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## TIME- AND SPACE-ORDER EFFECTS IN TIMED BRIGHTNESS DISCRIMINATION OF PAIRED VISUAL STIMULI

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### Abstract

*Despite the considerable import of both response probability and response time for testing models of choice there is a dearth of chronometric studies of time- and space-order effects in discrimination of paired visual stimuli. In this study, systematic asymmetries in discriminating the brightness of paired visual stimuli are examined by way of binary response probability scaled in terms of log-odds ratios, as well as by signed response speed (i.e., the inverse of response time with the sign of the judged difference). For two stimuli separated by a time interval, psychometric and chronometric results revealed equivalent time-order effects, and when presented simultaneously, separated by a spatial interval, no effects of space order were found. Implications of these findings for random walk and diffusion models of sensory discrimination are discussed.*

Fechner (1801-1887) was among the first to discover that when two stimuli are presented for comparison people systematically overestimate the magnitude of one stimulus and underestimate the magnitude of the other. The term, time-order effect (TOE) is used to refer to such asymmetries in paired comparisons of stimuli separated by a time interval, and the term space-order effect (SOE) to asymmetries in comparisons of paired stimuli separated spatially. By convention, a positive effect is taken to refer to an overestimation of the first (or left) stimulus as compared to the second (or right) stimulus and a negative effect as an underestimation of the first (or left) as compared to second (or right) stimulus.

In brightness discrimination, the TOE has been found to change from positive to negative with increasing inter-stimulus interval (ISI) from 1-9 seconds (Meada, 1959). Concerning the SOE, Kellogg (1931) reports a negative asymmetry in split-disk brightness discrimination, in that participants tended to choose the right-half more frequently than the left despite equally balanced brightness difference. Yet, in darkness discrimination of paired luminance gradients, participants tend to choose gradients with the darkest end on the left as compared right (Mattingley et al., 1994). So, there is some preliminary evidence to suggest that asymmetries in brightness discrimination are perceptual, but precisely what processes underlie them have yet to be fully determined.

Asymmetries in sensory discrimination are all too often dismissed as bias, which may appear as a result of prejudiced decision criteria (Allen, 1977), or verbal categorization of stimuli toward the mean of the stimulus series (John, 1975). Others envisage some kind of retention loss (Link, 1978) such that the activation inspired by one stimulus is compared to a lower fidelity mental representation of the other. In regard to the SOE, similar appeal has been made by reference to known functional asymmetries in neural anatomy (Mattingley et al., 1994), noncentral fixation and scanning effects (Masin, & Agostini, 1991).

In the paired comparison of stimuli, bias is associated with the notion of an additive effect. For instance, Davidson & Beaver, (1977) extended the classic BTL model (Bradley & Terry, 1952; Luce, 1959) to predict the probability,  $p(A>B|A,B)$  of choosing A over B, given that A was presented first (or left), by inclusion of a constant order effect  $w$ , which is additive

in terms of,  $\ln\psi$ :  $\logit [p(A>B|A,B)]=\ln\psi(A)-\ln\psi(B)-\ln w$ , where  $\psi(\bullet)$  is a ratio scale.

Alternatively, on the basis that the TOE and SOE are perceptual phenomena, Hellström (1979) proposed a sensation weighting (SW) model that posits a weighting of activation inspired by each stimulus event and a reference level (ReL) based on generic information. Formally, this model is defined as

$$d=k\{[s_1\psi_1 + (1 - s_1)\psi_{r1}] - [s_2\psi_2 + (1 - s_2)\psi_{r2}]\}, \quad (1)$$

where  $d$  is the subjective difference between the compared stimuli,  $k$  is a scale constant,  $s_1$  and  $s_2$  are weighting coefficients (1 and 2 indicate the temporal order or spatial position of the stimuli; i.e., left=1, right=2),  $\psi_1$  and  $\psi_2$  are the sensation magnitudes of the stimuli and  $\psi_{r1}$  and  $\psi_{r2}$  are the sensation magnitudes of the ReLs.

