occurs for ipsilateral but not for contralateral auditory stimulation. Their data led them to postulate that visual and auditory location are represented in a common system.

In another context, perceptual adaptation as a result of what Wallach (1968) calls "process assimilation" seems to require some sort of common space or common dimension. Wallach provides evidence that two paired cues which specify a common perceptual parameter tend to agree on the value of the parameter they specify. He calls this tendency "process assimilation." For example, the process assimilation hypothesis predicts that when auditory and visual information about the direction of a sound source conflict, the interpretation of the two different sources of information will change so as to minimize the conflict. This change does occur (Canon, 1970). The fact that process assimilation occurs clearly implies that auditory and visual directional information are comparable, for if they were not, then no conflict between them would occur and no process assimilation would take place. However, it is not clear whether this comparison occurs because both auditory and visual information are experienced on a common dimension, or whether each is experienced on a modality-specific dimension before translation between them occurs.

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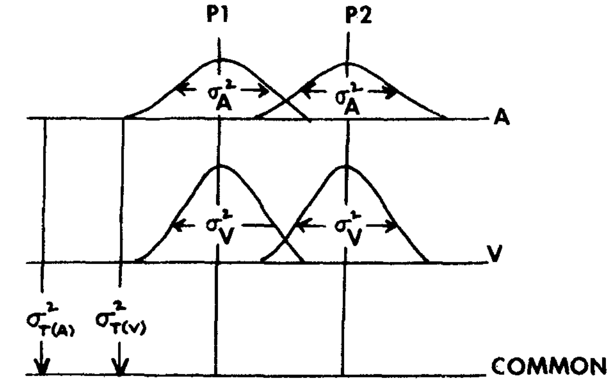

Fig. 1. Experimental setup and theoretical constructs used in the analysis of a "common space." The top two axes show the distribution of apparent positions of P1 and P2 on the auditory and visual dimension. The bottom axis shows the hypothesized common dimension and the mapping to it.

Much work in developmental psychology suggests that infants start off with two disjunct spaces and that a developmental process coordinates them into a common space, although there is recently some dissent from this position. Piaget, for example, believes that the infant starts out with separate spaces for each modality, which are coordinated by the internalization of action on objects which occupy positions in each space. This coordination is presumably complete at the end of the second year (Piaget, 1963). Birch and Lefford (1963) also believe that the infant starts out with separate spaces which are coordinated by the gradual development of intersensory integration, a process probably completed by early adolescence. Warren (1970), who has shown that visual facilitation of auditory localization is not completed until adulthood, concurs with Birch and Lefford. However, Aaronson and Rosenbloom (1971) have shown that at least the basis for a common space is present about a month after birth, by demonstrating that an infant exhibits distress when his mother simultaneously occupies different auditory and visual positions, so the issue is quite complex.

Each of the authors cited above has a different criterion for the existence of a common space. Aaronson and Rosenbloom's criterion for a common space is distress when a familiar object occupies quite different auditory and visual positions. Piaget's criterion is the coordination of actions based on information from the different modalities; Warren's criterion is adult-like visual facilitation of auditory localization; and Birch and Lefford's is intersensory transfer of discrimination ability. Moreover, none of these different criteria contain any specification of how completely they must be met in order for there to be a common auditory-visual space. Consider Aaronson and Rosenbloom's work for example. Suppose an infant exhibits distress when his mother's voice is displaced 90 deg from his mother's visual position, but does not exhibit distress when his mother's voice is displaced only 10 deg. The criterion is not stated explicitly enough to enable one to know if this result does or does not imply the existence of a common space. Parallel remarks, of course, can be made about any of the other authors' criteria, and the only response to them is to provide a further explication of the concept of a common space or, equivalently, of a dimension of experience common to all the modalities.

