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Contraction bias in temporal estimation

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Abstract

When asked to compare the perceptual features of two serially presented objects, participants are often biased to over- or under-estimate the difference in magnitude between the stimuli. Overestimation occurs consistently when a) the two stimuli are relatively small in magnitude and the first stimulus is larger in magnitude than the second; or b) the two stimuli are relatively large in magnitude and the first stimulus is smaller in magnitude than the second; underestimation consistently occurs in the complementary cases. This systematic perceptual bias, known as the *contraction bias*, was demonstrated for a multitude of perceptual features and in various modalities. Here, we tested whether estimation of time-duration is affected by the contraction bias. In each trial of three experiments (n=20 each), participants compared the duration of two visually presented stimuli. Findings revealed over- and under-estimation effects as predicted by the contraction bias. Here, we discuss this asymmetry and describe how these findings can be explained via a Bayesian inference framework.

Keywords: Contraction bias; timing; interval comparison task; duration estimation; Bayesian inference

1. Introduction

Our perceptual system is susceptible to distortion in judgment, in the form of systematic biases. When trying to compare two serially presented objects on a specific dimension, e.g., when choosing which of two lamps provides better lighting, the perceived perceptual difference may be biased by factors unrelated to the objective physical difference, such as the order of presentation and recent history with other exemplars. One commonly observed perceptual distortion is the *contraction bias* - the tendency of observers to underestimate stimuli that are larger than expectations and overestimate stimuli that are smaller than expectations (Poulton, 1979; Sapey-Triomphe et al., 2021; Vierordt, 1868). This bias results in drawing perception

toward the *expected value*, which is typically the center of a magnitude's distribution (*The central tendency*; Hollingworth, 1910; Jazayeri & Shadlen, 2010; Karaminis et al., 2016; Poulton, 1979; Stevens & Greenbaum, 1966). Evidence shows that the center is not an absolute value, but a relative one – as it is determined relative to the context that was previously perceived (Damsma et al., 2021; Jazayeri & Shadlen, 2010; Maaß et al., 2019, 2021; Roach et al., 2017; Schlichting et al., 2018). This tendency was demonstrated in various domains, including visual length (Allred et al., 2016), color (Olkkonen & Allred, 2014), and time (Karaminis et al., 2016; Turchioe, 1948).

A specific case of the contraction bias in sequential stimuli is the *time-order effect* (*TOE*). According to this effect, the perceived difference between two items in a series can be smaller or larger than the objective difference, depending on both the order of presentation and the relation between the stimuli and the mean (Bartlett, 1939; Fechner, 1860; Hellström, 1985; John, 1975; Needham, 1935). Two stimuli with large magnitude (i.e., stimuli that fall above the distribution center), presented sequentially, tend to be perceived as smaller than their actual size, but with a larger contraction for the earlier-presented stimulus (S_1) than for the later one (S_2). If S_1 is the larger of the two, this will result in a decrease of the perceived difference between the two stimuli relative to the real difference (Fig. 1a). However, if S_1 is the smaller of the two, this will result in an increase of the perceived difference (Fig. 1b). Despite the fact that both cases feature the same physical relation between the two stimuli, their perceived relative size in these cases is determined by the context – their serial order. A reversed pattern occurs with stimuli that are smaller than the distribution center. Both stimuli tend to be perceived as larger than their actual size, but this effect is larger for the earlier-presented stimulus S_1 . If S_1 is the larger of the two, this will result in an increase of the perceptual difference between the two stimuli relative to the real difference (Fig. 1c). In contrast, if S_1 is the smaller of the two, the outcome will be a decrease of the perceptual difference (Fig. 1d).

Fig. 1 The contraction bias effect. When making judgment on two serially presented stimuli (S_1 and S_2), the representation of S_1 (in green) tends to shift toward its distribution center (M , dashed horizontal line) to a larger degree than S_2 (in blue). When stimuli magnitude is relatively large ($> M$; a-b), stimuli will be biased downward. If $S_1 > S_2$ (a), this will cause the objective physical difference to be underestimated and perceived as smaller than it is ($\delta_{\text{objective}} > \delta_{\text{perceived}}$), but if $S_1 < S_2$ (b), the downward bias will increase the perceived perceptual difference ($\delta_{\text{objective}} < \delta_{\text{perceived}}$). The reverse pattern of over- and under-estimation will occur when the stimuli magnitudes are relatively small ($< M$; c-d), since the contraction bias will shift the stimuli representation upward.

