Notes and Comment

What determines the detection of changes in motion velocity? A comment on Dzhamfarov, Sekuler, and Allik (1993)

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We comment on a recent model aimed at explaining data on speed of reaction to motion onset and to changes in motion velocity. The model is based on calculating the running variance of the stimulus positions passed during the motion. We show that although the model is successful in explaining data on motion onset and supra-threshold velocity changes, it may not be able to explain data on time of reaction to changes in velocity when these are near the detection threshold.

Dzhamfarov, Sekuler, and Allik (1993) presented a model intended to account for the processes of detection of and response to onset of visual motion. The model is based on a network consisting of bilocal motion encoders. The positions, x and $x + \Delta x$, of the sampling areas of the encoders are spatially interconnected in an all-to-all fashion. Each spatial connection, with a given span Δx , contains a set of parallel lines with built-in delays Δt . All delay values are associated with all pairs of sampling areas. Every pair of sampling areas, with a span of Δx , and every pair of sampling moments (t and $t + \Delta t$) define one elementary encoder. The encoder is activated if the motion of the stimulus $x(t)$ meets the requirement $x(t + \Delta t) - x(t) = \Delta x$.

Dzhamfarov et al. (1993) suggested averaging (within a moving temporal window τ) across the outputs of the network, every activated encoder being assigned with a weight equal to its squared spatial span $(\Delta x)^2$. In this way, the result of the averaging, the "kinematic power" $E(t)$, becomes particularly simple: It is the running variance of the spatial positions passed by the stimulus within the moving window τ . When $E(t)$ exceeds a criti-

cal level E_c , motion is detected and a response is elicited. Thus, the reaction time (RT) is the sum of a velocity-dependent detection time $DT(V)$, which is necessary for the variance $E(t)$ to reach the critical value E_c and a velocity-independent motor component RT_0 . The model is generalized for the case of response to change in velocity of motion by reducing the detection of a velocity change from V_1 to V_2 , to a detection of the onset of motion with velocity $|V_2 - V_1|$.

A prevalent hypothesis is that visual motion is detected by motion detectors, each of which is tuned to a given velocity (see, e.g., Borst & Engelhaaf, 1989). An idealized motion detector of this type consists of two sampling areas with a span of Δx and is associated with a single delay Δt . Hence, it can be activated only by a *single* velocity equal to $\Delta x / \Delta t$. In the network proposed by Dzhamfarov et al. (1993), each pair of spatial sampling areas is associated with *all* delays that are assumed to cover densely a range from zero to some large value. These subgroups of the network may be considered as speedometers that are able to measure *any* velocity. Thus, the model provides an interesting alternative to the generally accepted motion detector hypothesis.

It is instructive to examine the model for two different aspects of motion detection: motion onset and velocity change.

Motion Onset

Kinematic power $E(t)$ is given by the following expression:

$$E(t) = \frac{1}{\tau} \int_{t-\tau}^t x(u)^2 du - \left[\frac{1}{\tau} \int_{t-\tau}^t x(u) du \right]^2, \quad (1)$$

where τ stands for the length of the temporal window. For the case of an onset of motion with velocity V we have

$$x(t) = \begin{cases} 0 & \text{for } t < 0 \\ V \cdot t & \text{for } t \geq 0, \end{cases} \quad (2)$$

where $x(t)$ is the spatial position of the stimulus and zero indicates the moment of the motion onset. The detection time $DT(V)$ can be found analytically by substituting Equation 2 in 1, solving the integrals, substituting a critical level E_c for $E(t)$, and solving (approximately) for t . After solving the integrals we have for $t < \tau$

$$E(t) = (V \cdot \tau)^2 \left[\frac{1}{3} \left(\frac{t}{\tau} \right)^3 - \frac{1}{4} \left(\frac{t}{\tau} \right)^4 \right] \quad (3)$$

and for $t \geq \tau$,

This work was supported by Grant I-402/94 from the National Fund for Scientific Research, Bulgaria, and Deutsche Forschungsgemeinschaft Grant 436 BUL-113/32; Ho 965/3-3, Germany. We are indebted to C. R. Cavonius for his valuable comments on the manuscript, and to L. Blanke and C. Wested for technical assistance. Correspondence should be addressed to J. Hohnsbein, Institut für Arbeitsphysiologie an der Universität Dortmund, Ardeystr. 67, D-44139 Dortmund, Germany (e-mail: hohnsbein@arb-phys.uni-dortmund.de).