The idea of a dimension common to all the modalities dates back at least to Titchener (1915), who hypothesized the existence of four dimensions of experience—intensity, extensity, protensity, and attensity—which were shared by stimuli which differed in quality. (For a review of this literature, see Boring, 1942.) Recently, Teghtsoonian (1971) proposed the very Titchenerian hypothesis that there is a single intensity dimension common to all the modalities. This assumption might well be implicit also in the psychophysical procedure of cross-modality matching (Stevens, 1966), or at least in that version of it which Krantz (1972) has termed "mapping theory." Related issues have also been posed concerning the judgment of temporal order of stimuli in different modalities, in which the construct of a simultaneity center for the different modalities (Corwin & Boynton, 1968) corresponds roughly to the construct of a common dimension for the different modalities (cf. also Sternberg & Knoll, 1972).

We will begin by developing a criterion for the existence of a common auditory-visual space. Our analysis of the problem is in many ways similar to earlier work by Fisher (1962) as reported in Howard and Templeton (1966, pp. 353-357). Howard has recently remarked (in Connolly, 1971, p. 370) that this work should be repeated, and the aim of the present study is to do just that. The present study differs from the earlier work which used classical psychophysical techniques, in that it uses psychophysical procedures and concepts derived from signal detection theory.

The task which forms the basis for our analysis is a same-different task involving two points, which we will call P1 and P2, which occupy two different directions. Located at each point is a point source of light and a point source of sound (Fig. 1). The experiment involves a same-different judgment of the following sort. The S is first presented with a stimulus, auditory or visual, occupying P1 and P2. After a short delay, the S is presented with another stimulus, auditory or visual, again occupying P1 or P2. There are three conditions, an AA condition, in which both stimuli are auditory, a VV condition, in which both stimuli are visual, and an AV condition, in which one stimulus is auditory and the other is visual. On same (S) trials, the first and second stimuli occupy the same position, and on different (D) trials, the first and second stimulus occupy different positions.

The signal detection approach to the analysis of the same-different task, and the explication of the assumption of a common dimension, proceeds as follows. In reading the subsequent discussion, refer to Fig. 1. We make the following *stimulus assumptions*: (1) The direction of the auditory stimulus is internally represented on a dimension we label A, and the visual stimulus is internally represented on a dimension we label V. (2) Stimuli with Objective Position P1 give rise to a random distribution of internal subjective positions. This distribution is normal, with mean P1 and variance σ_A^2 if the stimulus is auditory and σ_V^2 if the stimulus is visual. (We have indicated on Fig. 1 that $\sigma_A^2 > \sigma_V^2$, because auditory discrimination of position is more difficult than visual discrimination of position.) Similarly, we assume that stimuli with Objective Position P2 give rise to a normal distribution of subjective positions, whose mean is P2 and whose variances are σ_A^2 and σ_V^2 for the auditory and visual stimuli, respectively. We also make the following *task assumptions*: (1) In doing auditory or visual discriminations, Ss subtract the apparent position of the first stimulus from the apparent position of the second, and respond "different" if the magnitude of the difference exceeds some criterion, k, and respond "same" otherwise. (2) In doing the AV task, Ss first translate the apparent auditory or visual position of each stimulus to a common dimension of position. At this point in our argument, the common dimension of position referred to is a nominal common dimension, i.e., is introduced only for the sake of homogeneity of analysis. Our later discussion will state when this nominal common dimension is the only spatial dimension and when it exists in addition to auditory and visual dimensions. In any event, we hypothesize that after this translation occurs, Ss subtract the value of the first and second stimuli on the nominal common dimension and respond in the same fashion as they did in the auditory and visual discriminations. The translation process is assumed to not shift the mean of the distribution of subjective positions, but rather to make the distribution more variable, by adding an additional source of variance, which we will label translation variance. This translation variance may be different for translation from the auditory and visual modalities, and we use the symbols $\sigma_{T(A)}^2$ and $\sigma_{T(V)}^2$ for the translation variances corresponding to the auditory and visual modalities, respectively. (3) In addition, it is possible that the S's criterion may also vary; we will call the criterion variance σ_k^2. It is also possible that the apparent position of the first stimulus may vary as a function of the interstimulus interval. We assume that the mean position of the first stimulus does not change, but that the distribution of apparent positions becomes more variable. Let us call the variance added to the original variance σ_t^2 (Kinchla & Smyzer, 1967; Kinchla & Allan, 1969). Finally, for purposes of notation, let $\sigma_X^2 = \sigma_k^2 + \sigma_t^2$.

