JOURNAL OF MATHEMATICAL PSYCHOLOGY 36, 498–523 (1992)

Visual Kinematics
II. Space Contraction in Motion and Visual Velocity

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The apparent contraction of spatial separation between moving visual objects along the direction of motion (Space Contraction in Motion effect, SCM) occurs under both steady fixation and free looking conditions. In both cases the perceived spatial separation-in-motion for a given angular velocity does not depend on parameters of the moving objects themselves and equals a fixed proportion of the separation-at-rest. The perceived spatial separation decreases as angular velocity increases, defind in external rather than retinal coordinates. For a given angular velocity the spatial separation decreases as a function of factors increasing the perceived speed of motion. Thus both the perceived speed and the SCM effect are greater under steady fixation than under free looking conditions, and they both increase when motion takes place between more narrow screen borders. A hypothesis is proposed that SCM depends on perceived rather than objective velocity. © 1992 Academic Press, Inc.

1. INTRODUCTION

1.1. *Space Contraction in Motion: Basic Properties*

It has been shown in the preceding paper (Visual Kinematics I; Dzhafarov, 1992a) that perceived spatial relations within a uniformly moving group of visual objects (in a frontoparallel plane) change as a function of motion velocity. The perceived spatial intervals between the objects are contracted in the direction of motion, but not transversely, compared with the intervals between the same objects at rest. This phenomenon has been called Space Contraction in Motion (SCM). A general principle (Mapping Homogeneity Principle, MHP) and a methodological paradigm (Double-Perturbation, or 2P, paradigm) have been proposed that allow one to separate, both conceptually and operationally, the geometric transforma-

I am grateful to J. Allik for numerous and most fruitful discussions, and to V. Kapustin for building instruments and conducting the experiments. Both were coauthors of preliminary reports presented at two international conferences on perception: in Tallin, Estonia, 1984, and in Prague, Czechoslovakia, 1984. I am indebted to J. Malpeli and J. Yellott for important suggestions and critically reading the manuscript. I also thank Ch. Izmailov, R. Sekuler, T. Cornsweet, T. Indow, A. Parducci, G. Johannson, S. Runeson, C. van Hofsten, V. Sarris, and G. A. Lienert for discussions and comments. Address reprint requests to Ehtibar Dzhafarov at the Department of Phychology, University of Illinois at Urbana—Champaign, 603 East Daniel street, Champaign, IL 61820.

0022-2496/92 $5.00

tions in motion from the "distributional" transformations due to visual integration–interaction mechanisms (the mechanisms, like visual smear or masking, that change the distribution of color/brightness in visual space, rather than the spatial metric per se).

Briefly stated, the MHP means the following.[1] First, if a light distribution $\mathbf{l}(x, y, t)$ is perceptually mapped into a color/brightness distribution $\mathbf{L}(X, Y, T)$, then a shifted replica of $\mathbf{l}(x, y, t)$ is mapped into a shifted replica of $\mathbf{L}(X, Y, T)$. Second, the shifts along perceptual axes $\langle X \rangle$, $\langle Y \rangle$, and $\langle T \rangle$ depend on the corresponding physical shifts along $\langle x \rangle$, $\langle y \rangle$, and $\langle t \rangle$ only componentwise. Finally, if physical shifts Δx_1 and Δx_2 correspond to perceptual shifts ΔX_1 and ΔX_2, then $\Delta x_1 + \Delta x_2$ corresponds to $\Delta X_1 + \Delta X_2$. It follows from the MHP that perceptual shifts are proportional to physical shifts (for a given stimulus): e.g., $\Delta X = \phi_{xX} \Delta x$, where ϕ_{xX} generally depends on parameters of the stimulus being shifted, $\mathbf{l}(x, y, t)$. Another important consequence is that a uniform physical motion is mapped into a uniform perceptual motion along the corresponding axis. A light distribution $\mathbf{l}_s(x, y)$ moving with velocity v along the $\langle x \rangle$-axis can be presented as $\mathbf{l}(x, y, t) = \mathbf{l}_s(x - vt, y)$. According to the MHP it is mapped into $\mathbf{L}_v(X - VT, Y)$, i.e., a certain visual object $\mathbf{L}_v(X, Y)$ moving with a velocity V along the $\langle X \rangle$-axis. Index v in $\mathbf{L}_v(X, Y)$ indicates that the moving shape itself generally changes with motion velocity (due to a combined effect of geometric and distributional transformations).

If the perceptual frontoparallel metric were in a fixed correspondence with the physical metric (irrespective of stimuli perceived), the proportionality coefficient ϕ_{xX} would not depend on any stimulation parameters. It has indeed been shown that ϕ_{xX} does not depend on stimulation luminance/contrast and shape/size parameters. It has been found, however, that when a steady fixation is maintained, ϕ_{xX} is a decreasing function of motion velocity, v (the SCM effect). The function $\phi_{xX}(v)$ is well-defined because for any given velocity the ratio $\phi_{xX} = \Delta X(v)/\Delta x = \Delta X(v)/\Delta X(0)$ has been found constant for different values of $\Delta x = \Delta X(0)$ (for stationary stimuli ϕ_{xX} can always be put equal to 1). An important fact is that SCM does not occur in the direction orthogonal to the motion path: $\phi_{yY} = \Delta Y(v)/\Delta y = 1$ for all v.

1.2. *Velocity Determining SCM: Retinal, Objective, or Perceived*

The question arises whether maintaining a steady fixation is a necessary condition for SCM. Steady fixation is unnatural when viewing moving objects, as it requires a dissociation of the attention focus and the fovea ("phenomenal diplopia"). A natural tendency would be, of course, to follow, or to attempt to

[1] In this paper I follow the notation agreements adopted in Visual Kinematics I: uppercase and lowercase symbols will refer to perceptual and physical parameters and coordinates, respectively; boldface roman symbols denote vectors of parameters; angle brackets denote axes or frames of reference. The $\langle x \rangle$-axis in the physical plane and the $\langle X \rangle$-axis in the perceptual plane will always be assumed to be collinear with the direction of physical motion and perceived motion, respectively.

follow, the visually measured spatial intervals. The MHP, as a foundation of understanding SCM, is even more applicable to a free looking condition than to a steady fixation one. Indeed, the possibility to freely move one's gaze eliminates or minimizes the effect of retinal inhomogeneities that could cause violations of the MHP, at least for tiny spatial details.

In this paper experimental evidence will be presented that SCM indeed occurs under both steady fixation and free looking. For both observation conditions the amount of contraction increases with angular velocity defined in external coordinates (with respect to the observer's head). The relative contraction, $\Delta X(v)/\Delta x$, does not depend on Δx in either case, making the contraction coeficient ϕ_{xX} well defined. It will be shown that the dependence of ϕ_{xX} on v under the two observation conditions follows quantitatively similar patterns, but the effect is somewhat weaker under free looking. The effect can be made stronger by decreasing the distance between clearly visible screen borders (moving stimuli appear from behind one of the borders, uniformly move toward the other, and disappear behind it). For a given angular speed both switching from free looking to fixation and decreasing the width of the screen lead to an increase in perceived speed. I will discuss the hypothesis that it is the perceived velocity (rather than angular velocity defined in external or retinal coordinates) that determines the magnitude of SCM.

2. Experiments

2.1. *Double-Perturbation (2P) Paradigm*

The four experiments described in this paper were designed within the framework of the 2P paradigm introduced in Visual Kinematics I. Figure 1 (top) schematically presents the 2P stimuli used in these experiments: two identical rectangular luminance increments on a uniform background moving along their longer dimension with a common velocity (the appearance–disappearance mode is shown in the bottom of Fig.1). Application of the MHP to the 2P stimulation can be summarized in the following way. Two identical perturbations of a homogeneous luminance field moving identically except for a spatial shift should undergo identical distributional deformations, and therefore (if the perceptual metric is stimulation-independent) their spatial separation cannot be affected. If, contrary to this prediction, the separation changes in motion, then the only possible conclusion under the MHP is that the frontoparallel metric as such is different for moving and resting stimuli.

The parameters characterizing 2P stimulation should be clear from the figure (see Visual Kinematics I for a detailed discussion). Note that elevation and azimuth are defined only if a fixation point is present. In all experiments the dependent variable was an estimate of the perceived spatial seperation, ΔX, between two segments constituting a 2P stimulus. The estimates were made by adjusting the length of a stationary light segment to match ΔX.

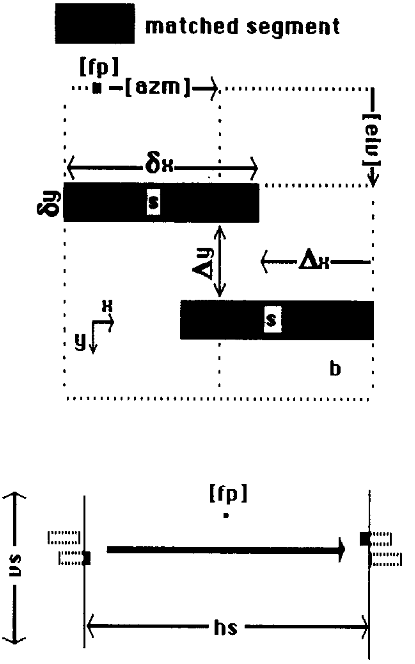

FIG. 1. 2P stimulation used in the experiments reported in this paper: fp, fixation point; azm, azimuth; elv, retinal elevation; $\delta x{:}\delta y$, shape parameters; $s{:}b$, contrast parameters; $\Delta x{:}\Delta y$, shift parameters; hs:vs, screen size parameters. fp, azm, and elv are enclosed in brackets because they are not defined in free looking experiments. The bottom panel schematizes the "gradual" appearance–disappearance mode of presentation used.

