DIFFERENTIAL EFFECT OF STIMULUS BRIGHTNESS IN VISUAL DURATION DISCRIMINATION

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Abstract

Twelve subjects participated in duration discrimination experiments with visually marked temporal intervals. Average interval duration was 4.8 seconds; the difference between the first and second interval was varied at nine levels. Experimental sessions consisted of two blocks: first (72 trials) with stimuli of equal brightness, second (144 trials) with stimulus brightness varied (bright–dim or dim–bright). Gaussian psychometric functions were fitted to the data and points of subjective equality (PSE) estimated for each subject/condition. The PSEs are generally negative, indicating a presentation order effect known from previous studies. In addition, we observe small but significant difference between PSEs for unequal brightness conditions, bright–dim versus dim–bright. These results bring evidence for a cross-modal interaction between subjective duration and brightness of the duration carrier: brighter stimuli are, on average, perceived as shorter. An interpretation in terms of the 'dual klepsydra model' of duration discrimination is attempted.

Time perception is known to be easily influenced by internal as well as external factors. This fact is reflected by the multitude of extant theories and models, emphasizing either the organismic, state-dependent component or the environmental, input-dependent component of temporal cognition and timing behavior [1, 2, 8]. A provisional synthesis is provided by the extended 'internal clock model' (ICM), based on the internal pacemaker–counter principle but with effective pulse rate modulated by attentional state [9].

In our 'dual klepsydra model' (DKM) of internal time representation we adopt a different scheme: attended durations are represented by integration of 'flows' of neural activity in imperfect, lossy accumulators [4, 5]. The dissipative component of the model ('loss rate', specified by parameter κ) acounts for the progressive shortening of the reproduction response [4] and for the presentation order effect in pairwise comparison of elapsed durations [6]. We hypothesized that the 'loss rate' is determined mainly by the functional state of the neural substrate, whereas the 'inflow ratio' (parameter η) may be affected by external factors [4, p. 489]. Separation of endogenous and exogenous determinants is a potential virtue of the DKM, which has not been fully realized as yet.

Following up our hypothesis, we applied a standard discrimination paradigm [6], using visual stimuli of distinctly different luminosities as 'duration carriers',[1] and tested for a differential effect of brightness contrast (exogenous factor) on duration perception.

Materials and methods

Participants. — Twelve subjects (6 female, 6 male, age range 22 to 30 years), all with normal or corrected-to-normal vision and reportedly of good health, participated in the study.[2] The subjects signed informed consent regarding the purpose of the study before the experimental session, and received EUR 10 for their participation when the session was completed.

Apparatus and stimuli. — A two-way, forced-choice duration discrimination task was used. The subjects had to compare durations of two time intervals, marked by the appearance of two visual stimuli sequentially presented on a computer screen. After the second interval elapsed, the subjects
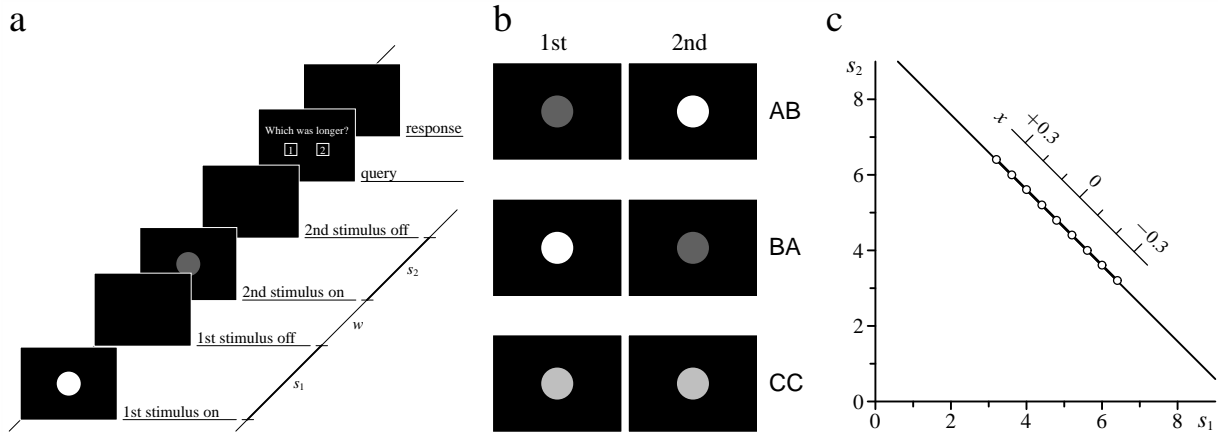
Figure 1. (a) Time chart of a discrimination trial (condition BA): s_1, s_2 = durations of the 1st and 2nd stimulus displays, respectively; w = blank pause between the 1st and 2nd stimulus. (b) Different luminosities, bright white vs. dim grey or *vice versa*, were used in the 'contrasting' conditions AB, BA; stimuli of equal luminosity were used in the 'homogenous' condition CC. (c) Manifold of stimulus durations $\mathcal{S}_c \equiv \{(s_1, s_2) \mid s_1 + s_2 = c\}$, where $c = 9.6$ s, from which nine equispaced pairs (s_1, s_2) were chosen; x = scale of relative difference (Eq. 1).