These assumptions provide a framework for stating the common space hypothesis, as well as the disjunct space hypothesis. If the common space hypothesis is correct, and audition and vision share a common dimension, then $\sigma_{T(A)}^2 = \sigma_{T(V)}^2 = 0$, which means that no additional variance is introduced in the intermodality discrimination which is not present in the intramodality discrimination; and the nominal common dimension may be assumed to be the only spatial dimension. If the disjunct space hypothesis is correct and audition and vision do not share a common dimension, then either $\sigma_{T(A)}^2 \neq 0$ or $\sigma_{T(V)}^2 \neq 0$, or both. Depending upon the nature of the nonzero translation variances, one form or another of the disjunct space hypothesis is correct. If both translation variances are nonzero, then there is a third spatial dimension to which both auditory and visual directions are translated. If one translation variance equals zero, but the other does not, then the dimension for which the translation variance is zero is the dimension to which the other direction dimension is translated. If $\sigma_{T(V)}^2 = 0$, and $\sigma_{T(A)}^2 \neq 0$, for example, then auditory direction must be translated into visual direction. The analysis described below cannot be used to decide which form of the disjunct space hypothesis is correct, but the technique presented below can be extended to decide between them, as will be explored in subsequent publications.

For purposes of later use, the common and disjunct space hypotheses may be put another way. Since the hypothesized translation variances must be positive, a condition equivalent to $\sigma_{T(A)}^2 = \sigma_{T(V)}^2 = 0$, the common space hypothesis, is that $\sigma_{T(A)}^2 + \sigma_{T(V)}^2 = 0$. Similarly, a condition equivalent to $\sigma_{T(A)}^2 \neq 0$ or $\sigma_{T(V)}^2 \neq 0$, the disjunct space hypothesis, is that $\sigma_{T(A)}^2 + \sigma_{T(V)}^2 > 0$. We record these conditions as Eq. 1.

$$\begin{aligned} &\text{Common space hypothesis: } \sigma_{T(A)}^2 + \sigma_{T(V)}^2 = 0 \\ &\text{Disjunct space hypothesis: } \sigma_{T(A)}^2 + \sigma_{T(V)}^2 > 0 \end{aligned} \quad (1)$$

We note that it is impossible, on the basis of the present analysis, to distinguish between hypothesizing that translation of auditory and visual direction to a common spatial framework is perfect and hypothesizing that no translation is required. However, no translation process for which one can imagine a neurophysiological basis can realistically be expected to be perfect. Consequently, if the auditory and visual translation variances are zero, one may reasonably infer that auditory and visual directional information are immediately referred to a common spatial framework, with no translation required.

The rest of our analysis is straightforward. We make use of the well-known facts that the difference between two independent normal random variables is also normal, and that its mean is equal to the difference of the means of the two variables, and its variance is equal to the sum of the variances. As we will be computing d′

scores, we will also use the fact that both criterion variance and variance due to temporal uncertainty add to stimulus variance in the computation of d′ (Wickelgren, 1968). Finally, by the same logic, it may be shown that translation variance, should it exist, would add to stimulus variance in the same way as criterion and temporal variance.

It follows, then, that for D trials, the mean of the difference in apparent positions of the first and second stimulus is (P2 – P1), and for S trials, the mean of the difference in apparent positions is 0. For AA trials, the variance of the difference in apparent positions is $2\sigma_A^2 + \sigma_X^2$; for VV trials, the variance of the difference in apparent positions is $2\sigma_V^2 + \sigma_X^2$; and for AV trials, the variance of the difference in apparent positions is $\sigma_A^2 + \sigma_V^2 + \sigma_X^2 + \sigma_{T(A)}^2 + \sigma_{T(V)}^2$. These expressions are obtained by adding the sources of stimulus variance and the sources of extrastimulus variance. In the AA and VV conditions, the sources of extrastimulus variance are temporal drift and criterion uncertainty. In the AV condition, the sources of extrastimulus variance are those just mentioned and, in addition, that arising from translation of the auditory and visual dimension to a common dimension. The values of d′ for these conditions may then be computed—they are the mean of the difference in apparent position in the D trials minus the mean of the difference in apparent positions in the S trials, divided by the common standard deviation in the S and D trials (Green & Swets, 1966). The scale of d′ is an interval scale, and so we may set (P2 – P1) = 1. The resulting values of d′ for each condition are given in Eqs. 2. The notation is simply that the value of d′ for a condition is subscripted by the name of that condition, and the superscript prime in d′ is omitted for purposes of clarity in later equations.