The experiments were carried out under two observation conditions: fixation, when a fixation point was constantly present and required to fixate; and free looking, when no fixation point was present and the observers were asked "to look freely" at the estimated spatial intervals in motion. In both cases viewing was binocular, and the observer's head was fixed in a chin rest with a forehead support.

2.2. *Stimulation Parameters and Procedure*

The following parameters' values will be referred to as "standard": $\Delta y = 1.2°$, $\delta x{:}\delta y = 12.9°{:}0.5°$; $s{:}b = 30\ \text{cd}\cdot\text{m}^{-2}{:}3\ \text{cd}\cdot\text{m}^{-2}$; hs:vs = 36.8°:10.7°; elv = 1.0° (when fixation was maintained). Within an experiment the parameters that were not varied as an independent variable had standard values. In all four experiments the velocity varied at seven levels from 22.1°/s to 86.4°/s; motion direction was always from left to right.

In all experiments the adjustments of the stationary length segment (match-estimates) were made after a moving 2P stimulus had been presented four times in brief succession. Trials were initiated by the experimenter after a warning signal. All observation and stimulation conditions varying within an experiment were used in a randomized order, with the total of 20 match-estimations per condition.

Only free looking was used in Experiments 1, 2, and 4; in Experiment 3 the two observation conditions, free looking and steady fixation, were randomly alternated.

In Experiment 1 Δx varied at three levels: 2.4°, 4.1°, and 5.0°. In Experiment 2 Δx was fixed at 4.1°, but the lenght of the segments themselves, δx, varied at three levels: 5.7°, 12.9°, and 21.0°. In Experiment 3 the varied parameter (in additon to the observation condition) was Δx, as in Experiment 1, but in a more narrow range: 2.5°, 3.2°, and 4.1°. Finally, in Experiment 4 Δx was fixed at 4.2°, and the varied parameter was the horizontal screen size (hs): 4.5°, 9°, and 18°.[2])

2.3. *Observers*

Seven observers with normal or corrected-to-normal acuity participated in the experiments: participation in a given experiment is indicated in the plots of individual data. All observers, except for KVL, were naive to the aims and designs of the experiments.

3. SCM: Free Looking versus Fixation

3.1 *Existence and Basic Properties of the Effect*

Figures 2 and 3 show the results of Experiments 1 and 2, in which no fixation point was present and the observers were allowed to look at the display in a natural way. The match-estimates of $\Delta X(v)$ for every value of angular velocity v have been normalized by the physical value of Δx (which varied in Experiment 1, but was constant in Experiment 2). This is equivalent to normalizing by $\Delta X(0)$, the perceived separation at rest. In these and other figures throughout this paper, vertical bars attached to a symbol show ± 1 standard devation averaged over all conditions represented by this symbol. The averaging of standard deviations leads to little information loss, because the variability shows only weak and nonsystematic dependence on stimulation parameters. Ignore for now the theoretical curves; they will be discussed in Section 3.2.

The most important finding in Figs. 2 and 3 is that *the normalized ΔX-estimate, $\Delta X/\Delta x$, monotonically decreases with velocity, v.* The effect is very robust: the amount of contraction reaches 70% as v approaches 90°/s. One should conclude, therefore, that *steady fixation is not a necessary condition for SCM.* Considerable contraction occurs even at $v = 20$–40°/s, which is low enough and lasts long enough (about 1 s or more) to be smootly pursued (Robinson, 1965; Westheimer, 1954). Although eye movements have not been recorded in these experiments, it is well

[2] The experimental setup (an optical–mechanical system) will not be described here, because it has been done in detail in Visual Kinematics I (Experiments 8 and 9f of that paper). Experiment 9f of Visual Kinematics I is in fact the steady fixation part of Experiment 3 of the present paper.

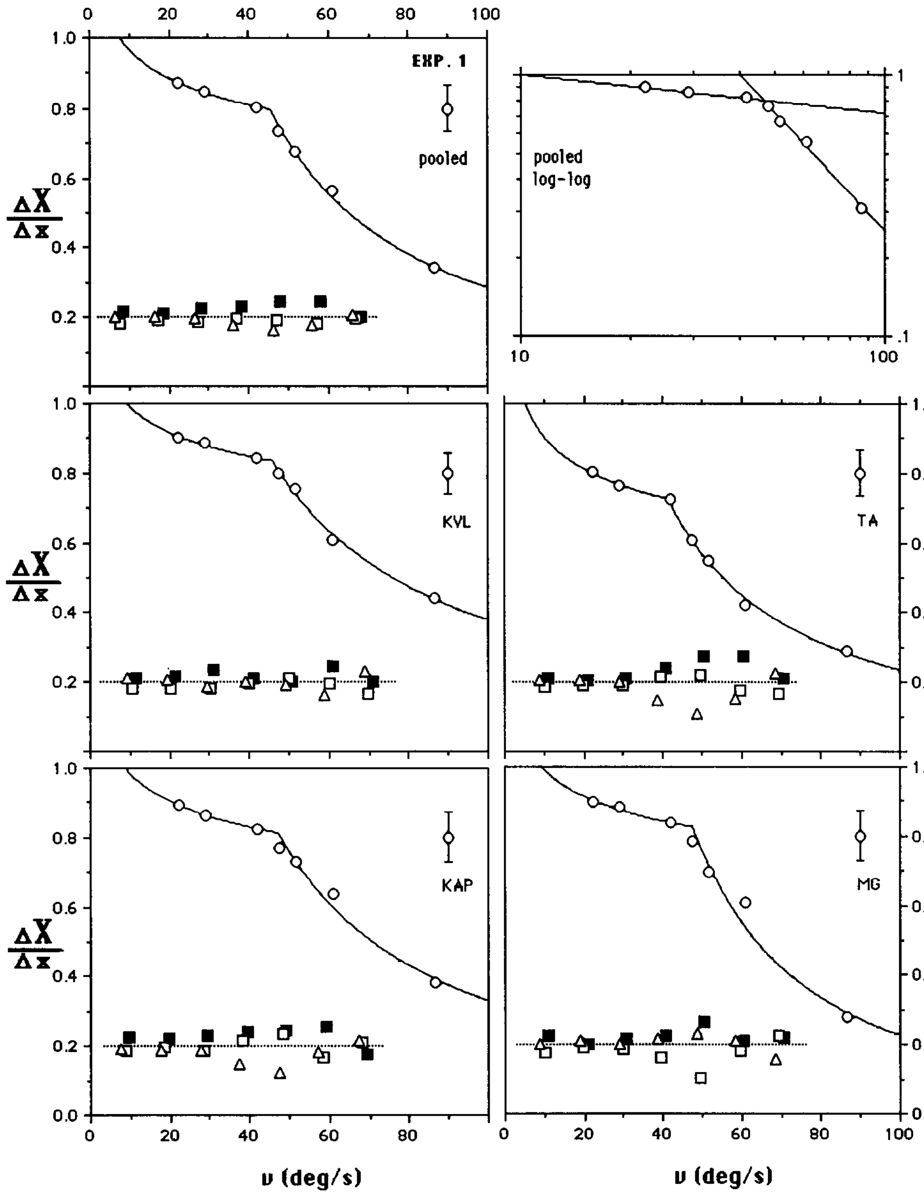

FIG. 2. ΔX (match-estimation), in units of Δx, as a function of angular velocity and Δx. Free looking. In individual plots circles represent 60 estimates (20 estimates per Δx). Theoretical line is described by Eq. (1). (See Appendix for details of data pooling and fitting procedure.) Inset: each triad of symbols (■, □, △) corresponds to one of the seven values of v used in the experiment (in increasing order from left to right); vertical deviation of the symbols from the horizontal line equals the difference between the means computed separately for the three Δx-values (5.0°, 4.1°, and 2.5°, respectively) and their grand mean. Vertical positioning of the inset is arbitrary.