were prompted to indicate which of the two durations was longer (Fig. 1a). The experiment was controlled by a portable computer with a pointing device ('mouse') attached, which was connected to a 17" CRT monitor with a screen resolution of 800×600 pixels. Duration carriers were achromatic luminous filled circles of 100 pixels (∼42 mm) diameter, displayed on a dark background at the screen center, and observed from an average distance of ∼70 cm (angular size ∼3.5°).

Three different brightness levels of duration carriers were used: dim grey (A, RGB values 64,64,64), bright white (B, RGB values 255,255,255), and light grey (C, RGB values 128,128,128). Display luminance ratio between dim grey (A) and bright white (B) was ∼1:70. Dim grey (A) and bright white (B) were used in the 'contrasting' conditions, where the brightness of the 1st and 2nd duration carrier was alternated. Light grey (C) was used in the 'homogenous' condition, where the 1st and 2nd duration were marked by stimuli of equal brightness (Fig. 1b).

Durations of the 1st and 2nd stimulus were chosen so that $s_1 + s_2 = 9.6$ s, whereas the difference $s_2 - s_1$ was varied at nine levels, symmetrically distributed around zero with a step of 0.8 s (Fig. 1c). The interstimulus interval w was 1.2 s in all trials. For the purpose of data reduction, stimuli were parameterized by the relative difference

$$x = \frac{s_2 - s_1}{s_1 + s_2} .$$
(1)

Experimental procedure. — Each subject participated in one experimental session. The session began with three warm-up trials,[3] followed by two experimental blocks. In the first block, stimuli of equal brightness were used to mark the 1st and 2nd interval ('homogenous' condition CC). Pairs of stimuli (s_1, s_2) were presented eight times for each of the nine values of the relative difference x (Eq. 1) in a randomized order, resulting in 9×8 = 72 trials. In the second block, the brightness of the 1st and 2nd carrier was randomly alternated ('contrasting' conditions AB or BA) (Fig. 1c). As in the first block, there were eight repetitions for each x value presented in a randomized order, thus resulting in a total 2×9×8 = 144 trials.

Data reduction

For every subject and condition, data were sorted by the relative difference x and the presentation condition (CC, AB, BA) and then relative frequencies of the response "2nd interval was longer" (2) were evaluated. In addition, data from the contrasting conditions AB and BA were merged on an

individual basis to obtain a 'pseudo-homogenous' condition, in the following referred to as XX. Gaussian psychometric functions (PMF)

$$\Pr(\mathbf{2}|x) = \Phi\left\{ k\,\frac{x-\theta}{\omega} \right\}, \tag{2}$$

were fitted to the data, using the maximum likelihood estimates of parameters θ and ω.[4] Given an estimate $\widehat{\theta}$, the point of subjective equality (PSE) $(s_1^\circ, s_2^\circ) \in \mathcal{S}_c$ is determined by

$$s_1^\circ = \frac{1-\widehat{\theta}}{2}\,c\,, \quad s_2^\circ = \frac{1+\widehat{\theta}}{2}\,c\,. \tag{3}$$

For descriptive purposes, a 'ratio of subjective equality' (RSE)

$$\frac{s_2^\circ}{s_1^\circ} = \frac{1+\widehat{\theta}}{1-\widehat{\theta}} \tag{4}$$

was also calculated. Negative values of $\widehat{\theta}$ (*i.e.*, RSE < 1) indicate 'subjective shortening' of past durations, which is explained by a loss of internal representation. Then the corresponding value of κ can be estimated for the homogenous conditions CC, XX by iterative solution of the equation

$$s_2^\circ = \mathrm{krf}(s_1^\circ, w)\,, \tag{5}$$

where krf denotes the klepsydraic reproduction function [4] with parameter $\eta = 1$.[5]

Results

Of primary interest are indifference points θ, identifying the PSEs (Eq. 3) and other derived parameters. Statistics reported below are based on estimates of $\widehat{\theta}$ for individual subjects. One-sample t tests (11 d.f., two-tailed Ps) were used to secure deviations of $\widehat{\theta}$ from zero for a given condition, or intra-individual differences of $\widehat{\theta}$ between conditions.