$$
\begin{aligned}
d_{AA} &= 1/\sqrt{2\sigma_A^2 + \sigma_X^2} \\
d_{VV} &= 1/\sqrt{2\sigma_V^2 + \sigma_X^2} \\
d_{AV} &= 1/\sqrt{\sigma_A^2 + \sigma_V^2 + \sigma_X^2 + \sigma_{T(A)}^2 + \sigma_{T(V)}^2}.
\end{aligned}
\tag{2}
$$

We may solve the above system of equations for $\sigma_{T(A)}^2 + \sigma_{T(V)}^2$ by noting that

$$
\begin{aligned}
\sigma_A^2 + \sigma_V^2 + \sigma_X^2 + \sigma_{T(A)}^2 + \sigma_{T(V)}^2 &= \frac{1}{d_{AV}^2} \\
2\sigma_A^2 + \sigma_X^2 &= \frac{1}{d_{AA}^2} \\
2\sigma_V^2 + \sigma_X^2 &= \frac{1}{d_{VV}^2}
\end{aligned}
\tag{3}
$$

Multiply the first equation of Eqs. 3 by 2 and subtract the sum of the second and third equations. The result is

$$\sigma_{T(A)}^2 + \sigma_{T(V)}^2 = \frac{1}{2}\left[\frac{2}{d_{AV}^2} - \frac{1}{d_{AA}^2} - \frac{1}{d_{VV}^2}\right] \tag{4}$$

All the expressions on the right-hand side of Eq. 4 are observable, and so $\sigma_{T(A)}^2 + \sigma_{T(V)}^2$ may be computed from data.

The general assumption made in the literature is that the common space hypothesis is correct. This may be checked by computing $\sigma_{T(A)}^2 + \sigma_{T(V)}^2$ for a group of Ss and seeing whether this sum equals 0. Of course, special problems arise in testing what is essentially a null hypothesis, but we will defer discussion of these until the Results section.

This experiment involved a special case of Eq. 4, in which visual discrimination was perfect, so that d_{VV} is infinite. [If this is the case, then $2\sigma_V^2 + \sigma_X^2$ must be small relative to $(P2 - P1)^2$.] It follows that $1/d_{VV}^2 = 0$, and the expression for $\sigma_{T(A)}^2 + \sigma_{T(V)}^2$ in Eq. 4 becomes

$$\sigma_{T(A)}^2 + \sigma_{T(V)}^2 = \frac{1}{2}\left[\frac{2}{d_{AV}^2} - \frac{1}{d_{AA}^2}\right]. \tag{5}$$

For future reference, we note that if Eq. 5 holds, and in addition the common space hypothesis is correct, so that $\sigma_{T(A)}^2 + \sigma_{T(V)}^2 = 0$, then

$$d_{AV} = \sqrt{2}\, d_{AA}. \tag{6}$$

The aim of the present experiment is to solve for $\sigma_{T(A)}^2 + \sigma_{T(V)}^2$ using Eq. 5, and determine whether the sum equals 0. In addition, we will present evidence bearing on Eq. 6.

We note, too, that the subsidiary hypotheses made in posing the common space hypothesis are also testable. The signal detection analysis of the same-different task may be checked by examining the properties of the ROC curves in this task (cf. Gaussin & Hupet, 1972; Markowitz & Swets, 1967), although this is a weak test of the hypothesis (Leshowitz, 1969). The specific formulation of the common space hypothesis in terms of translation variance is somewhat more problematic, but it also has empirical consequences. If $\sigma_{T(A)}^2 + \sigma_{T(V)}^2 > 0$, then evidence for a translation process of the sort hypothesized here could be obtained by demonstrating that the translation variances for a specific experimental S are independent of the specific values of d′ from which they are computed. We will not deal with this point further in the paper, since we did obtain data confirming the common space hypothesis.