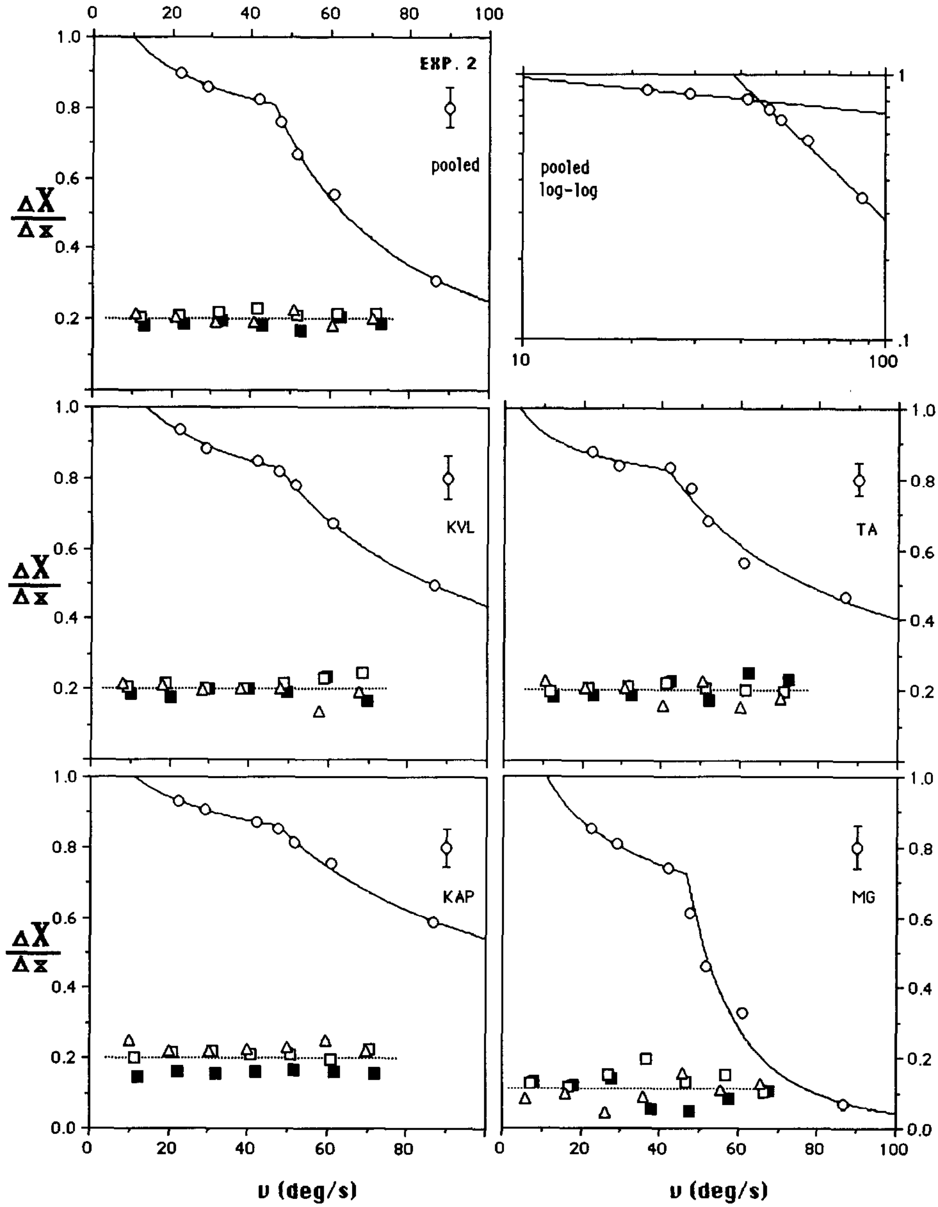

FIG. 3. ΔX (match-estimation), in units of Δx, as a function of angular velocity and δx. Free looking. In individual plots circles represent 60 estimates (20 estimates per δx). The rest of the information is the same as that in Fig. 2, except that ■, □, and △ correspond now to the three δx-values 21.0°, 12.9°, and 5.7° respectively.

known that under free looking one would tend to pursue the object to which one attends (Yarbus, 1967). In fact it takes training and effort not to pursue when a steady fixation is required. It is not likely then that the existence and magnitude of the SCM effect are determined by retinal velocity. Recall from the descriptions given in Sections 2.1 and 2.2 that there was little spatial, temporal, or directional uncertainty in these experiments: motion was always from left to right along the same horizontal line and was repeated four times at regular intervals. Therefore effective pursuit could be possible for much higher velocity than 20–40°/s (Barmack, 1970; Hallett, 1986).

Another important result (Fig. 2, insets) is that, as for steady fixation, *$\Delta X/\Delta x$ is approximately constant for different values of Δx at all velocities.* For each velocity, the three symbols in the insets represent mean deviations of $\Delta X/\Delta x$ for three different values of Δx from their grand mean: the horizontal line represents a zero devation. Obviously, the deviations are very small compared to the magnitude of the SCM effect. For the largest of the three Δx-values used, 5.0°, $\Delta X/\Delta x$ tends to exceed slightly the two other normalized estimates, but its deviation from the mean computed over all three values is negligible. There is no such trend (decrease in $\Delta X/\Delta x$ with increasing Δx) for two smaller values of Δx, 4.1° and 2.4°. (Even for values exceeding 5° this tendency could not be replicated in an informal, but extensive series of observations using the numeric magnitude estimation procedure.) In any case, $\Delta X/\Delta x$ does not exhibit any robust dependence on Δx, corroborating thereby the MHP as a reasonable approximation (the proportionality between Δx and Δx for any v and other stimulation parameters is one of the major consequences of the MHP; see Section 1.1).

The values of δx used in Experiment 2 (Fig. 3, insets) were much larger than those used in the experiments reported in Visual Kinematics I, but the results presented in the insets of Fig. 3 are essentially the same: with one exception (observer KAP) there is no monotonic tendency in the dependence of $\Delta X/\Delta x$ on δx, and the deviations from the means computed over all three values of δx are very small compared to the size of the SCM effect. These results corroborate the earlier conclusion that *SCM cannot be induced by changes in the apparent size of the constituting segments* (contrast or assimilation illusions; see Visual Kinematics I for a detailed discussion). The monotonic trend seen in the results of observer KAP is too small to alter this conclusion: as δx increases from 5.7° to 21.0°, the normalized estimate, $\Delta X/\Delta x$, decreases by only 0.07. The results of this observer indicate, however, that a "contrast illusion" can sometimes be involved in ΔX-estimations as a biasing factor. Note that the bias is approximately constant for all velocities and, very probably, would be present even at $v = 0$.

3.2. *Regularity of the SCM Dependence on Angular Velocity*

Inspection of Figs. 2 and 3 shows inter-individual differences in the amount of contraction, especially at higher velocities. There are also considerable quantitative differences between the results of a single observer in the two experiments—which raises an important problem to be discussed separately (Section 4.2). At the same time, a certain pattern of the $\Delta X/\Delta x$ versus v curves is the same for all observers in all experiments. Namely, *when* $\log(\Delta X/\Delta x)$ *is plotted against* $\log(v)$, *the curve clearly consists of two linear parts, with a transition point lying between* 40°/s *and* 50°/s (Figs. 2 and 3; top right). The absolute value of the slope is considerably smaller below than above this point. The first, slowly descending, straight line when extrapolated into the region of still smaller velocity values, intersects with the no-contraction horizontal, $\Delta X = \Delta x$, at a velocity between 5°/s and 15°/s. The assumption that between this value and zero there is no SCM effect is consistent with my informal observations. One cannot exclude, however, that the slowly descending part of the curve changes into a region of even slower decrease at some point below 20°/s. In any case, the following formula can be proposed as an empirical approximation for the dependence of ϕ_{xX} (estimated by $\Delta X/\Delta x$) on v:

$$\phi_{xX}(v) = \begin{cases} 1 & \text{if } v < v_0 \\ (v_0/v)^\alpha & \text{if } v_0 < v < v_1 \\ (v_1/v)^\beta (v_0/v_1)^\alpha & \text{if } v > v_1, \end{cases} \tag{1}$$

where $v_0 \approx 10°/\text{s}$, $v_1 \approx 45°/\text{s}$ (transition points), $\alpha < \beta$ are the (absolute values of the) slopes of the two linear parts (in log–log coordinates). In the following text the three velocity intervals of (1) will be referred to as the low, medium, and high velocity regions. As indicated above, the value of v_0 is estimated by extrapolating the medium region curve until it reaches the no-contraction level; it is not based on direct measurements. I emphasize that (1) is an empirically observed regularity, rather than a theoretical deduction: it is consistent with but cannot be derived from the MHP or the kinematic theory presented in Visual Kinematics III (Dzhafarov, 1992b). It will be shown below that there is one additional restriction imposed on the dependence: constancy of the β/α ratio for a given observer (and, possibly, even between observers).

With very few exceptions (attributable to obvious outliers or to very small $\Delta X/\Delta x$-values; see Appendix) the theoretical approximations shown in this paper pass conventional goodness-of-fit tests. I do not report this information, however, because it hardly proves anything (except, probably, that I did not collect enough data to achieve statistical rejection). This paper focuses on *robust* dependencies exhibiting certain *obvious* regularities, the emphasis being on "robust" and "obvious." Weak dependencies and small deviations from theoretical curves that can be established only by statistical means are of little interest at this stage of analysis.

3.3 *Velocity in Retinal and External Coordinates*

It was mentioned above that the existence of SCM under free looking ,especially at velocities below 40°/s, makes it unlikely that the effect depends on retinal velocity. The simplest alernative is that SCM is uniquely determined by velocity with respect to the observer's head, in external coordinates. This hypothesis implies that the SCM effect is associated with a stage of visual processing at which the eye movement vector has been added to the retinal motion vector, thus "restoring" the objective angular velocity of a moving light distibution. As a result, the SCM magnitude should not depend on the eye movements pattern.