$$E(t) = \frac{(V \cdot \tau)^2}{12}. \quad (4)$$

An approximate solution for t in Equation 3 can be obtained by assuming that $t \ll \tau$ and omitting the term $\frac{1}{4}(t/\tau)^4$. Then, after solving for t we obtain

$$t = [3\tau \cdot E(t)]^{\frac{1}{3}} \cdot V^{-\frac{2}{3}}. \quad (5)$$

The detection time DT is that value of t for which $E(t) = E_c$; that is,

$$DT(V) = C \cdot V^{-\frac{2}{3}}, \quad (6)$$

where

$$C = (3\tau \cdot E_c)^{\frac{1}{3}}; \quad (7)$$

that is, C is a constant independent of V . Therefore, the reaction time is

$$RT = C \cdot V^{-\frac{2}{3}} + RT_0. \quad (8)$$

Dzhafarov et al. (1993) presented experimental data showing that the exponent in Equation 8 is indeed equal to $-\frac{2}{3}$. Data obtained by other authors (Ball & Sekuler, 1980; Tynan & Sekuler, 1982; Hohnsbein & Mateeff, 1992; see Allik & Dzhafarov, 1984, and Van den Berg & Van de Grind, 1989, for analysis and discussion of these results) indicate that the value of the exponent may be somewhat lower, about -0.5 , but this does not necessarily indicate a deficiency of the model. RT data tend to be noisy, and an exponent of $-\frac{2}{3}$ may also fit the data rather well, as Dzhafarov et al. (1993) have demonstrated in their study.

Equation 1 can be checked by other motion functions. Recently, we measured the RT to onset of motion with constant acceleration rather than constant velocity (Hohnsbein & Mateeff, 1994). In this case x takes the values

$$x(t) = \begin{cases} 0 & \text{for } t < 0 \\ \frac{1}{2} A \cdot t^2 & \text{for } t \geq 0 \end{cases} \quad (9)$$

where A stands for the acceleration. Replacing Equation 9 in Equation 1 and performing the same manipulations as in the case of onset of motion with constant velocity, one obtains

$$RT = C \cdot V^{-\frac{2}{5}} + RT_0. \quad (10)$$

In an experiment, we varied A between 1.5° and $100^\circ/\text{sec}^2$. The best fit of the relationship between the RT and the acceleration was obtained with an exponent of -0.375 , which was very near to the predicted value of -0.4 in Equation 10. Thus, the model is able to successfully explain the RT to onset of motion with constant acceleration.

In another experiment, we employed the same subjects to measure the RT to onset of motion with constant velocity and obtained a best fit of the data by an exponent of -0.55 . Again, this was somewhat lower than the predicted value of $-\frac{2}{3}$. Yet, these data do not contradict the model of Dzhafarov et al. (1993), since an exponent of $-\frac{2}{3}$ can also fit the data with only a negligible change in the goodness-of-fit.

An earlier hypothesis explaining RT to motion onset is that motion is detected and the reaction is elicited when the distance passed through by the stimulus reaches a critical value. This "critical distance hypothesis" predicts an equation similar to Equation 8 for the RT, but with an exponent of -1 , which is not supported by the experimental data. Formula 1 is successful in fitting the data, computing the variance of the positions rather than the distance traversed by the stimulus. Moreover, the variance is calculated within a moving temporal window, whereas no moving window is assumed in the critical distance hypothesis.

It is instructive to make a formal transition from Equation 1 to an equation that would essentially reflect the critical distance hypothesis. To this end, we simplified Equation 1 in the following way.