Further clues concerning the underlying causes of the TOE and SOE and those underlying perceptual discriminations, in general, may be obtained by examination of the time taken to make the discrimination (cf. Jamieson & Petrusic, 1975). Random walk and diffusion models propose some form of sequential sampling mechanism to explain patterns of response times and response probability in timed discrimination tasks (Link, 1975, 1992; Ratcliff, 1978). According to these models the process of comparison consists of the accumulation of noisy information about the difference between stimulus values over time, until either of two boundaries (A or  $-A$ ) is reached. Discrimination time is defined as the time from the start of the process until one boundary is reached and response probability determined by the likelihood of crossing either boundary.

Bias is assumed to arise as a result of changes in the initial state of evidence, bound rate change, or drift rate change (Diederich & Busemeyer, 2006). For instance, Link (1978) assumes that in paired comparison tasks the activation inspired by one stimulus is compared to a lower (or higher) fidelity mental referent of the other (Link, 1978, 1992). In support of this view Link (1978) re-examined Kellogg's (1931) data in terms of the predicted relationship between response probability and response time,

$$ERT_i = \frac{A}{m} [(2P_{Ai}-1) / (S_i-S_r)] + K, \quad (2)$$

where  $ERT_i$  is expected response time,  $A/m$  is an unknown slope,  $K$  is mean non-decision time,  $S_i$  is stimulus magnitude and  $S_r$  the value of the mental referent defined in units of the stimulus. The probability  $P_{Ai}$  of the random walk exceeding one boundary (A) given stimulus  $S_i$  is given by the equation of the logistic distribution function where estimates of the logistic variable can be obtained by least squares fit to  $S_i$  of the informational value  $\theta_i A$ , which is the logit of  $P_{Ai}$ :  $\ln(P_{Ai} / (1-P_{Ai}))$ .

Link (1978) found a close correspondence between ERT (Equation 2) and mean RT as reported by Kellogg (1931). However, Kellogg (1931) did not manipulate the spatial separation between stimuli nor the absolute physical magnitude of stimuli. His data show a constant asymmetry while the TOE and SOE are characterised by changes in magnitude and direction with changes in the configuration and absolute physical magnitude of the stimuli. Consequently, without due care, differences between current sequential sampling models and human ability will continue to exist because the processes identified are grounded on an oversimplification of the actual perceptual processes engaged.

Current random walk and drift diffusion models are based on the outcome of a simple comparator which merely accumulates a signed difference by subtraction. On these grounds, Experiments 1 and 2 were conducted to examine further the TOE and SOE in timed brightness discrimination of paired visual stimuli. If the comparison process is based on the simple subtraction of stimulus information, and if systematic asymmetries in brightness discrimination change in magnitude and direction with changes in the configuration and

absolute physical magnitude of the stimuli, then it is behoved of theories based on notions of bias to explain such effects. If, however, a more complex process of comparison is admitted time- and space-order effects may be explained by perceptual weighting and by inclusion of the influence of generic information.

### Experimental method

*Participants.* 40 participants took part in Experiment 1, and 40 different participants from the same student population took part in Experiment 2. All claimed to be right handed.

*Stimuli.* The visual stimuli were defined as circular spots with constant 5 mm diameter, presented on a gamma corrected 21" video monitor with a background illumination held constant at 0.01 cd/m<sup>2</sup>. In Experiment 1, the paired stimuli were presented successively. Each stimulus was presented at 9 different brightness levels from 3.5 to 5.9 cd/m<sup>2</sup> in 8 steps of 0.3 cd/m<sup>2</sup>, for 200 msec. The ISI was 400, 800, 1600 or 3200 msec. In Experiment 2, paired stimuli were presented simultaneously, for 200 msec, separated by a spatial interval. The spatial separation between stimuli was 10, 20, 40 or 80 mm, and the brightness of each stimulus ranged from 1.5 to 7.9 cd/m<sup>2</sup> in 8 steps of 0.8 cd/m<sup>2</sup>.