Experiment 3 (Fig. 4) shows this prediction to be wrong. In this experiment the trials with steady fixation were randomly alternated with those in which the observer was allowed to look freely and pursue the moving stimuli: the type of a trial was indicated by the presence or absence of the fixation point before the trial. In addition, Δx varied on three levels in a completely randomized design.

Considered separately for the two observation conditions, the results agree with those obtained in the previously discussed experiments. First, as the insets show, $\Delta X/\Delta x$ does not depend on Δx under either observation condition. Second, in both

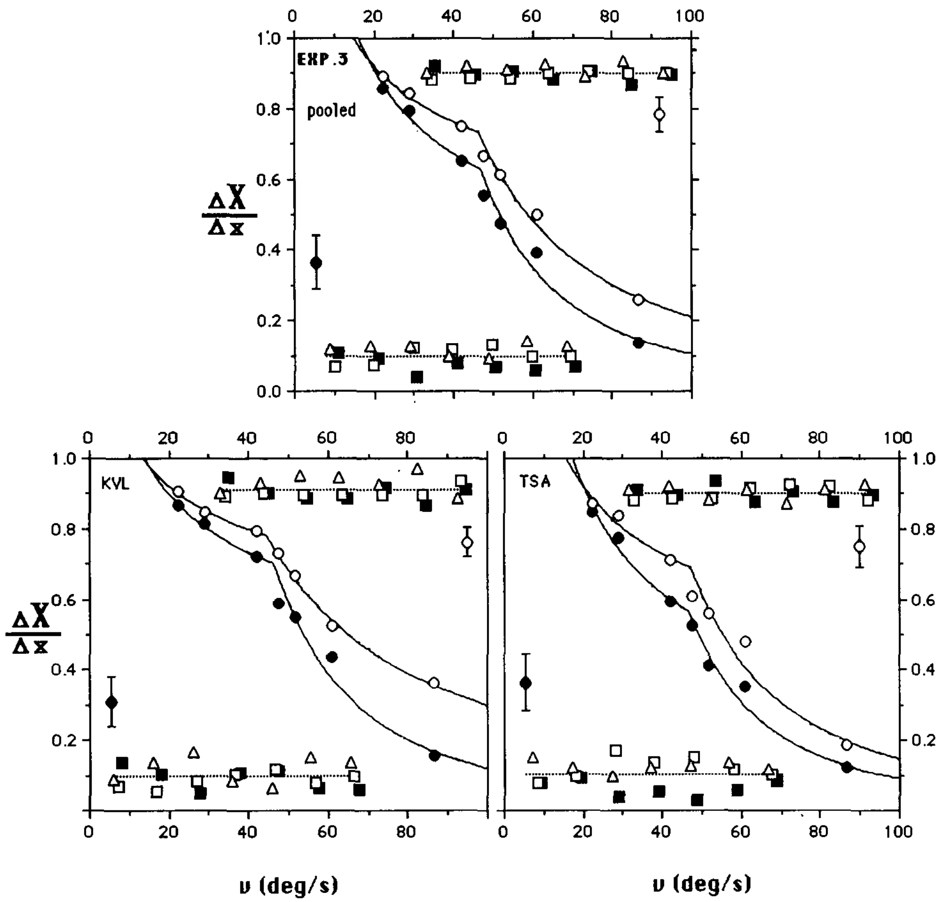

FIG. 4. ΔX (match-estimation), in units of Δx, as a function of angular velocity and Δx under fixation (●) and free looking (○). The rest of the information is the same as that in Fig. 2, except that the three Δx-values represented by symbols ■, □, △ are 4.1°, 3.2°, and 2.5°, respectively.

cases the dependence of $\Delta X/\Delta x$ on v can be reasonably well approximated by (1), with the transition points, v_0 and v_1, being practically indentical for the two curves and close to the values found in the previous experiments. The two curves, therefore, do not differ qualitatively. However, in disagreement with the objective velocity hypothesis, the two curves do not coincide: for all velocity values *the SCM effect is more pronounced under steady fixation than under free looking.* Mathematically this means that exponents α and β in (1) increase when switching from free looking to fixation (since v_0 and v_1 do not change). SCM, therefore, is not independent of eye movements.

One might suggest that after all it is retinal velocity that determines the magnitude of the SCM effect: thus, the effect is smaller under free looking due to imperfect tracking that reduces retinal velocity. For any angular velocity, v, this reduction (i.e., the eye velocity) can be found by the following algorithm: (first) find the $\Delta X/\Delta x$-value corresponding to v on the free looking curve; (second) find velocity v' corresponding to this $\Delta X/\Delta x$-value on the fixation curve; (third) take the difference between v and v'.

Actual computations yield the obviously unrealistic dependence of the eye velocity on v shown in Fig. 5. For one thing, nothing known about eye movements explains why the eye velocity should be practically zero for velocities close to 20°/s, and why the tracking attempts decrease between 40°/s and 60°/s and increase again for the higher velocities. But the most unrealistic feature of the curves is that the slopes of their descending parts and their local minima are precisely adjusted to make the break points on the curves of Fig. 4 correspond to the same angular velocity value (v_1). It is easy to see that any reasonably smooth dependence of the eye velocity on v would imply a horizontal, rather than a vertical, alignment of the break points.

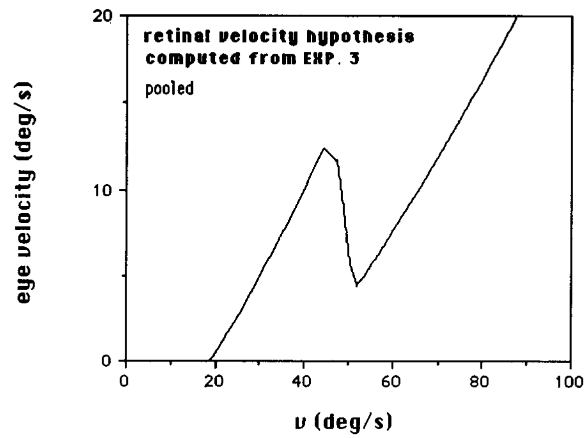

FIG. 5. Eye velocity computed from the data of Fig. 4. according to the hypothesis that SCM is determined by retinal velocity.

The conclusion is that neither the objective velocity hypothesis nor the the retinal velocity hypothesis can account for the dependence of SCM on v under steady fixation and free looking.

3.4. *Perceived Velocity Hypothesis* (*PVH*)

A different way to account for both the qualitative similarity and the quantitative difference of the two curves of Fig. 4 is suggested by the following short demonstration experiment (conducted with three observers). A 2P stimulus moving with a given angular velocity was repeatedly presented with a fixation point either switched on (with instruction to fixate) or switched off (with instruction to look freely): a marked increase in perceived velocity under steady fixation was indicated for all angular velocities ranging from 20°/s to 80°/s (the observers were asked to assign the ranks, from 0 to 100, to the perceived velocities: in both cases the curves for fixation lie above those for free looking). If when allowed to look freely the observers pursue the moving stimuli, then this effect is a variant of the classical Aubert–Fleischl phenomenon (Brown 1931; Mack & Herman, 1972, 1973; Dichgans, Wist, Diener, & Brandt, 1975). As far as I know, however, it has not been determined how effective and smooth a pursuit movement should be to produce the effect. One cannot exclude the posibility that the lack of fixation as such, or even of fixation effort, is sufficient to decrease the perceived velocity. This question, however, as interesting and important as it is, does not bear on the major issues analyzed in this paper: here the effect will be taken simply as an emperical fact, without discussing its possible causes.

One is naturally led to the hypothesis that stimulation/observation parameters that increase the SCM effect, i.e., decrease $\Delta X/\Delta x$ in a 2P stimulus, should also increase its perceived velocity. This is trivially true for the angular velocity, v, as one such parameter, but for a given v the perceived velocity, V, can vary as a function of other parameters, one of which has been just considered (free looking versus fixation).

One other way to increase V for a fixed v is to decrease the horizontal distance, hs, between the screen borders (see Fig. 1). This effect in closely related to, if not identical with, a variant of J. F. Brown's classical "transposition effect" (Brown, 1931), but again it will be taken as an empirical fact only, without discussing its possible mechanisms. Nor it is necessary to accept here the validity of Brown's original velocity matching measurements that led to the idea of "transposition." The screen size effect is very robust, and for velocities between 20°/s and 80°/s it was confirmed in a short demonstration experiment (three observers, rank-ordening) analogous to the one just described for fixation versus free looking.

