ON CONSTANCY OF VISUAL SPEED[1]

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When investigating the constancy of visual speed J. F. Brown[2] discovered what he called the transposition principle of velocity. In his account the constancy of visual speed and the principle of transposition occur as unrelated facts. This paper attempts to show that constancy of visual speed can be understood as a consequence of the transposition principle.

When objects which move with the same objective velocity are presented to the resting eye at different distances one perceives them as moving with approximately equal speed, although the displacements of their retinal images per unit of time vary in inverse proportion to the distance. This is what we call the constancy of visual speed. Its formal similarity to the constancy of size is obvious. Two identical objects presented at different but moderate distances from the eye have almost equal phenomenal sizes, although the linear extensions of the corresponding images are inversely proportional to the distances at which the two objects are presented to the eye. It seems plausible to assume that constancy of visual speed is simply a consequence of size constancy. One might argue that visual speed depends not on the length through which an image passes on the retina per unit of time but on the visual extension through which the object moves. Since the latter extension remains approximately constant even if its objective size is projected from different distances and therefore with varying retinal size, the constancy of visual speed seems to follow without any further assumptions.

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[2] J. F. Brown. Ueber gesehene Geschwindigkeiten. *Psychol. Forsch.*, 1927, 10, 84–101. Also J. F. Brown, The visual perception of velocity. *Psychol. Forsch.*, 1931, 14, 199–232.

This was indeed the reasoning which led J. F. Brown to his investigation of the constancy of speed. His actual observations, however, did not entirely confirm this view. While with moderate distances and under otherwise favorable conditions size constancy is almost absolute, constancy of speed proved to be considerably less perfect. When two objects moved at different distances from the eye, the objective velocity of the more distant object had to be distinctly greater, if the two phenomenal speeds were to appear as equal. Brown concluded that the constancy of speed cannot simply be deduced from the constancy of size. He therefore began a thorough investigation of "the factors that condition phenomenal velocity."

. In his experiments Brown had his observers compare the speeds in two movement-fields which from experiment to experiment differed in various respects. Probably his most important finding is the transposition principle, which he established in experiments in which the two movement-fields differed only with respect to their size, being transposed in all their linear dimensions in a certain proportion. A movement-field consisted of an opening in a black cardboard screen and black dots of equal size moving through this opening on a white background. The dots were pasted on a roll of white paper running over two moving drums which were hidden by the screen. The drums were far enough apart so that only a flat surface was visible through the opening. The field in the opening was uniformly illuminated. The surface of the paper was smooth so that no cues of its motion could be obtained, except from the dots. The observer was to compare successively the speed with which the dots in two such movement-fields passed through their respective openings. In one of the fields the velocity was variable and could be stepped upwards or downwards under the direction of the observer until the speed in the two movement-fields appeared to be the same, Then the velocities were measured and their quotient was computed. The movement-fields were placed far enough apart so that only one could be seen at a time.

In one of these experiments, for instance, the movement-fields were transposed in a ratio 2 : 1, *i.e.* all the linear measures in one of the moving fields, namely the size of the opening, the diameter of the dots and their distance from one another, were twice as large as the same measures in the other moving field. After the objective velocities were so adjusted that the phenomenal speed in the two movement-fields was the same, the objective velocity in the larger field (*A*) was found to be almost twice as great as in the smaller field (*B*). Where V_A is the velocity in *A* and V_B the velocity in *B* when phenomenal equality is attained, $\frac{V_A}{V_B}$ was found to be 1.94 (average for 7 observers).[3] When the spatial transposition of the two movement-fields was 4 : 1, the speeds in the two fields were judged to be equal when the ratio of the objective velocities was 3.7 (average for 5 observers).[4] Thus the objective velocity in the 4 times larger field *A* was approximately 4 times as great as was that in the smaller field *B*, when visually both movements seemed to have the same speed. On the basis of these results Brown formulated the principle of velocity transposition: If a movement-field in a homogeneous surrounding field is transposed in its linear dimensions in a certain proportion, the stimulus velocity must be transposed in the same proportion in order that the phenomenal speed in both cases be identical.