Assume a time function $E(t)$ that is determined by the equation

$$E(t) = \frac{1}{\tau} \int_{t-\tau}^t x(u) du \quad (11)$$

rather than by Equation 1 and a detection rule similar to that proposed by Dzhafarov et al. (1993); namely, motion is detected and the reaction is elicited after the *moving average position* exceeds a critical value. Substituting the functions of motion (Equations 2 and 9) in Equation 11 and solving for t , we obtain exponents of -0.5 for the case of RT to motion with constant velocity and -0.33 for the case of accelerated motion. The value of -0.5 fits the experimental data even better than does the value of $-\frac{2}{3}$, predicted by Equation 1. The predicted value of -0.33 is about equally well supported by the experimental data (-0.375) as is the prediction (-0.4) based on Equation 1.

Now, let us further consider a formula similar to Equation 11 but without the use of a moving window. Assume a time function of the type

$$E(t) = \frac{1}{\tau} \int_0^t x(u) du. \quad (12)$$

Here the detection rule becomes: Motion is detected when the stimulus has passed through some distance, determined by a critical value of $E(t)$. This detection rule is rather close to the critical distance hypothesis. But Formula 12 can no longer explain the data on RT to motion onset: Replacing Equations 2 and 9 in Equation 12 and solving for t we obtain an exponent of -1 for the case of onset of motion of constant velocity and -0.5 for the case of motion of constant acceleration. The latter value is close to the experimental data, whereas the data

for motion onset with constant velocity definitely rule out the predicted value of -1 .

However, with some reformulation, the critical distance hypothesis may also account for data from experiments with RT to motion onset: To this end, the hypothesis should read: Motion is detected (and a response is elicited) after the mean position of the stimulus, averaged within a moving temporal window τ , deviates by a critical distance from the initial position (Equation 11). But a model of the type in Equation 11 has the disadvantage that it does not account for the data from an experiment on RT to abrupt displacement of a single dot, whereas the model in Equation 1 can do this (see the Appendix of Dzhabarov et al., 1993). Therefore, Dzhabarov et al.'s model seems to be superior since it can deal with a broader class of perceptual events. On the other hand, the version of the critical distance hypothesis given with Equation 11 better predicts the value of the exponent in Equation 8, which is obtained in experiments.

Velocity Change

It is plausible to assume that the RT to a change of velocity V_1 to V_2 is some function of both V_1 and V_2 , but the relevant question concerns the exact and explicit form of this function. Dzhabarov et al. (1993) proposed a straightforward answer: The RT is the following function of the absolute difference between V_2 and V_1 :

$$RT = C(V_1) \cdot |V_2 - V_1|^{-\frac{2}{3}} + RT_0, \quad (13)$$

where $C(V_1)$ is no longer a constant but rather is an increasing function of the motion velocity V_1 before the change.

Equation 13 is based on the hypothesis that the detection system effectively subtracts the initial motion from the ongoing motion. This subtraction is achieved by readjustment of the weights with which the elementary outputs of the network are summated. Dzhabarov et al. (1993) called this process "subtractive normalization"; the process reduces the detection of a change in motion velocity from V_1 to V_2 to a detection of motion onset with velocity $V = |V_2 - V_1|$.

The hypothesis that the RT to velocity change is a function of $|V_2 - V_1|$, rather than of V_2/V_1 or $(V_2 - V_1)/(V_2 + V_1)$, is ingenious and seems to work rather well. In this form, the model incorporates the cases of reaction to onset of motion ($V_1 = 0$) as well as reaction to a velocity change ($V_1 > 0$). It easily deals with velocity changes in which $V_2 = 0$ or even $V_2 < 0$; that is, when the motion stops or reverses its direction. In a recent paper (Mateeff, Dimitrov, & Hohnsbein, 1995), we pointed out that the model provides a straightforward qualitative explanation of the data on temporal thresholds for detection of velocity changes with velocity differences ranging between 2° and $14^\circ/\text{sec}$.