Individual $\widehat{\theta}$ values were predominantly negative in all experimental conditions (CC: 10/12, AB: 8/12, BA: 11/12, XX: 9/12). For carriers of equal luminosity, the group mean $\overline{\theta}_{CC}$ was -0.0579 (SD 0.0551), significantly deviating from zero ($t = 3.640$, $P < .01$). Merged data from contrasting conditions AB and BA yielded a group mean $\overline{\theta}_{XX} = -0.0554$ (SD 0.0604), *i.e.* practically identical to $\overline{\theta}_{CC}$, and also significantly deviating from zero ($t = 3.178$, $P < .01$). Except for lower acuity in the condition XX, indifference points for the two conditions are almost identical (Fig. 2a). This concurrent shift of PSEs indicates a presentation order effect (POE), which can be interpreted in terms of 'lossy' internal representation. PSE for the condition CC is $s_1^\circ = 5.078$ s, $s_2^\circ = 4.522$ s, yielding RSE = 0.89, and $\kappa = 0.0193$ s^{-1}. Similarly for the condition XX: $s_1^\circ = 5.066$ s, $s_2^\circ = 4.534$ s, RSE = 0.895, $\kappa = 0.0185$ s^{-1}.

Treating the contrasting conditions AB and BA separately, we obtain group means $\overline{\theta}_{AB} = -0.0332$ (SD 0.0810) and $\overline{\theta}_{BA} = -0.0780$ (SD 0.0621). The indifference point deviates from zero significantly only in the condition BA ($t = 4.442$, $P < .001$), but not in condition AB ($t = 1.418$, $P \approx .2$). Divergence between the two conditions also can be seen in PMFs fitted to group-averaged data (Fig. 2b). Comparing these values against results for the homogenous conditions, we find

$$\overline{\theta}_{BA} < \overline{\theta}_{CC} \approx \overline{\theta}_{XX} < \overline{\theta}_{AB}\,,$$

where the indifference points for the opposite variations of carrier brightness, bright–dim versus dim–bright, are displaced approximately symmetrically w.r.t. to the equal-brightness condition. This suggests that variations of stimulus brightness induce a second-order effect, superimposed on the primary presentation order effect.
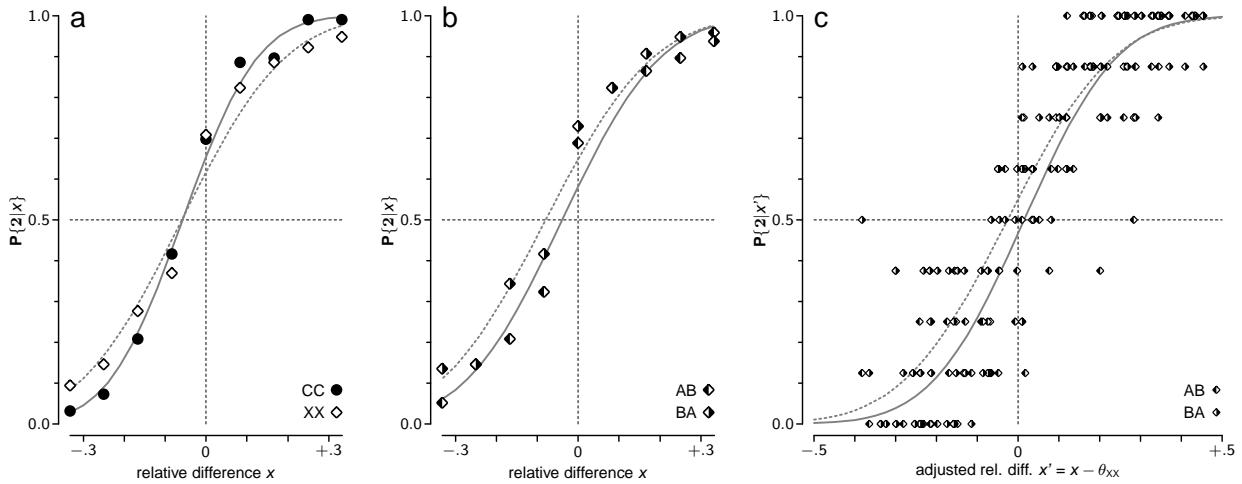
Figure 2. (a) Psychometric functions (PMFs) fitted to group-averaged data for the homogenous conditions CC (equal brightness: solid curve) and XX (dim–bright and bright–dim averaged: dashed curve). (b) PMFs fitted to group-averaged data for the contrasting conditions AB (dim–bright: solid curve) and BA (bright–dim: dashed curve). (c) PMFs for the contrasting conditions, plotted as functions of relative difference x individually adjusted to the threshold θ_{XX}. The small rhomboids indicate individual relative frequencies, not group averages as in panels a,b.