The velocity ratios actually measured by Brown departed significantly from the figures called for by this principle, particularly when the difference in the dimensions of the two movement fields was still larger. When the transposition was in the proportion 10 : 1, the ratio of the velocities was 8.22[5] (average for 4 observers; *cf.* below for additional results). Still these various departures from the theoretically expected values seem very small when we compare them with the enormous effects of the transposition phenomenon which were

[3] J. F. Brown. Ueber gesehene Geschwindigkeiten. *Psychol. Forsch.*, 1927, 10, p. 91, Table 5.

[4] *Ibid.*, p. 92, Table 8; also J. F. Brown, The visual perception of velocity. *Psychol. Forsch.*, 1931, 14, p. 216.

[5] J. F. Brown. The visual perception of velocity. *Psychol. Forsch.*, 1931, 14, p. 216.

actually found. In the last mentioned case with a transposition of 10 : 1 where the departure from the expected value was 18 per cent, the actually measured effect of the transposition phenomenon was as high as 722 per cent.

In a quite similar way Brown had previously determined to what degree constancy of speed is actually realized. Two identical movement-fields were placed at different distances from the observer and the ratio of their velocities was varied until the speeds in the two fields seemed to be equal. The movement in the more distant field was then 1.12, 1.15, and 1.21 times faster than the other, where the ratio of the distances from the observer was 1 : 3.3, 1 : 6.6 and 1 : 10 respectively.[6] Perfect constancy, of course, would have yielded in each case the ratio 1 instead of the listed quotients. Again, the actually found figures depart only little from the values to be expected for perfect constancy, when we compare them with the values which we should find if phenomenal speed were proportional to the velocities on the retina. On the other hand the departure from ideal constancy is here significantly larger than the departure which size constancy shows, a difference great enough to justify Brown's conclusion that constancy of speed cannot be deduced from size constancy.

We are thus facing an apparently paradoxical state of affairs. On the one hand we find a speed constancy of high degree, when speeds in movement-fields at different distances from the eye are compared; on the other hand the transposition experiments show that at a constant distance objective velocities may appear equal when one is as much as 8 times faster than the other. The fact that the reported transposition experiments were done under unnatural dark-room conditions affords no comfort. When Brown repeated the experiments with daylight illumination so that the continuity of the spatial framework was plainly given, he obtained for the same ratios of transposition, namely 2 : 1, 4 : 1 and 10 : 1, the velocity ratios 1.57, 2.71 and 6.17.[7] Even under these condi-

[6] *Ibid.*, p. 208, Table 1.
[7] *Ibid.*, p. 215, Table 7.

tions of adequately structured visual field the transposition phenomenon remains striking.