The results of Experiment 4, in which V was manipulated by means of the screen size effect, are presented in Fig. 6. The screen size, hs, varied on three levels used in random order: 18°, 9°, and 4.5°, i.e., the largest size was about half that used in all other experiments (36.8°).The total horizontal extent of the 2P stimuli used in this experiment (see Fig. 1), $\Delta x + \delta x$, was $4.2° + 12.9°$, so for the two lower values of hs a stimulus has been partially occluded at any moment of physical time. The

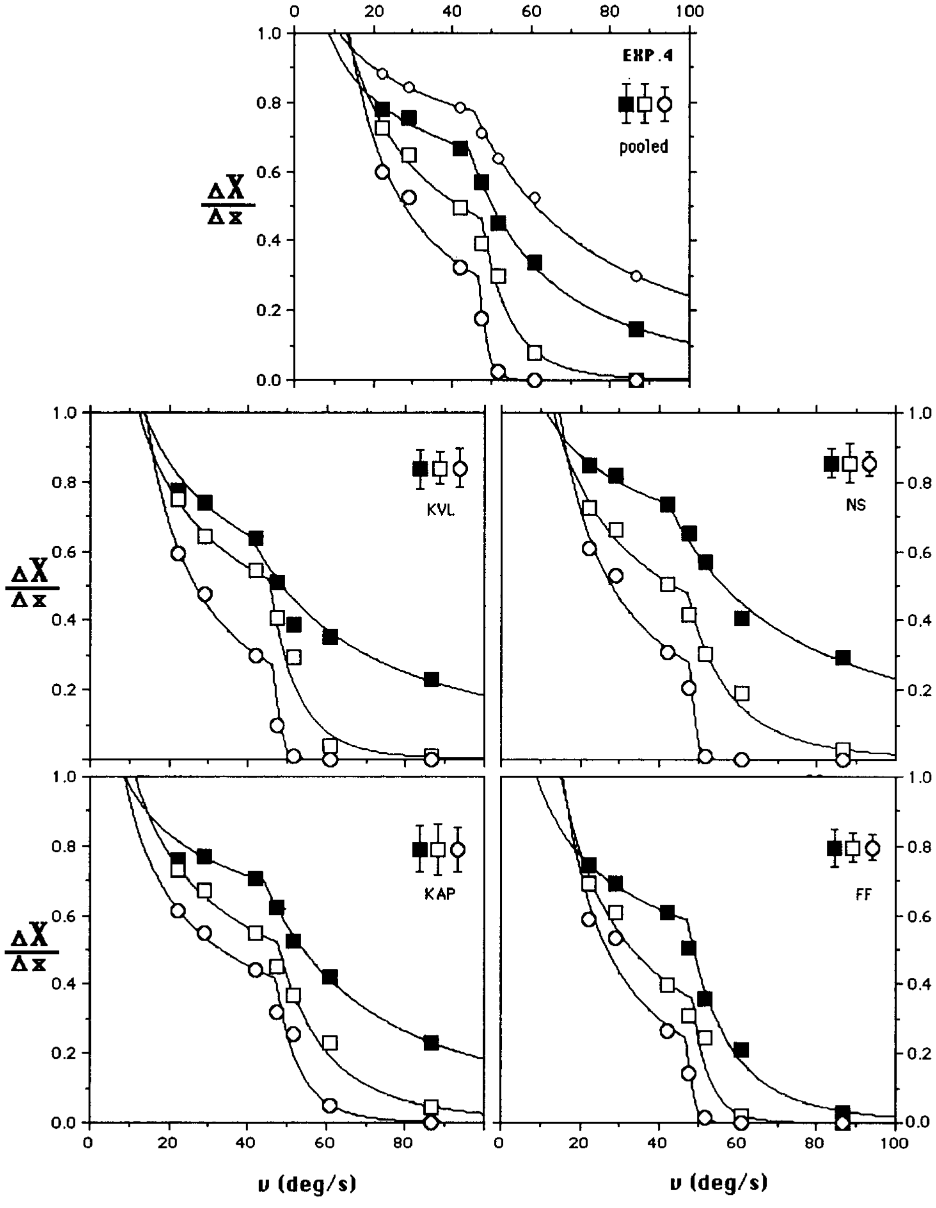

FIG. 6. ΔX (match-estimation), in units of Δx, as a function of angular velocity for the three screen size values, hs: 18° (■), 9° (□), and 4.5° (○). Free looking, 20 estimates per symbol (in individual plots). The circles in the panel for pooled data represent ΔX-estimates pooled over all experiments with free looking and standard screen size, 36.8°: Experiments 1 + 2 + 3 (free looking) + one experiment reported in Visual Kinematics III.

results show that the effect of hs on SCM is very strong and qualitatively agrees with the assumption that SCM is related to perceived velocity: for a given v the contraction effect is more pronounced for a narrow screen. All three curves are below the corresponding values of $\Delta X/\Delta x$ obtained with the standard screen size (36.8°). An important fact is that the three curves exhibit the same qualitive pattern found in the previous experiments, although the fit of (1) is somewhat worse than before (most probably because very small values of $\Delta X/\Delta x$ are involved). The transition points, v_0 and v_1, are practically identical and close to the values found in the previously discussed experiments. Again, in terms of (1), the SCM increase with decreasing hs means an increase in the values of exponents α and β.

In Fig. 7 the results of Experiment 4 have been plotted against the exposure time values, τ, computed as the time during which the frontal edges of both constituting segments were simultaneously between the borders: $(\text{hs} - \Delta x)/v$. This figure confirms the conclusion arrived at in Visual Kinematics I that *SCM is not determined by exposure time*: one and the same value of $\Delta X/\Delta x$ in the three curves corresponds to very dissimilar values of τ.[3]

The experiments considered in this and the preceding paper of the Visual Kinematics series show that a number of parameters that influence the appearance of moving 2P stimuli, such as shape/size and luminance/contrast, do not affect ϕ_{xX}, the proportionality coefficient between ΔX and Δx. At the same time, it was phenomenologically obvious that these were the parameters whose variation did not cause noticeable changes in perceived velocity. Experiments 3 and 4, on the contrary, deal with variations in stimulation/observation parameters that do affect perceived velocity, and these parameters were found to affect ϕ_{xX} as well. The Perceived Velocity Hypothesis (PVH) is a generalization of these findings: *for a given v, changes in stimulation/observation parameters increase SCM only if they increase the value of V.*

The perceived velocity increase is stated here as a necessary, but not sufficient, condition. This paper provides no proof for the statement that V cannot change without the magnitude of SCM being changed, and it does not follow from (although is not excluded by) the general kinematic theory presented in Visual Kinematics III. Nor does it follow from the PVH that SCM depends on V exclusively, irrespective of the value of v. Consider, for example, two motions with angular velocities v' and v'', presented on screens of sizes hs′ and hs″, respectively, all other parameters being equal. If $v' > v''$ and hs′ = hs″, then SCM is more pronounced for v' (and $V' > V''$). If now hs″ decreases, then, according to the PVH, the SCM effect for v'' increase (and so does V''). What the PVH does not state (but does not exclude either) is that when hs″ is sufficiently small to make the two perceived velocities, V' and V'', equal, then the corresponding SCM magnitudes must be equal too.

[3] Extremely short exposure time values, however, certainly increased the difficulty of the task. This in turn could have led the observers to adopt certain guessing strategies, when in doubt, that suppressed variability but also might have introduced biases in match-estimations.

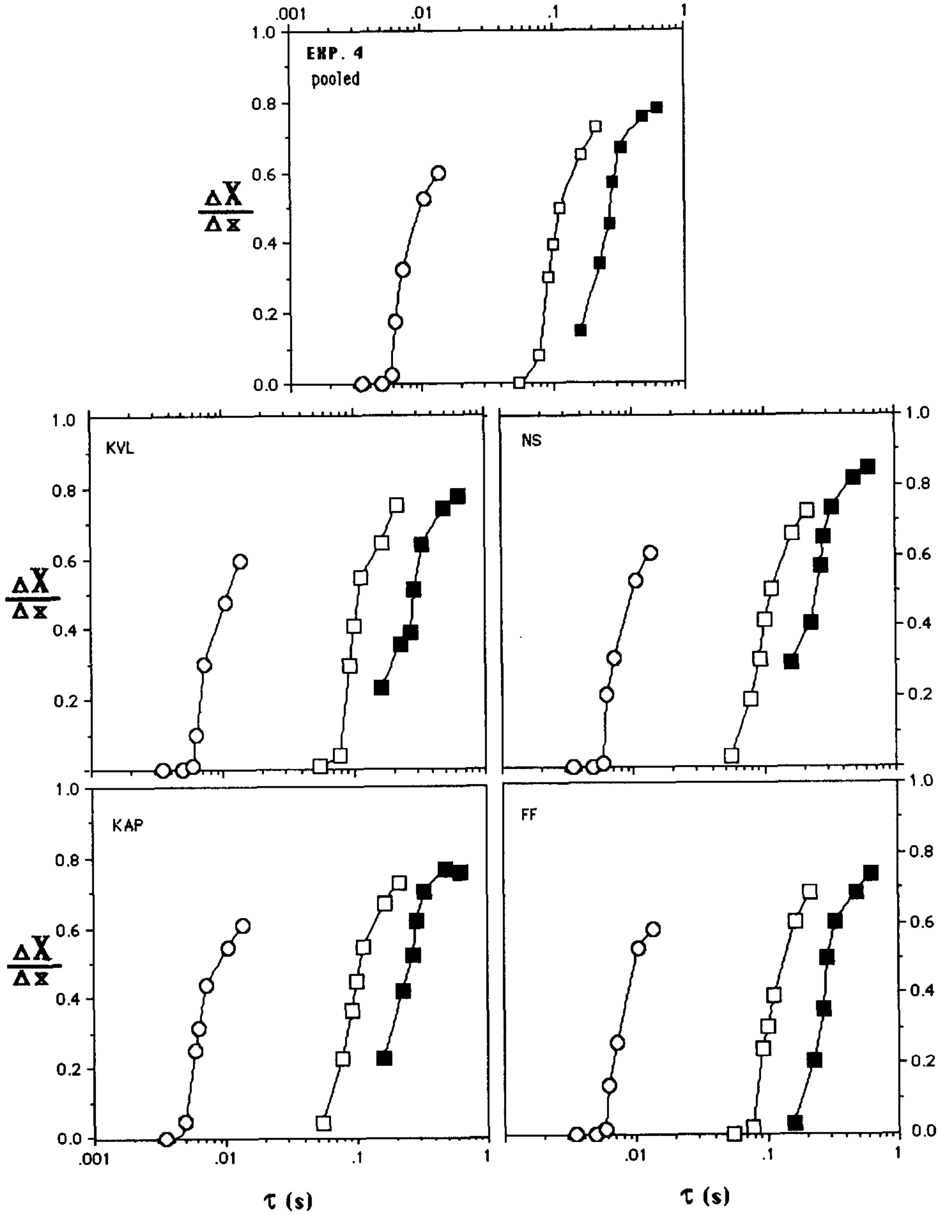

FIG. 7. $\Delta X/\Delta x$ from Fig. 6 replotted against exposure time: $\tau = (\text{hs} - \Delta x)/v$.