*Design.* The 9 separate brightness levels of each visual stimulus were combined semi-factorially to form a 'diamond' shape about mean physical brightness, to create 25 different stimulus pairs. In Experiment 1, the physical differences (i.e., first minus second) between the stimuli in each pair ranged from -1.2 to +1.2 cd/m<sup>2</sup> in 4 steps of 0.6 cd/m<sup>2</sup> across one diagonal, and mean stimulus brightness ranged from 4.1 to 5.3 cd/m<sup>2</sup> in 4 steps of 0.3 cd/m<sup>2</sup> across the opposing diagonal. In Experiment 2, the physical difference between the stimuli ranged from -3.2 to 3.2 in 4 steps of 1.6 cd/m<sup>2</sup> across one diagonal and mean stimulus brightness ranged from 3.1 to 6.3 in 4 steps of 0.8 cd/m<sup>2</sup> across the opposing diagonal.

In each experiment participants took part in four 30-min sessions, one on each of 4 days. Within each session, each stimulus was shown in pseudo-randomly constructed cycles of 100 items. The first 25 trials (Exp.1) and 100 trials (Exp. 2) were designated as practice trials, immediately after which each participant was required to complete a further 400 trials per session. New random orders were used for each participant and each session.

In Experiment 1, 20 participants were instructed to press a left response key if they perceived the first stimulus to be brighter than the second, or a right key if they perceived the second stimulus to be brighter than the first. The other 20 participants were instructed to use the reverse stimulus-response assignment. In Experiment 2, all participants were instructed to respond by pressing the left response key if they perceived the left stimulus to be brighter than the right, and the right key if they perceived the right stimulus to be brighter than the left.

*Procedure.* At the beginning of each session participants were presented with written instructions on the video monitor. The importance of responding as quickly and as accurately as possible was stressed. The inter-trial interval was 3000 msec. On the average, participants took 30 minutes to complete each session.

### Results

In Link's analysis (Equation 2) the drift rate  $\mu$  is estimated by  $m(S_i - S_r)$ , where  $m$  is a constant. The actual perceived stimulus difference is not measured directly but represented by  $\theta_i A$ , which needs only to be monotonically related to  $\mu$ . Therefore, ignoring the non-decision part of RT, an alternative way of thinking about  $\mu$  is in terms of  $\mu^* = A/RT$  for first brightest responses and  $\mu^* = -A/RT$  for second brightest responses; termed, signed response speed (SRS).

Table 1. Mean log-odds ratios of the proportion first (left) brightest responses over second (right) brightest responses and mean signed response speed for the 5 brightness levels by ISI.

Experiment 1: Successively presented stimuli									
Mean brightness (cd/m <sup>2</sup> )	ISI (msec)	Mean log-odds ratio				Mean signed response speed			
		400	800	1600	3200	400	800	1600	3200
4.1		-0.06	0.20	0.15	0.11	-0.52	1.27	0.70	0.59
4.4		-0.06	0.16	0.09	0.01	-0.62	1.01	0.53	-0.06
4.7		-0.14	0.06	0.06	-0.02	-0.87	0.34	0.53	-0.22
5.0		-0.21	-0.01	-0.12	-0.16	-1.06	0.13	-0.44	-0.91
5.3		-0.23	-0.06	-0.08	-0.27	-1.01	-0.01	-0.25	-1.3
Experiment 2: Simultaneously presented stimuli									
Mean brightness (cd/m <sup>2</sup> )	ISI (mm)	10	20	40	80	10	20	40	80
3.1		-0.07	0.03	0.07	0.12	-0.63	0.31	0.79	1.24
3.9		-0.16	0.01	0.10	0.13	-1.55	0.01	0.10	1.06
4.7		-0.07	0.02	0.14	0.13	-0.63	0.07	1.55	1.23
5.5		-0.13	-0.08	0.09	0.21	-1.12	-0.76	1.13	1.87
6.3		-0.04	-0.03	.015	0.21	-0.29	-0.20	1.44	1.72

Here, SRS is calculated as 100/RT for first brightest response, and -100/RT for a second brightest response. The use of SRS reduces the influence of outliers and can be scaled in a similar, directly comparable, manner as response probability.