In an intricate state of affairs like this the first thing to do is to examine closely the immediate stimulus situation. It is in the present case represented by the retinal images of the movement-fields. In a transposition experiment the retinal images of the two movement-fields bear to each other the same proportion as the objective movement-fields themselves, and the rates of the shifting dots on the retina are also proportional to the objective velocities. In the constancy experiment the situation is different in that here the movement-fields are presented at different distances from the eye, and the retinal images have different sizes, although they correspond to objectively identical fields. More specifically, their dimensions are inversely proportional to the distances at which the corresponding movement-fields are presented. When, for instance, of two identical movement-fields, *A* is presented at 2 m. distance and *B* at 4 m. distance, the image of *A* is linearly twice as large as the image of *B*. Let us assume for the moment that constancy of speed is perfect, so that the speed in the fields *A* and *B* would seem to be the same when the objective velocities are equal. Since displacements in *A* and *B* produce retinal displacements which are twice as large in the case of *A* as they are in the case of *B*, phenomenal speeds are equal when the *retinal velocity in A is twice as great as that in B.* Let us now consider a case of the transposition phenomenon under the assumption that the principle of transposition also holds perfectly. If *A′* be a movement-field twice as large in all dimensions as *B′* and if both be presented at the same distance from the eye, the retinal image of *A′* is twice as large as that of *B′*. According to the transposition principle, the phenomenal speed in both fields is the same when the objective velocity in *A′* is twice as great as in *B′*. This being the case, *the velocity in the retinal image of field A′ is also twice as great as is that in the retinal image of B′.* We thus find that the two different experimental situations yield essentially the same processes *on the retina.* The constellations of phenomenal equality in the constancy experiment on the one hand and in a transposition experiment on the other hand, both referred to the retina, are exactly alike. Thus, if we apply the principle of transposition *to the retinal images* of the two movement-fields in a constancy experiment, this principle leads to equality of phenomenal speed, *i.e.*, to just the fact which is commonly called constancy of speed. In this manner constancy of speed can be explained without any further hypothesis. Incidentally, in this explanation there is no reference to constancy of size. *The transposition principle alone, if applied to retinal images and retinal displacements, yields constancy of visual speed.*

In this connection, it may be useful to give the transposition principle another formulation. Velocity is usually measured as displacement per unit of time. We then may say: In movement-fields of identical shape and different dimensions the phenomenal speed is the same when the displacements per unit of time are equal fractions of the respective openings. Or simply: In transposed movement-fields, the perceived speeds are the same when the *relative* displacements are equal. Since in a transposition experiment the retinal images of the movement-fields have the same size proportions as the actually presented movement-fields, the principle applies directly to the retinal images. On the other hand, if in a constancy experiment the distance of a field *A* from the eye is half that of an identical field *B*, the retinal image of *A* is linearly twice as large as that of *B*. According to our principle, the two images will again yield the same phenomenal speed when the retinal displacements per unit of time cover equal fractions of their respective movement-fields on the retina. What does this mean in objective physical terms? The very problem of constancy of speed arises from the fact that the same physical displacement causes different retinal displacements, depending upon the objective distance of the movement-field. More concretely, the retinal displacements are inversely proportional to the distance of the field. But, as I just mentioned, the retinal image of the field itself is also linearly in inverse proportion to the distance. Consequently the retinal displacement per unit of time remains a constant fraction of the retinal movement-field when in objectively identical fields the same objective velocity is given at varying distances. Thus, from the point of view of the transposition principle, the condition for constant phenomenal speed is fulfilled precisely when objective circumstances are those of constancy of speed.

Actually, constancy of speed is not perfect. But the results of transposition experiments, too, fall somewhat short of exact proportionality as shown by the figures that have been quoted. In the case of the transposition phenomenon, Brown attributes the departures from the ideal values to defective homogeneity of the surrounding fields. Although as a rule the transposition experiments are performed under darkroom conditions, the illumination of the movement-fields themselves somewhat lightens the surroundings. That inhomogeneity of the surrounding fields reduces the transposition phenomenon is one of Brown's well-established results. He reports 3 series of transposition experiments under different conditions of illumination. We shall quote here only the results which he obtained with a transposition ratio of 10 : 1. They are representative for the trend in the 3 series. One experiment was made in daylight illumination, and gave the velocity ratio $\frac{V_A}{V_B}$ 6.17, where V_A refers to the 10 times larger field. Another experiment was done in a dark room, but the illumination of the movement-fields somewhat lightened the surroundings of the fields. This had a definite effect on the result, as Brown points out conclusively.[8] $\frac{V_A}{V_B}$ was here 6.83. In the third series the illumination of the movement-fields "was cut down considerably so that the surrounding fields approached homogeneity." The ratio here obtained was as high as 8.22. Indeed the departure from the ideal ratio (which would here be 10) is doubled when the observation is made with daylight illumination (6.17 as against 8.22). Brown was able to obtain a further decrease in proportionality. He covered the two cardboards in which the openings of the