To assess this second-order effect, we compare indifference points for the contrasting conditions intra-individually,[6] calculating $\Delta\theta \equiv \theta_{BA} - \theta_{AB}$ for each subject. The group average $\overline{\Delta\theta}$ is -0.0465 (SD $= 0.0752$), expectedly and significantly negative ($t = 2.140$, $P \approx .05$). PSEs for the bright–dim order are shifted towards negative values (lower RSE) compared to dim–bright order; in other words, "durations of brighter carriers are perceived as shorter." — The net effect of brightness variation is illustrated in Fig. 2c, where relative frequencies of response **2** in conditions AB, BA are plotted as functions of variable $x' \equiv x - \theta_{XX}$ and PMFs were re-fitted to these data.[7]

Discussion and conclusion

Analysis of duration discrimination data with varied luminosity of stimuli revealed two effects:

1. *Discrimination asymmetry.* Indifference points (θ) in all conditions are shifted toward negative values, significantly in conditions CC and BA, non-significantly in condition AB. This is interpreted as a general presentation order effect (POE), resulting in 'subjective shortening' of the first time interval (s_1) against the second interval (s_2) by $\sim 11\%$.

2. *Differential effect of varied luminosity.* Indifference points differ significantly between contrasting conditions AB and BA. The negative shift of θ_{BA} relatively to θ_{AB} indicates a cross-modal interaction between stimulus brightness and its perceived duration.[8]

We obtained a very good agreement between PSE shifts in conditions with equal (CC) or undifferentiated (XX) luminosity of durations carriers (Fig. 2a) This allows us to interpret the 'brightness split' of the PMFs in the contrasting conditions (Fig. 2b,c), with the PSEs symmetrically displaced around θ_{XX}, as a secondary effect superimposed on the POE.

DKM explains the POE in interval discrimination [6], as well as the progressive shortening of response in interval reproduction [4], by a continuous loss of accumulated duration representation (parameter κ). However, the internal representation depends also on flows i_1 and i_2 into the internal accumulators during perception of the 1st and 2nd interval, respectively; hence the rôle played by the 'inflow ratio' $\eta \equiv i_1/i_2$ as a second parameter in the DKM. We proposed [4] that κ is determined mainly by the functional state of the neural substrate—a conjecture supported by some findings on chronobiological [3] or neurochemical [7] influences on κ—and we argued that the inflow ratio η may be affected by external/environmental factors such as, for example, physical properties of

perceived duration carriers. In other words, the DKM provides a conceptual framework, as well as computational tools, for separation of endogenous (organismic) and exogenous (environmental, stimulus-based) factors co-determining perception of temporal durations.

Data from the reported study give an opportunity to apply this approach. The assumption of relatively stable loss rate during experimental sessions is supported by almost exactly identical κ estimates for conditions CC and XX, which refer to separate blocks of trials. It is thus plausible to take κ in condition XX as a given constant and, based on this knowledge, calculate inflow ratios η accounting for additional shifts of PSEs in the contrasting conditions AB and BA. The resulting values are $\eta_{AB} = 1.0455$ and $\eta_{BA} = 0.9524$,[9] where $\eta > 1$ and $\eta < 1$ implies $i_1 > i_2$ and $i_1 < i_2$, respectively. The estimates suggest that inflow into a duration integrator is reduced by $\sim$5 per cent in perception of the bright stimulus, compared to the dim stimulus. Consequently, duration of the bright stimulus is relatively under-represented—in brief, "brighter seems shorter."