METHOD

Stimuli and Apparatus

The stimuli in the experiment were produced by one of two 1½-in. Archer speakers (0.2 W, 8 ohms), and one of two small Archer light bulbs (2.38 V), mounted on a wall roughly 1.26 m off the floor and roughly 0.60 m apart. The S was seated 6.04 m from the wall, with the plane of his head midway between the speakers and the lights. The lights were mounted directly above each speaker. In subsequent discussion, the location of the left speaker will be referred to as Position 1 and that of the right speaker will be referred to as Position 2.

The entire experiment took place in the dark. The light bulbs themselves were taped over with electrical tape, leaving only a small area exposed so that the stimuli from them approximated point sources. A dark sheet was draped behind the apparatus so as to assure that the brief illumination of the lights did not illuminate the wall behind the S and provide cues which would distinguish the lights.

The auditory and visual stimuli were provided by manually pushing a button which connected one of the speakers or one of the lights to a 6-V battery. Although stimulus duration was not controlled precisely, the duration was roughly 500 msec.

Procedure

There were three conditions to be run: the AA condition, which involved discrimination of auditory position, the VV condition, which involved discrimination of visual position, and the AV condition, which involved discrimination of auditory from visual position.

The experimental task was what we have termed a same-different task. It involved two sorts of trials: same (S) trials and different (D) trials. The nature of the trials was somewhat different for the AV condition than for the AA and VV conditions, and so will be described separately. Consider first the AA and VV conditions. On the S trials, the first stimulus occupied Position 1 or Position 2 and the second stimulus occupied the same position as the first. On the D trials, the first stimulus occupied Position 1 or Position 2 and the second stimulus occupied the alternative position. Consider now the AV condition. On the S trials, the first stimulus occupied Position 1 or Position 2 and was either auditory or visual, and the second stimulus occupied the same position as the first, but was of the alternative modality, i.e., auditory if the first stimulus was visual, and vice versa. On the D trials, the first stimulus occupied Position 1 or Position 2 and the second stimulus occupied the alternative position and was of the alternative modality.

Eight hundred trials were run in each condition: 400 S trials and 400 D trials. In the AA and VV conditions, there were two types of S trials and two types of D trials, depending on whether the first stimulus occupied Position 1 or Position 2, and each was equally likely to occur on any given trial. There were then 400 S trials and 400 D trials, 200 of each type. In the AV condition, there were four types of S trials and four types of D trials, depending upon whether the first stimulus occupied Position 1 or Position 2, and was auditory or visual. Each was equally likely to occur on any given trial. There were 400 S trials and 400 D trials, 100 of each type.

A typical trial proceeded as follows. The first stimulus was presented for roughly 500 msec; there was an interstimulus interval of roughly 1.5 sec, and then the second stimulus was presented for roughly 500 msec. Following this, Ss made a judgment about whether the second stimulus occupied the same position or a different position from the first. They made their responses verbally to the E, and had 3 sec to do so before the next trial.

The three conditions were presented in a counterbalanced order; the counterbalancing was accomplished by using three replications of the set of six permutations of the three conditions. However, after the 14th S was run, it became apparent that discrimination in the VV condition was always perfect and so the condition was discontinued.

The entire experiment took 4 h to run. It was run in one sitting with two 15-min breaks between conditions.

Subjects

Eighteen Ss in all were used in the experiment, three for each of the possible permutations of conditions. There were nine male and nine female Ss. Their ages ranged from 21 to 29 years, and none reported any visual or hearing deficit, other than that their vision was corrected by glasses.

RESULTS

For each S in each condition, the data obtained were the probability of the responses same or different when the stimuli presented in fact occupied the same or different positions. Of these probabilities, only two are independent, e.g., P(D/D) and P(D/S), the probability of the response "different" to D and S trials, respectively. These two were used in subsequent data analysis. They were converted to z scores, namely z(D/D) and z(D/S), and the value of d' in each condition was computed from the expression $d' = z(D/D) - z(D/S)$. (For a rationale for this technique, see Auerbach, 1971.)[1] Of these d' scores, one was always infinite, namely that for the VV condition, and so it did not figure in the analysis which followed.