A very important assumption in the model is that $C(V_1)$ is not simply a coefficient introduced to equate the dimensions on both sides of Equation 13. Dzhabarov et al. (1993) suggested that $C(V_1)$ is constant for low val-

ues of V_1 (between 0° and $4^\circ/\text{sec}$) and increases beginning with some value of V_1 between 4° and $8^\circ/\text{sec}$. This assumption is necessary to account for the experimental finding obtained by Dzhabarov et al. (1993) and by Hohnsbein and Mateeff (1992) that the RT to onset of motion with velocity V is equal to the RT to offset of motion with the same velocity only in the case when V is relatively low. For higher velocities—say, 12° to $16^\circ/\text{sec}$ —the RT to onset is about 40 msec shorter than the RT to offset of motion with the same velocity.

Questions may arise when the model of Dzhabarov et al. (1993) is used for explaining the RT to velocity changes that are near the detection threshold. According to the model, the running variance $E(t)$ increases as shown by Equation 3, replacing V with $\Delta V = |V_2 - V_1|$. When t becomes equal or larger than τ , $E(t)$ reaches a plateau determined by Equation 4. Obviously, if the value of $E(t)$ at $t = \tau$ is less than the critical value of E_c , the change will be subthreshold and no response will be elicited. Therefore, the threshold velocity change ΔV_t can be determined from Equation 4 by replacing $E(t)$ by the critical level E_c and solving for ΔV . Thus, we have

$$\Delta V_t = \frac{(12E_c)^{\frac{1}{2}}}{\tau}. \quad (14)$$

Dzhabarov et al. (1993) suggested that τ is about 0.5 sec. Formulae 8 and 13 are derived from 3, assuming that $t \ll \tau$; that is, the detection time is much shorter than the length of the summation window. This approximation is obviously reasonable since the formulae can fit the data from the studies of Dzhabarov et al. (1993) and of Hohnsbein and Mateeff (1992). The longest RTs in these studies were about 300–350 msec. The asymptotic value RT_0 is about 200 msec; hence, the longest detection time in these experiments can be estimated to be 100–150 msec. The length of the summation window τ should be "much larger" than this value. If it is at least four to five times as large, the approximation error becomes acceptable, and therefore, the value of 0.5 sec, proposed by Dzhabarov et al., seems reasonable.

According to Dzhabarov et al. (1993), the value of the constant $C(V_1)$ in Equation 13 increases monotonically with increasing velocity V_1 before the change within the range of 4° to $16^\circ/\text{sec}$. Dzhabarov et al. pointed out that the increase of $C(V_1)$ can be due to an increase either in E_c or in τ (Equation 7). However, Equation 14 shows that the increase in $C(V_1)$ cannot be due to an increase in the length of τ . If this were the case, the absolute value of the threshold difference ΔV_t for detection of a change would decrease with increasing initial velocity V_1 ; that is, against the expectations on the basis of the Weber law. Obviously, $C(V_1)$ increases because the value of the criterion E_c is an increasing function of V_1 , whereas τ presumably remains constant. With this conclusion in mind, we can now approximately estimate the values of $E_c(V_1)$ and thereby the values of ΔV_t . Solving Equation 7 for E_c and substituting it in Equation 14, we obtain

$$\Delta V_t = 2 \cdot \left[\frac{C(V_1)}{\tau} \right]^{\frac{3}{2}}. \quad (15)$$

Analyzing their own data and the data of Hohnsbein and Mateeff (1992), Dzhaferov et al. (1993) obtained values of $C(V_1)$, in $\text{sec}^{\frac{1}{3}} \cdot \text{deg}^{\frac{2}{3}}$, that are about 0.195 for $V_1 = 8^\circ/\text{sec}$ and 0.285 for $V_1 = 16^\circ/\text{sec}$. Substituting these values in Equation 15 and assuming $\tau = 0.5 \text{ sec}$, V_t appears to be $0.49^\circ/\text{sec}$ for $8^\circ/\text{sec}$ and $0.85^\circ/\text{sec}$ for $16^\circ/\text{sec}$, which corresponds to a Weber ratio $\Delta V_t/V_1$ of about 5%.