[8] *Ibid.*, p. 216, discussion of curve *b*.

movement-fields were cut with a wallpaper which showed a regular geometric pattern. He then repeated the experiment, using an objective transposition ratio of 4 : 1, and of course daylight illumination. The resulting velocity ratio now was approximately 2, whereas the same pair of movement-fields gave a ratio of 2.7 when, again in daylight, a homogeneous black cardboard surrounded the movement-fields.[9]

This experiment clearly demonstrates the manner in which an inhomogeneous environment influences the velocity ratio. Such an environment disturbs the simple proportionality of the movement-fields. Phenomenal speeds are equal when the displacements per unit of time are the same in proportion to the dimensions of their respective fields. If both fields are surrounded by the same pattern, a common framework is introduced which will tend to equalize conditions and thus to reduce the influence of transposition. In the case of the ordinary daylight experiment the outer edge of the two equal cardboards is introduced as such a common framework.

The departure from perfect constancy of speed is not much discussed in Brown's paper. Constancies are rarely quite complete. Some authors attribute almost explanatory significance to the fact that actually visual size, brightness and shape lie somewhere between the properties of the 'real' objects and properties corresponding to the retinal situation. According to our discussion, contancy of speed is no longer an independent fact but rather a by-product of the transposition phenomenon. It is in this light that we have to discuss the departure from perfect constancy of speed.

Generally, constancy of size and of shape are enhanced when one changes from darkroom conditions to daylight illumination. For the transposition phenomenon the opposite is true. It decreases upon such a change. It should be interesting to note in what way constancy of speed reacts to changes of illumination. The figures quoted by Brown for speed constancy under the two different conditions show *no* significant difference.[10] At the first glance, it may seem

[9] *Ibid.*, p. 218.
[10] *Ibid.*, p. 208 f., Tables 1 and 2.

surprising that daylight illumination has not the same unfavorable effect on speed constancy as it has on the transposition phenomenon, when the two facts are interpreted as being fundamentally the same thing. But when we consider the matter again in terms of retinal images, and recall the way in which daylight conditions influence the transposition phenomenon, we find this result of Brown in line with our notions. Daylight conditions disturb the transposition phenomenon by introducing unproportional (equal) elements in the environment of the movement-fields. There should be no such unfavorable effect when strictly *transposed* surroundings are added to the transposed movement-fields proper. And this is what daylight illumination actually does in a constancy experiment. Here the movement-fields are objectively identical, and the transposed sizes of the retinal images are due to the fact that they are projected from different distances. But the same holds for the objectively identical forms in the immediate surroundings of the movement-fields, as, for instance, the edges of the cardboard screens and the supporting tables. Their retinal images are transposed in the same ratio as are the movement-fields themselves. In this way only proportional elements are added to the transposed movement-fields, and these cannot impair the effect of the transposition principle. On the other hand, they do not seem to improve it either. Brown's results, according to which the departure from ideal constancy is about the same for daylight illumination as for darkroom conditions, indicate that the addition of proportional elements does not serve to increase the effect of the transposition principle. Obviously, the movement-fields as such furnish a framework which guarantees this effect, and not much is changed when further proportional structures are added on the retina.

On the other hand it remains true that neither constancy of speed nor the transposition principle is completely realized. We have seen that in the case of speed constancy the deviations are not due to additional structures in the environment. We may therefore doubt whether in the case of transposition unproportional elements are *entirely* responsible for the deviations.

Incidentally, when we compare the departure from perfect constancy with the departure from complete transposition in the results of Brown's transposition experiments, we find that one of Brown's darkroom series yields about the same departure from the ideal transposition values as was found in corresponding constancy experiments.