Our major interest was to solve for $\sigma^2_{T(A)} + \sigma^2_{T(V)}$, the sum of the translation variances, using Eq. 5, and to test whether this sum equaled 0, as predicted by the common space hypothesis. To do this, we first computed the value of

$$\frac{1}{2}\left[\frac{2}{d^2_{AV}} - \frac{1}{d^2_{AA}}\right]$$

for each experimental S. We then tested the statistical hypothesis that the set of these values constituted a sample from a normal population of mean 0, and unknown variance, using a t test (Ferguson, 1966, p. 153). In fact, the mean value of

$$\frac{1}{2}\left[\frac{2}{d^2_{AV}} - \frac{1}{d^2_{AA}}\right]$$

for the entire sample of Ss, which constitutes the best estimate of $\sigma^2_{T(A)} + \sigma^2_{T(V)}$, was 0.006. The computed value of t was $t(17) = 0.50$, which is not significant, and we thus retained the hypothesis that $\sigma^2_{T(A)} + \sigma^2_{T(V)} = 0$.

One may raise questions about the logic of basing conclusions on a test of the hypothesis that the mean of a random variable equals 0, since this would seem equivalent to basing conclusions on accepting a null hypothesis, a procedure traditionally viewed with suspicion. We dealt with this issue by using the procedures of power analysis (Cohen, 1969). We used Cohen's power tables to compute the effect size detectable with a power of 0.80 and a Type I error of 0.05, with the sample size we used in the present experiment (N = 18), using the procedure that Cohen suggests (p. 15). We used the observed value of the sample standard deviation as an estimate of the population standard deviation of $\sigma^2_{T(A)} + \sigma^2_{T(V)}$ to obtain an estimate of the value of $\sigma^2_{T(A)} + \sigma^2_{T(V)}$ detectable in our experiment with the power specified. The result was that a value of $\sigma^2_{T(A)} + \sigma^2_{T(V)}$ equal to 0.03 would be detectable with a power of 0.80. Under these conditions, we regard retaining the hypothesis that

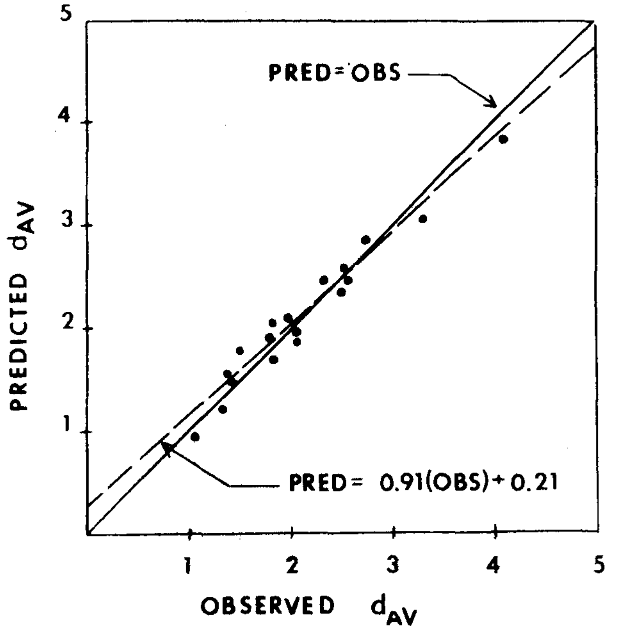

Fig. 2. Predicted value of d_{AV}, based on the common space hypothesis, as a function of the observed value of d_{AV}. Each data point is from a separate S. The best fitting straight line and line of perfect agreement are shown.

$\sigma^2_{T(A)} + \sigma^2_{T(V)}$ equals 0 as decisive confirmation of the common space hypothesis, since small deviations from the common space hypothesis are readily detectable.

The goodness of fit of the common space hypothesis to the data was further examined in several ways using Eq. 6, which is a consequence of the common space hypothesis.