There may be some inaccuracy in this way of estimating the Weber fractions, since E_c is in fact a random variable, but nevertheless the value of 5% seems too low. Weber fractions for discrimination of velocity have been obtained to be 6%–12% (McKee, 1981; DeBruyn & Orban, 1988). In a discrimination task, however, the velocity stimuli are temporally well separated from each other, whereas in a change detection task the velocity V_2 immediately follows velocity V_1 . As Nakayama (1985, p. 652) pointed out, when two different velocities are adjacent in time observers have great difficulties in perceiving the difference between them. Our pilot observations showed the same: Weber fractions for velocity discrimination (which were normally about 10%–15% using our random dot pattern) may substantially increase when the velocity stimuli are temporally contiguous. These observations are in keeping with the results of McKee and Nakayama (1988) and with the hypothesis that velocity information is integrated in time (Nakayama, 1985), but are in a quantitative disagreement with the Weber fractions that can be calculated from the model of Dzhaferov et al. (1993). In other words, the reaction time analysis predicts finite RTs to velocity changes that may be in fact subthreshold. It is an open question as to whether gradually increasing the value of V_2 above the threshold would elicit RTs in accordance with Equation 3.

The model may also encounter difficulties with RTs to near-threshold velocity changes in the low velocity range. To demonstrate this, we performed a small experiment. The apparatus and the methods used were the same as those described in the studies of Hohnsbein and Mateeff (1992) and Mateeff et al. (1995). The subject sat in front of a white screen (0.7 cd/m^2 luminance) and fixated binocularly a black point positioned straight ahead. A random dot pattern could be presented within an invisible aperture of 8.9° size, positioned 4.5° above the fixation point. The pattern consisted of multiple images of the light point of the electron beam of an oscilloscope. It consisted of 40 dots on the average (each 1.8 cd/m^2 luminance, ca. 0.8° dia). The oscilloscope display was controlled by a PC 486 via a 16-bit D/A converter. The dot pattern moved initially with velocity V_1 for a random period between 1.4 and 3 sec and then abruptly changed in velocity to V_2 . RTs to the following velocity changes were measured: $0.8^\circ \rightarrow 2.4^\circ/\text{sec}$, $2.4^\circ \rightarrow 4^\circ/\text{sec}$, $2.4^\circ \rightarrow$

Table 1
 $\Delta\text{RT}(2.4)$: Differences Between Median Reaction Times (RTs) in Milliseconds Obtained With Velocity Changes $2.4^\circ \rightarrow 0^\circ/\text{sec}$ and $0^\circ \rightarrow 2.4^\circ/\text{sec}$.

$\Delta\text{RT}(1.6)$: Differences Between Median RTs to Velocity Changes $0.8^\circ \rightarrow 2.4^\circ/\text{sec}$ and $2.4^\circ \rightarrow 4^\circ/\text{sec}$		
Subject	$\Delta\text{RT}(2.4)$	$\Delta\text{RT}(1.6)$
S.G.	6	41
S.M.	−4	32
P.C.	11	33
V.I.	6	20
G.D.	18	29
<i>M</i>	7.4	31*

*Significantly different from zero at $p < .01$ (two-tailed *t* test).

$0^\circ/\text{sec}$, and $0^\circ \rightarrow 2.4^\circ/\text{sec}$. The first two velocity pairs differed by $1.6^\circ/\text{sec}$ and the second two by $2.4^\circ/\text{sec}$. After a training session the subject was presented with a total of 80 trials per velocity change; these were presented in eight blocks of 40 trials. The blocks were randomized within and among subjects. RTs lower than 100 msec and higher than 800 msec (such RTs appeared in less than 5% of the trials) were discarded and then the median RTs were computed.