4. PVH: Versions and Consequences

4.1. *"Absolute" and "Relative" Versions of the PVH*

The PVH can be concretized in several different ways, the simplest two of which will be considered here. Irrespective of whether one of these variants constitutes an optimal model, it is important to demonstrate the very possibility of representing the dependence of SCM on V in metrical terms. The preceding discussion dealt with perceived velocity as an ordinal-scale concept only: it was sufficient to assume that (for a given v) any two values of V could be compared in terms of "greater than" or "equal to."

The first version is based on the radical assumption that SCM depends on V exclusively:

$$\phi_{xX}(v, \mathbf{p}) = \phi_{xX}(V), \tag{2}$$

where $\mathbf{p}$ is the vector of stimulation/observation parameters, other than v, that might affect V.

Equation (2) means the following when applied to Figs. 4 and 6. First, any two points lying on different curves, but on the same horizontal level (below 1), correspond to a single value of V. Second, V_0, the perceived velocity at v_0, is approximately constant for different curves. Formally, these requirements can be trivially satisfied by assuming that for $v > v_0$ in (1), $1/\phi_{xX}(v)$ is a fixed monotonic transformation of the psychophysical function $V(v)$. Denoting this transformation by $F(V)$, (1) can be rewritten as

$$\phi_{xX}(V) = \begin{cases} 1 & \text{if} \quad F(V) < 1 \\ 1/F(V) & \text{if} \quad F(V) \geq 1 \end{cases} \tag{3}$$

which, obviously, agrees with (2). Exponents α and β enter into this formula latently as parameters of the psychophysical function that change depending on experimental conditions; v_0 and v_1 also enter into this formula latently, as constants characterizing the psychophysical function.

This simple version of the PVH encounters at least two difficulties. First, there is no evidence that the course of the psychophysical function, $V(v)$, changes abruptly around 10°/s and 45°/s (abrupt change meaning a step increase in the first dervative). To derive (1) from (3), one would have to assume that the perceived velocity scales reported in the literature (Aglom & Cohen-Raz, 1984, 1987; Caelli, Hoffman, & Lindman, 1978, data; Ekman & Dahlbäck, 1965; Mashour, 1964) have a built-in compensation for the abrupt changes occurring in the true perceived velocity function. This assumption seems somewhat ad hoc, even though the "subjective magnitude scales" are indeed probably only monotonic transforms of true psychophysical functions (Poulton, 1979; Gescheider, 1988). The second difficulty is associated with the implied constancy of V at $v = v_0$. Although some evidence does exist that the Aubert–Fleischl effect virtually disappears at velocities below 10–15°/s (Dichgans *et al.*, 1975), the effect in this region has been reported by other investigators (Mack & Herman, 1972, 1973). Brown (1931) also reported his "transposition" effect for angular velocities below 10°/s.

The second version of the PVH to be considered does not lead to these problems, and it more naturally arises from the empirical regularity expressed by (1). Moreover, it introduces one additional restriction on shape of the SCM curves, which will be shown to agree with empirical data. In this version (2) is replaced with the more general formula

$$\phi_{xX}(v, \mathbf{p}) = \phi_{xX}(V, V_0, V_1), \tag{4}$$

where V_0 and V_1 correspond to angular velocities v_0 and v_1, respectively, and both V_0 and V_1 need not be invariant with respect to different stimulation/observation conditions. Put differently, in the visual computations of spatial intervals in motion, the perceived speeds corresponding to v_0 and v_1 serve as fixed "reference" values even though their numerical values can differ under different conditions. Due to this interpretation, this version of the PVH will be referred to as "relative" (the preceding version then can be called "absolute"). The relative PVH implies that a representation of the angular velocity is not lost at the perceived velocity level, at least in the sence that a perceived motion is identified as belonging to one of the three angular velocity regions separated by the fixed transition points, v_0 and v_1.

Assume now that

$$F(V) = \lambda v^{\alpha}, \tag{5}$$

where F is a fixed monotonic transformation, and α (and, probably, λ) may change depending on stimulation/observation conditions (but not v). Equation (1) then can be written as

$$\phi_{xX}(V, V_0, V_1) = \begin{cases} 1 & \text{if } V < V_0 \\ F(V_0)/F(V) & \text{if } V_0 < V < V_1 \\ [F(V_0)/F(V)]^{\Phi}\, F(V_0)/F(V_1) & \text{if } V > V_1, \end{cases} \tag{6}$$

where Φ is a fixed constant (Φ must be invariant with respect to changes in stimulation/observation conditions if SCM is to depend on these conditions exclusively through their effect on perceived velocity). Exponents α and β of (1) equal, respectively, α and $\alpha\Phi$ in (5) and (6).

It follows that for any given $v > v_0$, if V increases through an increase in α, the magnitude of SCM increases too. The magnitude of SCM will not change, however, if α is constant and V increases through an increase in λ. An increase in V, therefore (for a given v), is a necessary but not sufficient condition for an increase in SCM (it becomes a sufficient condition, of source, if one assumes that λ is a fixed constant). Another consequence of the relative PVH is that under different experimental conditions (e.g., different curves in Figs. 4 and 6) a given SCM level will generally corespond to different values of perceived velocity.

To appreciate the difference between the two versions of the PVH, absolute and relative, consider their predictions associated with induced motion and motion aftereffect (Dunker, 1929; Mack, 1986; Sekuler, 1975; Wolgemuth, 1911). According to the absolute version, SCM can occur if a 2P stimulus, stationary or moving with velocity $v < v_0$, is placed within a frame or on a structured background moving in the opposite direction, or if the 2P stimulus is viewed after a prolonged observation of an opposite-direction motion. It is only required that the resulting perceived speed is sufficiently high, so that in (3) $F(V) > 1$. According to the relative PVH no such experimental manipulation can induce SCM in the low-velocity region, $v < v_0$, because the value of V will remain below V_0.[4]

4.2. *Power Relationschip between Different SCM Curves*

It follows from (5) and (6) that all variability in the SCM magnitude is due to changes in α and that the empirically observed β/α ratio should be approximately constant across different conditions (because it equals Φ). The invariance of the β/α ratio implies that any two SCM curves within one experiment should be power transforms of each other, with a single exponent over the entire velocity range:

$$\phi'_{xX}(v) = \{\phi''_{xX}(v)\}^{\kappa}, \tag{7}$$

where the proportionality coefficients, ϕ'_{xX} and ϕ''_{xX}, correspond to two different stimulation/observation conditions, e.g., two values of hs, or the fixation and free looking conditions. Equivalently, two or more SCM curves should be power transforms of a single variable (which for symmetry can be chosen to be the geometric mean of the curves). That this indeed is the case for the two observation conditions of Experiment 3 is demonstrated in Fig. 8a. Only pooled data are shown, but the pattern is the same for both observers considered separately.

For Experiment 4, due to the very small values of $\Delta X/\Delta x$ obtained for the two highest velocities at hs $= 9°$ and the three highest velocities at hs $= 4.5°$, the power relationschip couls not be demonstrated as convincingly as for Experiment 3. Nevertheless, given the huge differences between the values of α and β in the curves for 9° and 4.5° (Fig. 6), the approximation shown in Fig. 8b for pooled data is reasonably good. For individual data the quality of approximation is comparable.

In Experiments 3 and 4 changes in the values of α or, equivalently, the values of V_0 and V_1, determining α through (5), have been induced by deliberate experimental manipulations. It is natural to suppose that being susceptible to such manipulations, α can also vary "spontaneously," e.g., due to differences in the observer's visual motion experiences prior to an experiment. This variability could lead to quantitative differences in the SCM magnitude even if a single observer is repeatedly tested under similar conditions. Such differences, for example, clearly

[4] I could not see SCM in a small stationary 2P stimulus placed eccentrically on a large radially striped rotating disk, even though the induced motion effect was compelling. A systematic study is needed, however, to ensure that the induced speed is sufficiently high. I am gratful to J. Mapeli and an anonymous reviewer for discussing the issue of illusory motion in relation to SCM.