For the purpose of such a comparison we consider again the velocities on the retina. Unfortunately, there is only one case in which transposition in the dark room and an experiment on constancy can be strictly compared; a constancy experiment in which the ratio of the distances of the movement-fields from the observer was 1 : 10, and a transposition experiment in which the movement-fields were transposed in the ratio 10 : 1. In both cases the retinal images of the movement-fields bear the same size proportions. In the constancy experiment equality of speed was attained when the velocity in the more distant field was 1.21 of that in the nearer (average of five observers, Table 1).[11] This means that the retinal velocity corresponding to the more distant field was .121 of that corresponding to the other; for, the image of the more distant field was one-tenth of the size of the other field, and the same, of course, was true of the retinal displacements. With this figure we have to compare the result for the size ratio 10 : 1 when transposition was measured in a dark and nearly homogeneous room. The velocity ratio here obtained was 8.22 (average of four observers). The ratio of the retinal velocities which we computed for the corresponding constancy experiment was .121. This is the quotient of the velocity in the smaller retinal movement field and the velocity in the larger one. Since Brown presents the velocity ratios for transposition experiments in the converse fashion (velocity in the larger field divided by that in the smaller field), we have to express the result of the constancy experiment as 1/.121 instead of .121. If this is done the figures become comparable. The value of 1/.121 is 8.26, in notable agreement with 8.22, the result of the transposition experiment.

In a constancy experiment with the distance ratio 1 : 5 the ratio of the objective velocities was 1.14 when phenomenal equality was attained (average of four observers, Table 2).[12] For the corre-

[11] *Ibid.*, p. 208.
[12] *Ibid.*, p. 209.

sponding transposition ratio, 5 : 1 no data are available from the darkroom series in question. But the velocity ratio 3.7 for the transposition ratio 4 : 1, which is rather close to 5 : 1, taken together with the ratio 8.22 for 10 : 1,[13] permits by interpolation the computation of the value for the ratio 5 : 1, which is 4.45. In order to make the result of the constancy experiment, namely 1.14, comparable to this figure, we reduce this to retinal velocities and take again the reciprocal value (*cf.* above). The result is 4.39, again a close agreement.

We may conclude from these cases of agreement, that the transposition experiments to which they refer were done under optimal conditions; *i.e.*, that a further decrease in the illumination would not improve the transposition of velocities in movement-fields of different sizes. For, the results of these transposition experiments correspond exactly to those of the constancy experiments with which they were compared. And in these, we have seen, results were optimal because all additional structures were properly transposed on the retina by virtue of the essential experimental conditions.

We now have to ask ourselves what factors limit the exact validity of the transposition principle. Recently D. Cartwright[14] was able to show that the difference threshold for the position of a point within an opening exhibits the same dependence on the properties of the opening as does phenomenal speed. In a three times larger opening the threshold for changes of position of a point was found to be 2.7 times larger than that in a smaller opening. Approximately the same ratio was obtained by Brown, when he determined the physical velocities which gave equal phenomenal speeds in openings of the relative sizes 3 and 1. In a second instance a similar agreement was found between the ratio of velocities which yielded equal phenomenal speeds, and the ratio of the thresholds of position measured under comparable conditions. This parallelism suggests a close relationship between visual speed and the threshold for changes of position. Actually, several phenomena in the field of visual speed can be explained, if we realize that our sensitivity for changes of position de-

[13] *Cf.* above.

[14] D. Cartwright. On visual speed. *Psychol. Forsch.*, 1938, 22, 320–342.

pends on a great many factors. Here it seems relevant that this sensitivity follows Weber's law within certain limits. Strict validity of Weber's law for spatial changes would mean that the thresholds for changes of position is proportional to the size of the openings in which the threshold is measured. From this point of view one might expect the transposition principle of velocities to be fully realized. Actually, Weber's law does not strictly hold in this field. This follows clearly from Cartwright's experiments. But the departure from Weber's law seems to be of about the same magnitude as the departure from ideal transposition of velocity. Thus the departure from ideal transposition of velocity may be attributed to the fact that Weber's law does not strictly hold in the case of spatial changes.

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