Let us define the following RT differences:

$$\Delta\text{RT}(2.4) = \text{RT}(2.4 \rightarrow 0) - \text{RT}(0 \rightarrow 2.4) \quad (16)$$

and

$$\Delta\text{RT}(1.6) = \text{RT}(2.4 \rightarrow 4) - \text{RT}(0.8 \rightarrow 2.4). \quad (17)$$

Fitting Equation 13 to their own RT data, Dzhaferov et al. (1993) showed that the parameter $C(V_1)$ in Equation 13 was constant for V_1 up to $4^\circ/\text{sec}$. Therefore, with the initial velocities of our stimuli we should have $C(0) = C(0.8) = C(2.4)$. If this is the case, we should have both $\Delta\text{RT}(2.4) = 0$ and $\Delta\text{RT}(1.6) = 0$.

Our data for $\Delta\text{RT}(2.4)$ and $\Delta\text{RT}(1.6)$ are shown in Table 1. The mean of the difference $\Delta\text{RT}(1.6)$ is significantly different from zero, but the mean of $\Delta\text{RT}(2.4)$ is not. The fact that $\Delta\text{RT}(2.4) = 0$ suggests that $C(2.4) = C(0)$. A local maximum of $C(V_1)$ is rather improbable, and thus $C(2.4) = C(0.8) = C(0)$, which predicts $\Delta\text{RT}(1.6) = 0$. However, the results show that this is not the case. Contrary to the predictions of Dzhaferov et al.'s (1993) model, the two velocity changes of equal absolute value $\Delta V = 1.6^\circ/\text{sec}$ elicit reaction times that significantly differ from each other, $\text{RT}(2.4 \rightarrow 4)$ being about 24 msec longer than $\text{RT}(0.8 \rightarrow 2.4)$.

One could suggest that in fact $C(2.4) > C(0.8) \geq C(0)$ holds rather than $C(2.4) = C(0.8) = C(0)$ and that the difference between $C(2.4)$ and $C(0)$ is too small to result in a significant $\Delta\text{RT}(2.4)$ in a reaction time experiment. But this difference is large enough to result in a nonzero $\Delta\text{RT}(1.6)$. Also, this suggestion cannot explain quantitatively the data from the present experiment. Replacing the four different velocity changes in Equation 13 and then in 16 and 17, we obtain for the $\Delta\text{RT}(1.6)/\Delta\text{RT}(2.4)$ ratio

$$\frac{\Delta RT(1.6)}{\Delta RT(2.4)} = \frac{1.6^{-\frac{2}{3}}}{2.4^{-\frac{2}{3}}} \cdot \frac{C(2.4) - C(0.8)}{C(2.4) - C(0)}. \quad (18)$$

Taking into account that $C(2.4) > C(0.8) \geq C(0)$, the right-most term in Equation 18 is not larger than 1. Thus we have $\Delta RT(1.6)/\Delta RT(2.4) \leq (1.6/2.4)^{-2/3}$; that is, the ratio in Equation 18 should not exceed the value of 1.3. The data in Table 1 show that the $\Delta RT(1.6)/\Delta RT(2.4)$ ratios are much above this value. $\Delta RT(2.4)$ is too small to account for the large value of $\Delta RT(1.6)$.

The discrepancy between the data and the model can be easily explained if one looks at the display and inspects the visibility of the velocity changes. The change from $0.8^\circ \rightarrow 2.4^\circ/\text{sec}$, which is a 200% increment, is more visible than the change from $2.4^\circ \rightarrow 4^\circ/\text{sec}$, a 67% increment. Therefore, for velocity changes that are near the detection threshold the RT may be determined by the ratio between the velocities rather than by their difference.

In conclusion, Dzhafarov et al.'s (1993) model is able to successfully predict RTs to motion onset and to supra-threshold velocity changes. It should be applied with caution, though, when the velocity changes are near threshold. A more detailed estimation of the model is not yet possible, since there are not enough data on perception of changes in visual velocity.

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(Manuscript received December 14, 1994;
revision accepted for publication December 30, 1995.)