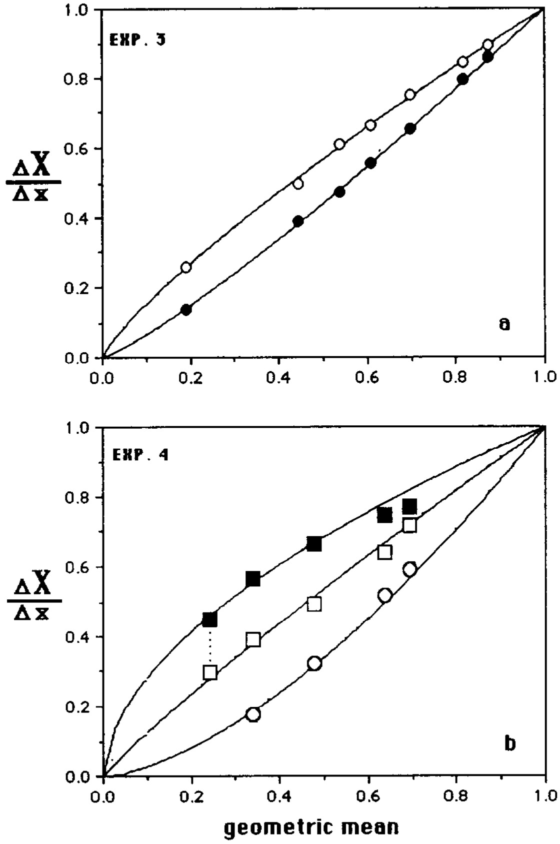

FIG. 8. (a) Pooled $\Delta X/\Delta x$ for fixation (●) and free looking (○) from Fig. 4 plotted against their geometric mean. (b) Pooled $\Delta X/\Delta x$ for the three hs-values from Fig. 6 plotted against their geometric mean. (See Appendix for explanations concerning very small values and the horizontal positioning of the two symbols connected by the dotted line.)

exist between Experiments 1 and 2 (Figs. 2 and 3). If they are indeed due to variability in α, then the results obtained in the two experiments for any given observer should be power transforms of each other, (7).

Figure 9 demonstrates this relationschip for all observers who participated in more than one experiment. Although for some observers the experiments were separated by intervals up to several months, the conformity with the predicted power-function relation is very good. One can conclude that the basic structure of the SCM effect, (6), is stable for any given observer, in contrast to a considerable (but uniparametric) variability in the psychophysical function for perceived velocity, (5).

Figure 10 shows that $\Phi = \beta/\alpha$ is relatively stable both across different experiments/conditions and across different observers. The theoretical curves in this

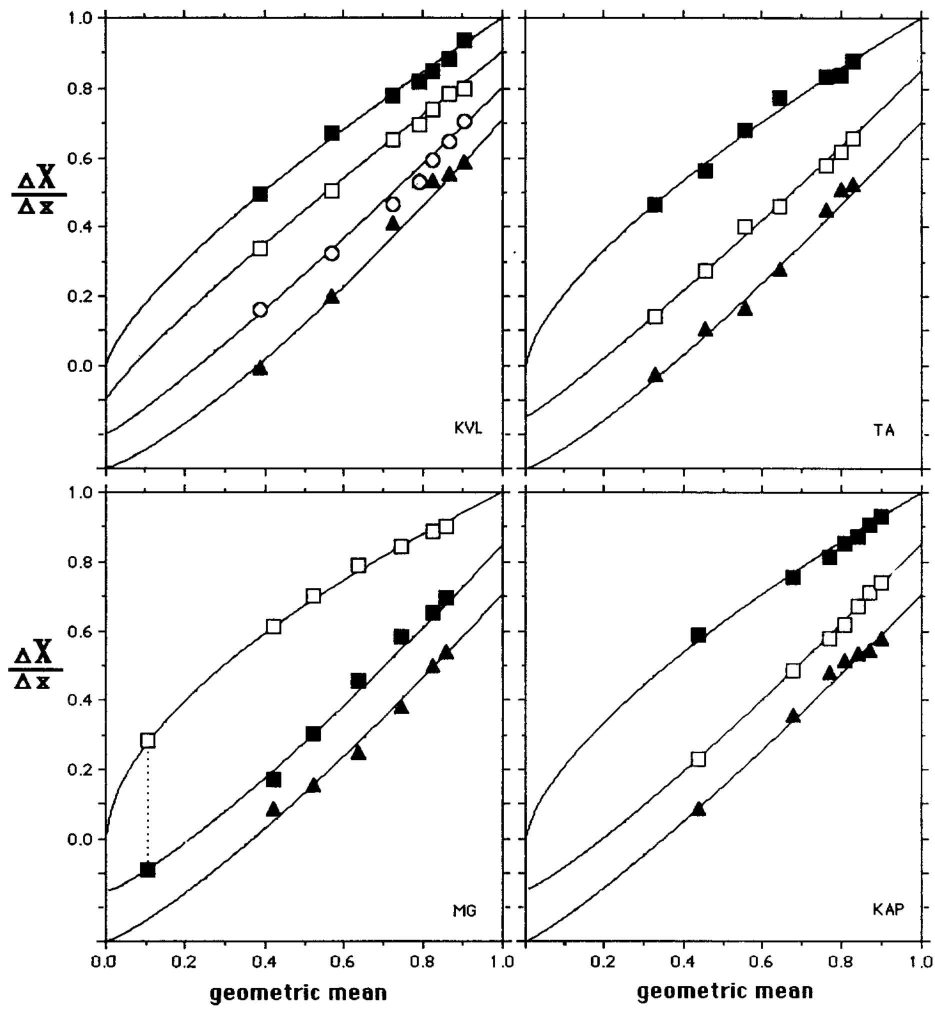

FIG. 9. SCM curves (individual data) obtained in different experiments with free looking and standard screen size, plotted against their geometric mean for each observer who participated in more than one experiment. The curves are vertically shifted for better readability. Symbols □, ■, and ○ represent Experiments 1, 2, and 3 (free looking). Symbol ▲ represent the 2P part of an experiment described in Visual Kinematics III.

figure are obtained by simultaneously fitting (5) and (6) to eight sets of experimental data. Put differently, the fitted equation is (1) with the following constraints: $\Phi = \beta/\alpha = \text{const}$; $v_0 = \text{const}$; and $v_1 = \text{const}$. Note that none of these constraints was explicitly imposed on the curves in Figs. 2, 3, 4, and 6; for instance, the approximate constancy of v_0 in those figures is an empirical fact found by

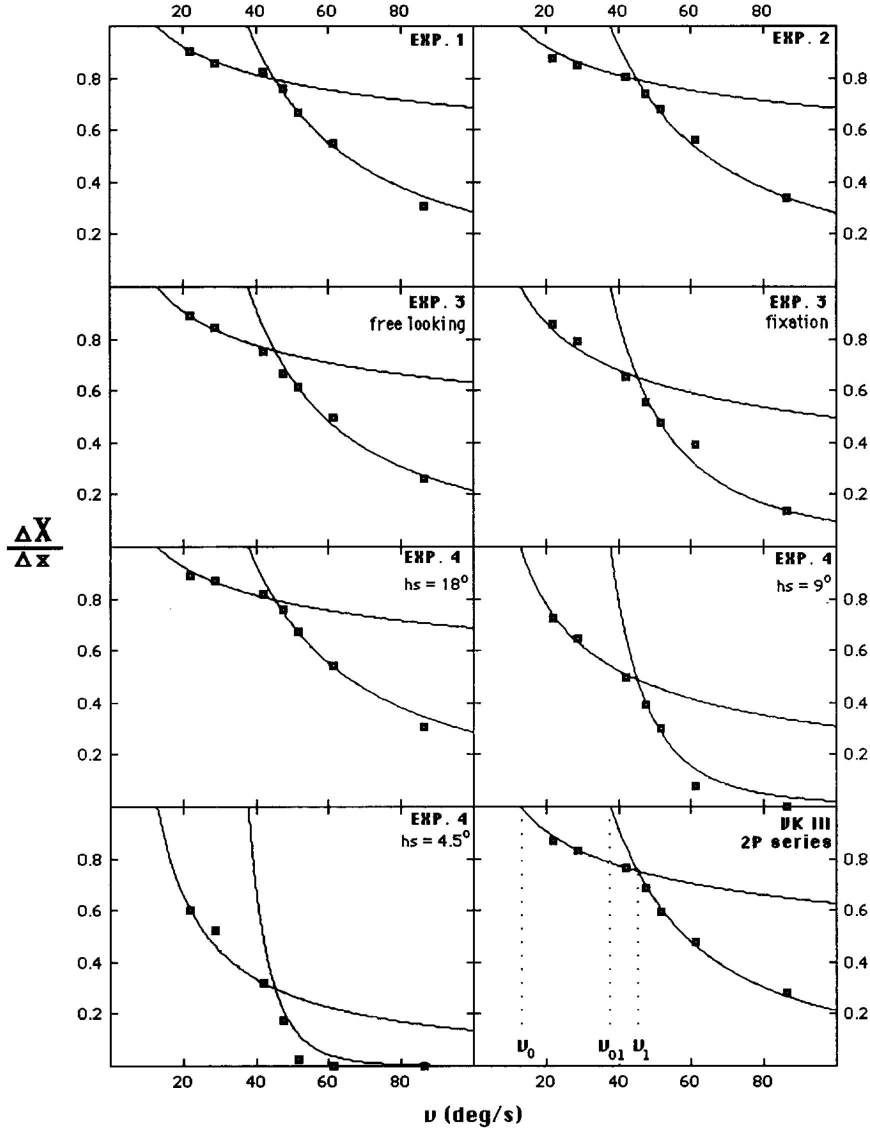

FIG. 10. SCM curves (pooled data) obtained in Experiments 1–4 and in the 2P part of an experiment reported in Visual Kinematics III. All data are simultaneously fitted by (5) and (6) with $\Phi = 7.0$, $v_0 = 13.1°/s$, and $v_1 = 45.1°/s$. The value of α varies from 0.2 to 1.0 depending on experimental conditions. In each panel the medium and high velocity branches are extrapolated in both directions. The constant horizontal positions of three intercept points, v_0, v_1, and v_{01}, are indicated in the bottom right panel.