To investigate the nature of the relationship between  $\text{logit}(p)$  and  $SRS$ , stepwise polynomial 3<sup>rd</sup>-degree regressions were fit to each participant's data over each stimulus condition and ISI (Exp.1), and spatial separation (Exp. 2), using mean  $SRS$  as the independent variable. On the group average, all cubic and quadratic terms in both Experiments 1 and 2 proved to be statistically nonsignificant, indicating that  $SRS$  and  $\text{logit}(p)$  are linearly related.

Now, consider the affect of changes in average stimulus brightness and ISI on the direction and magnitude of the TOE and SOE, as shown in Table 1. For successively presented stimuli, asymmetries can be seen to change systematically in magnitude and direction with changes in stimulus brightness and ISI, both in terms of log-odds ratios and mean SRS. For simultaneously presented stimuli, there is some indication that asymmetries go from negative to positive with increased spatial separation between the stimuli but no indication of any systematic variation with changes in average stimulus brightness.

To examine changes in the magnitude and direction of the TOE and SOE the data were analysed in terms of Hellström's SW model (Equation 1). On the basis of the SW model  $s_1-s_2$  indicates the direction of asymmetry, and the relation  $s_1 \neq s_2$  was tested by (two tailed) one sample t-tests. The results of this analysis are shown in Table 2.

Further, analysis of the influence of response assignment on the magnitude and direction of  $s_1-s_2$  revealed no statistically reliable effects (all  $ps>.05$ ).

Table 2. Weights  $s_1-s_2$  estimated by logistic regression of binary responses and std regression of SRS on log physical brightness (cd/m<sup>2</sup>) of the first (left) and second (right) stimuli.

Experiment 1: Successively presented stimuli									
ISI(msec)	Response frequency				SRS				
	400	800	1600	3200	400	800	1600	3200	
$s_1-s_2$	-0.74	-1.25	-1.26	-1.61	-0.02	-0.05	-0.05	-0.08	
P value for $(s_1-s_2) \neq 0$	.02	.001	.001	.001	n.s.	.003	.012	.001	
Experiment 2: Simultaneously presented stimuli									
ISI(mm)	10	20	40	80	10	20	40	80	
$s_1-s_2$	0.16	-0.11	0.03	0.09	0.004	-0.009	0.009	0.009	
P value for $(s_1-s_2) \neq 0$	n.s	n.s	n.s	n.s	n.s.	n.s.	n.s.	n.s.	

Table 3: Psychometric function of stimulus difference and linear fit of Equation 2

Experiment 1: Successively presented stimuli								
ISI (msec)	400		800		1600		3200	
	$0=\theta A=$ X $\Delta$ s+C	$(2P_{Ai}-1)$ $\mu$	$0=\theta A=$ X $\Delta$ s+C	$(2P_{Ai}-1)$ $\mu$	$0=\theta A=$ X $\Delta$ s+C	$(2P_{Ai}-1)$ $\mu$	$0=\theta A=$ X $\Delta$ s+C	$(2P_{Ai}-1)$ $\mu$
$S_r$	.14	.38	-.09	-.06	-.06	.06	.05	-.29
Multiple R (SSE)	.94 (.42)	.88 (1227)	.91 (.45)	.88 (898)	.94 (.18)	.89 (704)	.94 (.20)	.89 (633)
Slope (SE)	.93 (.15)	-294 (99)	.92 (.16)	24 (61)	.77 (.12)	57 (31)	.67 (.11)	-135 (110)
Intercept (SE)	-.20 (.12)	880 (99)	.04 (.13)	834 (25)	.01 (.09)	820 (15)	-.07 (.10)	862 (39)
Experiment 2: Simultaneously presented stimuli								
Spatial sep. (mm)	10		20		40		80	
$S_r$	.21	.53	.006	.43	-.29	-.09	-.38	-.58
Multiple R (SSE)	.98 (1.14)	.86 (2565)	.98 (.53)	.86 (2083)	.98 (.21)	.86 (1338)	.96 (.23)	.89 (713)
Slope (SE)	.73 (.08)	280 (115)	.73 (.07)	278 (93)	.54 (.04)	120 (74)	.36 (.05)	263 (175)
Intercept (SE)	-.21 (.18)	554 (33)	-.05 (.14)	526 (32)	.15 (.11)	569 (21)	.20 (.11)	623 (29)