The contraction bias was previously explained via the Bayesian framework (Ashourian & Loewenstein, 2011). According to the Bayesian framework, the observer integrates the sensory representation of the currently-presented stimulus (the likelihood) with the history of previously presented stimuli (the prior), creating a posterior distribution, which in turn is used as the prior for the next trial. The contraction bias phenomenon is a demonstration of how the present stimulation combines with prior knowledge to form the perceptual experience.

Previous studies found the contraction bias in a variety of perceptual judgment tasks of various modalities and stimulus features, e.g., in auditory intensity (Berliner et al., 1977) and pitch (Lieder et al., 2019; Raviv et al., 2012), visual length (Ashourian & Loewenstein, 2011) and height (Joynson et al., 1965), and tactile vibration (Preuschhof et al., 2010). There is a reason to hypothesize that the time domain would be different than other domains, with regards

to TOE. Unlike other psychophysical features, such as loudness, size or brightness, time does not have a sensory magnitude or a physical-sensory representation. Other psychophysics features are based on a perception of physical input by the sensory organs, which can be translated into a concrete perceptual representations. Only at later stages, these concrete representations can be turned into abstract representations which can then be manipulated in working and long-term memory. In contrast, the cognitive representation of time is purely abstract from its onset and has no phenomenal existence outside memory (Riemer, 2015). A few studies have examined contraction bias effects in the time domain and specifically in duration estimation. Most of these studies used pairs of stimuli in which one of the stimuli was a standard, i.e. the same interval was repeated trial after trial (e.g., Fraisse, 1948; Stott, 1935; Woodrow, 1951). However, behavioral effects that were obtained with this design can be attributed to the activation of memory representation of the repeating stimulus. In order to study perceptual biases irrespective of memory activation, it is crucial that both stimuli of each pair will vary across trials. One early study used four intervals and a more varied combination of them and found initial evidence for contraction bias in duration estimation (Allan, 1977).

In the following study, we expanded these earlier findings by establishing the contraction bias effect of duration estimation. Here, we have conducted three experiments (total $N=60$), using two-alternative forced-choice (2AFC) interval comparison tasks. We first tested the existence of the contraction bias effect in a reanalysis of previously collected data (Tal-Perry & Yuval-Greenberg, 2021), and then validated and expanded these findings in two preregistered experiments. Our results show a substantial contraction bias effect in all three datasets. These results suggest that contraction bias affects the way we perceived time, but that the bias interacts with the interval timescale. We discuss these findings and their implications for studies of time perception.

2. Method

2.1 Participants

A total of 60 participants were included in this study, 20 in each experiment and only one per experiment (Exp. 1: 12 females, one left-handed, mean age 22.25 ± 2.30 standard deviations [SD]; Exp. 2: 11 females, one left-handed, mean age 25.00 ± 3.60 SD; Exp. 3: 13 females, 2 left-handed, mean age 23.86 ± 2.59 SD). Exp. 1 was a reanalysis of previous data from Tal-Perry & Yuval-Greenberg (2021). Participants in that experiment performed two tasks (duration and tilt discrimination) but here we analyze only data of the duration task. Exp. 2 and 3 were preregistered (see Data Availability statement). Sample sizes of Exp. 2 and 3 were calculated according to a power analysis based on the data from Tal-Perry & Yuval-Greenberg (2021) and declared in the preregistration document. All participants reported normal or corrected-to-normal vision and no known neurological disorders. Participants were compensated for their participation via payment or course credits. Participants signed an informed consent form, and the experiment was approved by the ethical committee of Tel-Aviv University and the School of Psychological Sciences.

2.2 Stimuli

A cross ($0.4 \times 0.4^\circ$) was used as a fixation target and changed color as described in the procedure. This fixation cross was the only stimulus used in Exp. 2 and 3. In Exp. 1 there were also tilted Gabor patches (2° in diameter, with a spatial frequency of 5 cpd and 30% contrast). All stimuli were presented at screen-center, using a mid-black background.

2.3 Procedure

Procedure was identical between experiments, except when stated otherwise. Participants were sited in a dimly-lit room, at a distance of 100cm from the computer monitor (24" LCD ASUS VG248QE, $1,920 \times 1,080$ pixels resolution, 120 Hz refresh rate, mid-gray luminance was measured to be 110 cd/m^2), with their head resting on a head- and chin-rest. The experiments were controlled by Psychtoolbox v3 (Brainard, 1997) running on Matlab 2015a (The

Mathworks, USA). Participants' gaze position was monitored binocularly using EyeLink 1000 Plus infrared video-oculographic desktop mounted system (SR Research Ltd., Oakville, ON, Canada), with a sampling rate of 1000 Hz. The purpose of eye tracking was for real-time fixation validation.