extrapolation of independently fitted curves. Note also that the constancy of Φ, when combined with that of v_0 and v_1, translates into a constancy of v_{01}, the intercept of the (extrapolated) high-velocity branch with the no-contraction level (Fig. 10, bottom right panel).

The quality of approximation shown in Fig. 10 is only slightly worse than that when the power functions are fitted with no restrictions imposed (Figs. 2, 3, 4, 6, and one figure presented in Visual Kinematics III). This supports the hypothesis that Φ is subject to little variability, as is also the case for the two transition velocities. Although only pooled data are presented, one can deduce from Figs. 10 and 9 that Φ should have similar values for different observers. Indeed, let α_{SE} be the α-exponent for observer $S = 1, 2, ..., n_s$ in experiment/condition $E = 1, 2, ..., n_E$, and let β_{SE} be defind analogously. The intra-individual stability of Φ (Fig. 9) means that $\beta_{SE} = \Phi_S \alpha_{SE}$, where Φ_S does not depend on E. Then pooling across subjects (see Appendix) yields exponents $\alpha_E = \sum_S \alpha_{SE}/n_S$ and $\beta_E = \sum_S \Phi_S \alpha_{SE} n_S$, whose ratio will not be invariant across different E (Figs. 10 and 8) unless Φ_S is a constant.

The assumption that parameter α varies widely between observers and experiments can be related to the well-known variability of the power-function exponents obtained in "direct" scaling of visual velocity: the exponents reported vary by about a factor of 5, from as low as 0.3–0.4 (Aglom & Cohen-Raz, 1984) to as high as 1.6–1.8 (Caelli *et al.*, 1978, data; Ekman & Dahlbäck, 1965). In part this variability can be attributed to factors affecting the mapping of sensory magnitudes into responses (Aglom & Cohen-Raz, 1987; Gescheider, 1988). Sensory factors as such, however, should be involved as well, since no comparable variability is observed in estimation of length (Baird, 1970) or time intervals (Allan, 1979; Eisler, 1976). The results presented in Figs. 8–10 support this interpretation. (Note, however, that (5) does not identify the form of the psychophysical function for perceived velocity as a power function.)

5. Conclusion: SCM and PVH

The facts established in this paper and in Visual Kinematics I allow one to conclude that Space Contraction in Motion is more than another peculiar visual "illusion." The SCM effect seems to manifest spatiotemporal geometry of visual scenes in the way the Lorentz contraction manifests the fundamental spatiotemporal geometry of the physical world. The Lorentz contraction cannot be attributed to any special forces compressing moving physical bodies, i.e., changing the distribution of mechanical mass in a fixed system of spatiotemporal coordinates. The effect exists simply as one aspect of the physical meaning of the triadic concept space–time–motion. Put in more operational terms, the effect is due to the way spatial separations, time intervals, and velocity vectors should be measured in order to be called so. Similarly, the SCM effect is not due to special mechanisms changing distributions of color/brightness in a fixed framework of visual coordinates: it exists because of the way visual objects are assigned spatiotemporal coordinates and motion vectors. In a different context, the idea that the mechanisms responsible for motion perception could be associated with velocity-specific spatial maps was proposed by Burr (1980, 1981; Burr, Ross, & Morrone, 1986).

The PVH places the concepts of localization and motion on the same phenomenological level, which allows one to think about transformations of *perceived* spatiotemporal coordinates in motion as a function of *perceived* motion properties. Psychophysically this means, of course, that visual localization and visual motion depend on a common set of physical variables, but one need not establisch these dependencies in order to meaningfully relate the two perceptual variables to each other. Thus, although both perceived (relative) localization and motion velocity have been shown to change as a function of eye movements and stationary reference objects (screen borders in the experiments reported), these changes are consistent with the hypothesis of a regular relationschip between the perceived localization and velocity.

According to the relative version of the PVH it is not the value of perceived velocity itself on which SCM depends, but this value related to two reference values of perceived velocity representing two fixed objective velocities. Unless decisive arguments are found in favor of the simpler, absolute version of the PVH, this constitutes one of many instances in which the formal structure of visual kinematics differs from that of physical kinematics.

This issue will be elaborated upon in the next paper of the Visual Kinematics series, where I develop a theoretical language that places SCM in the general context of transformations of spatiotemporal coordinates in motion (defining thereby the very concept of visual kinematics). It will be shown that visual kinematics shares certain formal properties with the Lorentz and Galileian kinematics in physics (namely, the linearity of transformations), but differs from them in other fundamental aspects. I will also consider the problem of how these transformations are embedded in complex deformations of moving visual objects (beyond the 2P paradigm where the kinematic transformations are artificially isolated), and how they should be expected to affect dynamic spatial thresholds.

APPENDIX: COMPUTATIONAL DETAILS

This appendix contains comments on computations and graphical presentation of the results that are too technical to include in the main text.

Data averaging. All symbols in the graphs for individual observers represent arithmetic means of estimates, which is justified if the theoretical parameters in (1) are assumed to be relatively stable in a given experiment for a given condition and observer, and if variability in the estimates per condition is mainly due to an additive model-independent noise. Geometric averaging would be more consistent with the assumption that variability in the estimates per condition is due to a stochastic variation in theoretical parameters of (1). I do not have strong evidence for either assumption, which is, however, of little consequence because practically nothing changes in the results and theoretical fits when arithmetic averaging is replaced with geometric one (except, of course, that all mean values become smaller, and very small means become zero).

Assuming that arithmetric averaging of individual data suppressed the data noise considerably, the across-subject pooling had to be geometric. Indeed, (1) is a piecewise power function whose exponents, α and β, are generally different for different observers. The transition points, v_0 and v_1, occupy fixed ordinal positions among the velocities used, hence the empirical domains of the two power-function parts are the same for different observers. Under these conditions, geometric averaging is the only form of pooling that preserves the power-function form of the dependence, provided the latter holds for individual observers.

Very small values of $\Delta X/\Delta x$. Consider the mean values of $\Delta X/\Delta x$ in Fig. 6 for the two smaller screen sizes and the two or three highest velocities. The rounding error in the experiments was 2.5 mm $= 0.01°$, which means that for $\Delta x = 4.2°$ the values of $\Delta X/\Delta x$ below, say, 0.05 were measured very crudely. In fact when the mean of $\Delta X/\Delta x$-estimates per condition is below 0.05, most of these (normalized rounded) estimates are zero. In addition to rounding errors, very small values of $\Delta X/\Delta x$ could reflect underestimating biases adopted by the observers to suppress uncertainty. As a result, small $\Delta X/\Delta x$-values are less reliable than the values above, say, 0.1, and they were treated differently as explained below.

Fitting theoretical curves. The fit of (1) in Figs. 2, 3, 4, and 6 was obtained by a least-square linear regression in log–log coordinates computed separately for the three smaller velocity values and the four higher ones (see Figs. 2, 3, top right). Very small $\Delta X/\Delta x$-values were excluded from the regression computations, but are shown in the final graphs (to demonstrate that the predicted values are very small as well).

In Figs. 8, 9, and 10 two or more SCM curves are plotted against their geometric means. The fit of (7) was obtained by a zero-intercept least-square linear regression in log–log coordinates. Very small $\Delta X/\Delta x$-values had to be excluded from the regression analysis and from the final graphs in Figs. 8b and 9 (observer MG): even if only one of the three values is very small, it would shift the horizontal position of all three values, obscuring the fact that the power-function relationship holds for the two larger values. In such cases the regression was performed for only those triads not containing very small values. Then, for a triad contained one very small value, the two remaining values were horizontally positioned to simultaneously coincide with the corresponding curves. To emphasize the fact that this horizontal position is not a geometric mean, the positioned values are connected by dotted lines.

Finally, the theoretical curves in Fig. 10 were obtained by a straightforward least-absolute-value nonlinear regression fitting (5) and (6) to all eight data sets simultaneously. As usual, very small values were excluded from the regression, but are shown in the plots.

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RECEIVED: June 7, 1990