While the above-given interpretation is mathematically reasonable, its translation into under-lying neural processes remains a challenge. Indeed, why should *increased* sensory input (bright stimulus) effectuate a relative *decrease* of input into a duration integrator? In our original work on the dual klepsydra model, the internal 'flows' were abstract entities, not specified in terms of neuro-physiology. However, increasing attention has been recently paid to interoceptive sensations and their cortical integration as a possible neural basis of time perception [8, p. 1961ff]. Building upon this conjecture, we may speculate that an excitatory action from external (sensory) input causes a relative inhibition of neural structures integrating the stream of ascendent interoceptive sensations; and that a monotonic relation holds (at least within a particular range) between externally induced focal excitation and peripheral inhibition. This inhibitory mechanism would be naturally automatic, not requiring conscious relocation of 'attention'.[10]

Summarizing, our data reveal a small but significant cross-modal interaction between brightness and subjective duration of presented stimuli. The interaction effect is superimposed on the presentation order effect, which is accounted for by the loss term (κ) in the DKM. The estimate of mean κ is $\sim 2 \times 10^{-2}$ s^{-1}, in good agreement with previous studies [6, 7]. The interaction effect can be interpreted in terms of variations of the inflow ratio η. Estimates of η for the unequal brightness conditions indicate changes of internal flows by about $\pm 5\%$ due to brightness variation. To our knowledge, this is the first time that an external stimulus-induced change of inflows was numerically estimated from experimental data.

Concluding, we notice that the interaction effect is of very small magnitude and should be confirmed in a replication study before further interpretations or experimental variations are attempted. Nonetheless, the reported effect posits a series of questions for further research, such as: existence of the effect for other perceptual modalities (*e. g.*, somatosensory); functional dependence of the effect magnitude on variable physical properties of the carriers; individual differences in susceptibility to the interaction ('reactors' vs. 'non-reactors'[11]), etc. The proposed two-parametric model (DKM) provides an analytical tool for quantification of modality-specific interactions effects, and for their separation from the ubiquitous presentation order effect.

Notes

[1] We never perceive 'time as such'; we perceive events in the external world (*e. g.*, sensory stimuli) or in our bodies. Thus depending on the context, 'stimulus' may denote (i) the perceived event as such, or (ii) its temporal duration as a term in a functional stimulus–response relation. To resolve the ambiguity, we refer to sensorily-perceivable events as 'duration carriers', conforming to terminology used in [4].

[2] One subject showed extremely bad discrimination performance and conveyed only *after* the session his being on antidepressant medication; he was excluded from the study and replaced by another participant.

[3] These trials were arranged solely to make the participant familiar with the experimental procedure; the results were discarded.

[4] In Eq. (2), Φ is the normal cumulative distribution function, scaled in the argument by the factor $k = \Phi^{-1}\left(\frac{3}{4}\right) \approx 0.6745$, for the sake of convenience; θ is the indifference point (discrimination threshold), and ω is an inverse of discrimination acuity at the indifference point.

[5] More details on estimating the DKM parameters from PSEs are given in [6, p. 248].

[6] Because of inter-individual variations in the primary effect size, reflected by dispersion of individual θ_{XX}, a group-based comparison between $\overline{\theta}_{AB}$ and $\overline{\theta}_{BA}$ would be statistically ineffective.

[7] This means that each subject's data have been aligned w. r. t. the indifference point determined individually for the condition XX, in order to eliminate the influence of inter-individual variability of θ_{XX} (*cf.* endnote 6).

[8] Interaction between stimulus brightness and duration is well known from temporal integration phenomena, described *e. g.* by Talbot–Plateau's law. Here, however, we are operating in the supra-second domain, *i. e.* several orders of magnitudes far away from the domain of applicability of T.–P. law.

[9] Note that product $\eta_{AB}\,\eta_{BA} = 0.996$, *i. e.* almost exactly 1. This makes sense, since the reference value of κ was obtained from θ_{XX} under assumption $\eta = 1$, and we have two luminosity levels, A and B, exchanging their positions in the contrasting conditions. Expectedly, AB $\leftrightarrow$ BA $\;\Rightarrow\; i_1 \leftrightarrow i_2$, and thus $\eta_{BA} = \eta_{AB}^{-1}$.

[10] We note in passing that 'attention' plays a rôle of a *deus ex machina* in cognitivist adaptations of the ICM. In our concept, an attentive subject perceives events in the environment, and establishes a link between their duration and internal (neural) states providing a 'measure of time'. But 'time as such' is never perceived (*cf.* endnote 1), and semantic constructs such as 'attention to time' have no place in our theory.

[11] Analysis of datasets separated by participants' gender shows that the differential effect of stimulus brightness is prevalent in the subgroup of female subjects ($\overline{\Delta\theta} = -0.0939$, SD $= 0.0738$, $t(5\,\text{d.f.}) = 3.115$, $P < .05$), while male subjects do not contribute significantly to the effect ($\overline{\Delta\theta} = +0.0009$, SD $= 0.0402$, $t(5\,\text{d.f.}) = 0.056$, n.s.). Presently we have no plausible explanation for this finding, and we refrain from its interpretation, as it is based on a *post hoc* evaluation, and the gender-defined subsamples are very small.

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