At the beginning of each trial, a black fixation-cross was presented for an inter-trial interval (ITI) of 500 ms of stable fixation (gaze located within 1.5° from screen-center, as verified in real-time by eye-tracking) and an additional jittered 200-700 ms time period. At trial onset, fixation-cross color changed from black to blue, signaling the onset of the first interval (I_1). This blue cross remained on screen for the varying durations of I_1 (see details below), until it was replaced by a blank screen (in Exp. 2 and 3) or by a brief (33 ms) presentation of a Gabor patch followed by a blank screen (in Exp. 1). In all experiments the blank screen was presented for 300 ms before the blue fixation-cross reappeared, indicating the onset of the second interval (I_2), which also lasted for varying durations (see details below). At the offset of I_2 , the fixation-cross was, again, replaced by a blank screen (Exp. 2 and 3) or another Gabor patch followed by a blank screen (Exp. 1). Following this, participants were requested to report which of the intervals was longer, via a button press on one of two keys. In Exp. 1 they were asked to ignore the Gabor patches. Response time was unlimited. Upon responding, a green or red fixation-cross appeared for 500 ms, providing feedback on whether participant's response was correct or incorrect, respectively. Trial procedure is depicted in **Fig. 2**.

In Exp. 1, I_1 duration was set to 1.0-3.0 s in 0.5 s increments. In Exp. 2, I_1 duration was set to 1.2-3.6 s in 0.6 s increments. In Exp. 3, I_1 duration was set to either 0.8-2.4 s in 0.4 s increments (short-duration condition) or to 1.6-3.2 s in 0.4 s increments (long-duration condition). In all experiments, I_1 was uniformly distributed, and trial identity was random within a block. In all trials of the three experiments, I_2 duration was slightly shorter or longer than the current trial's I_1 duration. In order to equate psychological duration and physical time across intervals (Grondin, 2001), the difference between I_1 and I_2 was percentage-based and

Fig. 2 Trial procedure in Exp. 2 and 3. The duration distribution of the first interval (I_1) varied between experiments (see text for details). The second interval (I_2) was set to be slightly shorter or longer than the current trial's I_1 duration, with percentage difference set individually via a staircase procedure. Participants were asked to respond which of the two intervals was longer in duration, and feedback (red or green cross for correct and incorrect response, respectively) was displayed for 500 ms after a response was registered. In Exp.1 only (not depicted here), task-irrelevant Gabor patches were additionally displayed for 33 ms after I_1 and after I_2 , and participants were asked to ignore them.

depended on I_1 duration, with the percentage-difference determined individually per participants based on a staircase procedure, as described below.

Exp. 1 and 2 consisted of one session (of analyzed 80 trials). Exp. 3 consisted of two experimental sessions, with short-duration condition presented on one session and the long-duration condition on the other session. The distribution of the intervals in Exp. 3 changed between sessions, with session-order counter-balanced between participants (average of 23 days between sessions, range 5-80 days). Each experimental session started with a practice block of 10 random trials. A staircase block was then administered to determine the $I_1 - I_2$

percentage-difference individually, with staircase regiment used aiming at approximately 0.80 accuracy rate in the duration-discrimination task. The difference in duration between I_1 and I_2 was initially set to 25%, and the procedure followed a 1-up 3-down regiment using logarithmically changing step-size, with I_1 being randomly drawn from the experiment's duration distribution. Stopping rule was set to either four consecutive direction reversals, or 100 trials, whichever came first. The average $I_1 - I_2$ percentage-difference of the last 10 staircase trials was used for the main experiment (two sessions in Exp. 3), and determined the duration of I_2 . There was no evidence for differences between the three experiments in the individually-determined percentage-difference ($F(2, 59) = 1.11, p = .338$; Exp. 1: $M_{|I_1 - I_2|} = 19.7\% \pm 6.6\%$ SD; Exp. 2: $M_{|I_1 - I_2|} = 24.0\% \pm 11.4\%$ SD; Exp. 3: $M_{|I_1 - I_2|} = 21.8\% \pm 9.8\%$ SD). The staircase procedure was followed by five experimental blocks of 80 trials each. The total number of trials included in the analysis per participant was 400 in Exp. 1 and 2 and 800 in Exp. 3 (400 for the short-duration condition and 400 for the long-duration condition). In Exp. 2 and 3 all blocks of the main experiment were included in the analysis. In Exp. 1, which was originally designed for a different purpose, there were seven non-analyzed blocks: some including a different task (an orientation-discrimination task) and others including a different temporal routine (I_1 was fixed at 1 s throughout the block).