Additional tests of the extended BTL and SW models were conducted by regression of binary responses and separately SRS on  $[\ln(\Phi_1)-\ln(\Phi_2)]$  and  $[\ln(\Phi_1)+\ln(\Phi_2)]$ , where  $\Phi_1$  and  $\Phi_2$  are the physical brightness values of the first (left) and second (right) stimuli in  $\text{cd/m}^2$ . This analysis revealed significant coefficients for  $[\ln(\Phi_1)-\ln(\Phi_2)]$ , all  $ps < .05$ , and for Experiment 1 statistically significant and marginally significant coefficients obtained also for  $[\ln(\Phi_1)+\ln(\Phi_2)]$ , implying  $s_1 \neq s_2$ . Specifically, for stimuli separated by an ISI of 3200 msec,  $t(388)=1.59$ ,  $p=.056$ ,  $\beta=1.92$  (response probability) and  $t(388)=1.62$ ,  $p=.053$ ,  $\beta=0.11$  (SRS), and ISI of 1600 msec,  $t(391)=1.51$ ,  $p=.066$ ,  $\beta=1.82$  (response probability),  $t(391)=1.51$ ,  $p=.066$ ,  $\beta=0.11$  (SRS), which suggests that time-order effects in brightness discrimination do not arise merely as result of an additive bias (cf. Davidson & Beaver, 1977).

*Wave theory.* Following the procedures developed by Link (1978) an average estimate of each participant's mental referent,  $S_r$ , was obtained by solving the least squares fit at which  $\theta_i A = 0$ , as a function of the brightness difference ( $\Delta s$ ) in  $\text{cd/m}^2$  between the stimuli in each pair giving 80 data points for each condition per participant. Equation 2 was then fit to mean RT as a function of  $\Delta s$ . As shown in Table 3, this analysis revealed a good least squares fit to  $S_i$  of the informational value  $\theta_i A = \ln(P_{Ai} / (1-P_{Ai}))$ , and reasonable correspondence between ERT (Equation 2), and mean RT for each condition as obtained empirically in Experiments 1 and 2.

*Diffusion model* analysis is currently ongoing using the DMAT toolbox (Vandkerckhove & Tuerlinckx, 2008). In the first instance, six nested models of increasing complexity were fit to the data as a function of stimulus brightness difference in  $\text{cd/m}^2$ ; namely, i) all parameters fixed, ii) linear regression of  $\Delta s$  on drift rates by ISI, start position fixed midway between the two boundaries iii) linear regression of  $\Delta s$  on drift rates by ISI, start position free to vary, iv) logistic regression of  $\Delta s$  on drift rates by ISI, start position free to vary, and inter-trial range of start position free to vary, v) drift rates free to vary, start position free to vary, inter-trial range of start position free to vary, and vi) all seven parameters free to vary. The results of this analysis show no significant improvement in fit beyond linear regression of stimulus difference on drift rates allowing for changes in the intercept and slope with changes in ISI and variation in the start position of the diffusion process.

## Conclusion

The findings of Experiments 1 and 2 show characteristic time- but not space-order effects in timed brightness discrimination of visual stimuli. The TOE was found to change in magnitude

and direction with changes in the temporal separation between stimuli and with changes in the absolute physical magnitude of the stimuli, whereas statistical analysis of the SOE revealed no systematic changes in magnitude and direction with changes in the absolute physical magnitude of the stimuli. Taken together, these data provide further support for the view that the TOE is a perceptual phenomenon not explainable in terms of simple response bias, verbal categorization of stimulus values toward the mean, or by the idea that the activation inspired by one stimulus is compared to a lower (or higher) fidelity mental referent of the other. The use of SRS permits consideration of current random walk and diffusion models without assumptions concerning the simple subtraction of stimulus information and hence realistic modification of these models to allow for explanations of the paired comparison of stimuli based on sensation weighting and influence of generic information.

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