First, we plotted the value of d_{AV} predicted from the common space hypothesis, namely $\sqrt{2}\ d_{AA}$, as a function of the observed value of d_{AV}. The result is shown in Fig. 2. If the predicted and observed values of d_{AV} agreed perfectly, then all points would fall on the 45-deg diagonal. Clearly, the agreement is excellent. The best fitting straight line to the relation between predicted and observed values of d_{AV} obtained by the least squares method (Ferguson, 1966, p. 118) is Pred = 0.91 (Obs) + 0.21, which is also shown in Fig. 2. The correlation between the predicted and observed values of d_{AV} is $r = 0.98$, so that Eq. 6, the predicted relation on the basis of the common space hypothesis, accounts for 96% of the variance in the observed values of d_{AV}.

As a final test of the goodness of fit of the common space hypothesis to the data, we examined the question of whether the predicted and observed values of d_{AV} came from the same distribution. This cannot be examined directly, since the conventional test of this–the Kolmogoroff Smirnoff test–requires that the distributions being compared be independent and the observations we are considering are correlated (Siegel, 1956, pp. 127-136). As an approximation to this, we decided to simply compare the means and standard deviations of the samples of predicted and observed values of d_{AV}, using the t and F tests, respectively, and ignoring the dependence in the data (Ferguson, 1966, pp. 167 and 181). When the means are compared by subtraction, the value of t is $t(34) = 0.08$, which is not significant. When the standard deviations are compared by division, the value of F is $F(17,17) = 1.17$, which is not significant. We conclude that the predicted and observed values of d_{AV} come from distributions at least identical in their means and standard deviations, and this, of course, constitutes further evidence for the common space hypothesis.

DISCUSSION

The conclusion we draw from the data is that the common space hypothesis is indeed confirmed, and that auditory and visual direction are represented on the same underlying direction dimension, rather than there being two different direction dimensions and a translation procedure between them. This conclusion is based on the facts that (1) the estimated value of $\sigma^2_{T(A)} + \sigma^2_{T(V)}$ is 0.006, which is quite close to the value of 0 specified by the common space hypothesis; (2) we retained the statistical hypothesis that the observed values of $\sigma^2_{T(A)} + \sigma^2_{T(V)}$ are from a normal distribution, whose mean is 0; and (3) various goodness of fit tests, of which Fig. 2 is representative, show excellent agreement between the observed data and that predicted from the common space hypothesis. Although the conclusion may surprise nobody, disconfirmation of the common space hypothesis was certainly a logical possibility, and so it is of some interest that it was confirmed.

This research and this research technique have application to and import for many issues in space perception. The first and most obvious application of this research technique is to ask the question as to whether there is a common direction dimension concerning the other modalities; is there a common direction dimension between vision and proprioception, for example, or between proprioception and audition? The natural assumption is that there is a common dimension, but the issue is, of course, an empirical one. Then, too, the question may be asked: given that there is a common dimension, at what age does it arise? Here one's assumptions are much less clear-cut, and the answer might be quite informative.

The nature of the common dimension and of the possible translation processes may be explored in other ways. One possibility is to look for a physiological substratum for a common spatial framework, as Bernstein and Edelstein (1971) suggest. Another possibility is to investigate the possible translation processes involved, using reaction time as a dependent variable. Presumably, every translation process that occurs has its effect on reaction time in the intermodality same-different task. Of course, elucidating the nature of this effect requires further theoretical and experimental work. (For a related paper, see Simpson, 1973.)

REFERENCES

Aaronson, E., & Rosenbloom, S. Space perception in early infancy: Perception within a common auditory visual space. Science, 1971, 172, 1161-1163.

Auerbach, C. Correcting two-alternative forced-choice data for response bias. Perceptual & Motor Skills, 1971, 32, 533-534.

Bernstein, I. H., & Edelstein, B. A. Effects of some variations in auditory input upon visual choice reaction time. Journal of Experimental Psychology, 1971, 87, 241-247.

Birch, H. G., & Lefford, A. Intersensory development in children. Society for Research in Child Development Monograph, 1963, 28, No. 5.