2.4 Statistical analysis

Details on statistical analysis are described in the preregistration document on the project's OSF directory (see Data availability statement). The few places we deviated from preregistered procedure are indicated below.

Participant's single-trial response result (correct/incorrect) was modeled using a generalized linear mixed model (GLMM) assuming a binomial family of response and a logit link, i.e., using a logistic mixed model (Jaeger, 2008). The following fixed factors were modeled: a. I_1 Duration (Exp. 1: 1.0/1.5/2.0/2.5/3.0 s; Exp. 2: 1.2/1.8/2.4/3.0/3.6 s; Exp. 3:

0.8/1.2/1.6/2.0/2.4/2.8/3.2 s); b. I_2 Relative Duration - the duration of I_2 relative to I_1 (shorter/longer); and c. the interaction term between them. In Exp. 3, we additionally included I_1 Distribution (short-duration /long-duration) and its interaction terms as fixed factors, leading to a nested design (owing that not every I_1 level appeared in each distribution). A sequential difference coding scheme was used for I_1 Duration, i.e., each interval was compared to its neighboring interval, and sum contrasts were used for I_2 Relative Duration and I_1 Distribution.

To balance between Type-I and Type-II errors (Matuschek et al., 2017), the model's random effect structure was chosen as the model most parsimonious with the data (Bates, Kliegl, et al., 2015). A model with a random intercept by subject, random slopes for each fixed factor by subject and the accompanying correlation parameters was considered first. Converged models were fitted with random interaction slopes by subject, while models failing to converge or reaching singular values were trimmed of the random factor that explained the least amount of variance, repeating until model successfully converged with no singular values.

Statistical significance for main effects and interactions was determined by comparing a model with the effect to a reduced model without the effect (akin to Type-II Sum of Squares [SS]), using a likelihood-ratio test. To support null results ($p > .05$), Bayes Factor (BF) was approximated between the two models using Bayesian Information Criterion (BIC) approximation (Wagenmakers, 2007), and was reported with the null model in the nominator for interpretation ease (i.e., as BF_{01}). Simple effects for I_2 Relative Duration were calculated on back-transformed estimated odds ratios with I_1 Duration as the modulator. In Exp. 3, we additionally tested I_2 Relative Duration by I_1 Distribution interaction effects (i.e., contrast of contrasts), with the overlapping I_1 Duration levels (i.e., 1.6/2.0/2.4 s) as the modulator. While in the preregistered procedure we did not specify whether a multiple comparisons correction will be used, we applied a false-discovery rate (FDR) correction (Benjamini & Hochberg,

1995) for the simple effect analyses results, and report both the corrected and uncorrected p values for transparency.

Analyses were done in R v4.0.3 using R-studio v1.3.959 (R Core Team, 2018) and lme4 (Bates, Mächler, et al., 2015), with model diagnostics done using the performance (Lüdtke et al., 2020) and afex (Singmann et al., 2020) packages, BF approximated using bayestestR package (Makowski et al., 2019) and simple effects contrasted using the emmeans package (Lenth, 2020). An R-markdown file describing all the model fitting steps and diagnostic checks on the final model is available for each of the analyses at the project's OSF directory (see Data Availability statement).

3. Results

3.1 Experiment 1

Single-trial responses were analyzed using a GLMM, assuming a binomial family of response with a logit link function, with I_1 Duration (1.0/1.5/2.0/2.5/3.0 s), I_2 Relative Duration (shorter/longer), and their interaction as fixed factors, allowing for a random intercept, and random slope for I_2 Relative Duration by subject. Full model description and diagnostic checks are available on the project's OSF directory (see Data Availability statement).