Boring, E. G. *Sensation and perception in the history of experimental psychology.* New York: Appleton-Century-Crofts, 1942.

Canon, L. K. Intermodality inconsistency of input and directed attention as determinants of the nature of adaptation. Journal of Experimental Psychology, 1970, 84, 141-147.

Cohen, J. *Statistical power analysis for the behavioral sciences.* New York: Academic Press, 1969.

Connolly, K. J. (Ed.) *Mechanisms of motor skill development.* New York: Academic Press, 1971.

Corwin, T. R., & Boynton, R. M. Transitivity of visual judgments of simultaneity. Journal of Experimental Psychology, 1968, 78, 560-568.

Ferguson, G. *Statistical analysis in psychology and education.* New York: McGraw-Hill, 1966.

Fisher, G. H. Intersensory localization. PhD thesis, University of Hull, 1962.

Gaussin, J., & Hupet, B. An experimental validation of the signal detection theory for active touch. Psychonomic Science, 1972, 27, 339-341.

Green, D. M., & Swets, J. A. *Signal detection theory and psychophysics.* New York: Wiley, 1966.

Howard, I. P., & Templeton, W. B. *Human spatial orientation.* New York: Wiley, 1966.

Kinchla, R. A., & Allan, L. G. A theory of visual movement perception. Psychological Review, 1969, 76, 537-558.

Kinchla, R. A., & Smyzer, F. A. A diffusion model of perceptual memory. Perception & Psychophysics, 1967, 2, 219-229.

Krantz, D. H. A theory of magnitude estimation and cross-modality matching. Journal of Mathematical Psychology, 1972, 9, 168-199.

Leshowitz, B. Receiver operating characteristics and psychometric functions determined under several experimental conditions. PhD thesis, City University of New York, 1969.

Markowitz, J., & Swets, J. A. Factors affecting the slope of empirical ROC curves: Comparison of binary and rating responses. Perception & Psychophysics, 1967, 2, 91-101.

Piaget, J. *The origins of intelligence in children.* New York: Norton, 1963.

Siegel, S. *Nonparametric statistics for the behavioral sciences.* New York: McGraw-Hill, 1956.

Simpson, W. E. Latencies in intermodal spatial localization. Journal of Experimental Psychology, 1973, 99, 148-150.

Sternberg, S., & Knoll, R. L. The perception of temporal order: Fundamental issues and a general model. In S. Kornblum (Ed.), *Attention and performance, IV.* New York: Academic Press, 1972.

Stevens, S. S. Matching functions between loudness and ten other continua. Perception & Psychophysics, 1966, 1, 5-8.

Teghtsoonian, R. On the exponent in Stevens' law and the constant in Ekman's law. Psychological Review, 1971, 78, 71-80.

Titchener, E. B. Sensation and system. American Journal of Psychology, 1915, 26, 258-267.

Wallach, H. Information discrepancy as a basis of perceptual adaptation. In S. J. Freedman (Ed.), *The neuropsychology of spatially oriented behavior.* Homewood, Ill: Dorsey Press, 1968.

Warren, D. H. Intermodality interactions in spatial localization. Cognitive Psychology, 1970, 1, 114-133.

Wickelgren, W. A. Unidimensional strength theory and component analysis of noise in absolute and comparative judgments. Journal of Mathematical Psychology, 1968, 5, 102-122.

NOTE

1. It should be noted, however, that this data analysis presupposes that the distributions of the variable on which the S's judgment is based for both the same and different tasks be normal, and that they be of equal variance. The normalcy assumption would be an approximation if the same and different judgments involved responding to the absolute value of the difference in apparent position between stimuli. Alternatively, the task may be viewed as a composite of two tasks. In one, the first stimulus is presented to the S's left and the S must judge whether the second stimulus is in the same position or to the right of the first. In the other, the first stimulus is on the right, and the Ss must judge whether the second stimulus is in the same position or to the left of the first. In this case, Ss could respond to the difference in apparent positions directly, and no approximation is required. The equal variance assumption also may be only approximate, since, although it does follow from the theoretical assumptions, it has been violated in other instances, e.g., Markowitz & Swets (1967).

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