As can be seen in **Fig. 3a**, a prominent contraction bias effect was observed, such that participants performed higher at trials in which $I_2 < I_1$ when I_1 duration was shorter than the mean, and vice-versa (performance better at trials in which $I_2 > I_1$) when I_1 was longer than the mean, with the majority of participants displaying this pattern (see **Fig. 3b**). This effect was manifested as a significant interaction effect between I_1 Duration and I_2 Relative Duration ($\chi^2(4) = 336.06, p < .0001$), which was accompanied by a significant main effect for I_1 Duration ($\chi^2(4) = 88.97, p < .0001$) but no significant main effect for I_2 Relative Duration ($\chi^2(1) = 0.83, p = .364, BF_{01} = 59.19$). Simple effect analysis revealed significant differences between trials in which $I_2 < I_1$ and trials in which $I_2 > I_1$, for all I_1 interval durations except

Fig. 3 Performance in Exp. 1 ($N=20$). **a** Accuracy for Shorter and Longer I_2 trials for each I_1 duration. Error bars designate ± 1 standard error from the condition's mean, corrected for within-subject variability (Cousineau & O'Brien, 2014). Reported statistics based on odds ratio with I_2 shorter trials in the nominator (see Table 1) and are FDR-corrected. * $p < .05$; *** $p < .001$; ns indicates not significant ($p > 0.05$). **b** I_2 Relative Duration effects for each participant and I_1 duration, with overlapping data points represented in shaded color, and with the diagonal line representing the identity line (accuracy in $I_2 < I_1$ trials = accuracy in $I_2 > I_1$ trials).

I_1 duration	$I_{2s} - I_{2l}$ estimate [%]	z_{ratio}	p	p_{FDR}
1 s	32.73 [21.45 44.02]	5.68	< .001	< .001
1.5 s	0.47 [-6.75 7.68]	0.13	.899	.899
2 s	-7.23 [-13.94 -0.52]	-2.11	.035	.043
2.5 s	-17.28 [-24.06 -10.49]	-4.99	< .001	< .001
3 s	-16.65 [-22.90 -10.40]	-5.22	< .001	< .001

Table 1 Statistical analysis of Simple effects of Exp. 1 ($N=20$). Simple effects contrasting I_2 relative duration (Shorter minus Longer) for each I_1 duration. Model estimates were back-transformed to probability estimates for clarity, and are reported with 95% confidence interval. Reported statistics based on odds ratio with I_2 Shorter trials in the nominator. Both uncorrected and FDR-corrected p values are reported. Significant contrasts are in blue. I_{2s} and I_{2l} stand for Shorter and Longer I_2 relative to I_1 trials, respectively.

the $I_1 = 1.5$ s interval (see **Table 1**). This suggested that the equilibrium point where performance was similar between I_2 shorter and longer trials occurred at 1.5 s, and not at the center of the distribution at 2 s as could have been expected. Overall, the pattern of results from this experiment suggests that participants shifted their I_1 representation according to their subjective distribution center, but that this center was biased to be lower than the objective distribution's center.

The original experiment from which the data of Exp. 1 was taken included additional experimental conditions which were not analyzed here but may have affected performance. Specifically, participants of that experiment performed one block in which I_1 was fixed at 1 s, thereby providing a possible explanation for the observed shift in the equilibrium point. Exp. 2 was designed to test this question and also provide a replication and generalization of Exp. 1 findings. In Exp. 2 we used a variable I_1 distribution with a slightly different I_1 durations distribution than that used in Exp. 1, for generalization purposes.

3.2 Experiment 2

233 The observed pattern of results was similar to Exp. 1 (see **Fig. 4**), with effect direction
 234 supporting the existence of a contraction bias. As in Exp. 1, we observed a significant main
 235 effect for I_1 Duration ($\chi^2(4) = 51.11, p < .0001$), no effect for I_2 Relative Duration ($\chi^2(1) =$
 236 $0.84, p = .358, BF_{01} = 59.36$), but a significant interaction of I_1 Duration and I_2 Relative
 237 Duration ($\chi^2(4) = 411.30, p < .0001$). Simple effect analysis of I_2 relative duration by I_1
 238 duration was consistent with Exp. 1 results (see **Table 2**) – a significant difference was
 239 observed for all the I_1 intervals, except 1.8 s. Again, suggesting that the perceived distribution
 240 center was earlier than the objective one.

Fig. 4 Performance in Exp. 2 ($N=20$). **a** Accuracy for Shorter and Longer I_2 trials for each I_1 duration. Error bars designate ± 1 standard error from the condition's mean, corrected for within-subject variability (Cousineau & O'Brien, 2014). Reported statistics based on odds ratio with I_2 shorter trials in the nominator (see Table 2) and are FDR-corrected. $**p < .01$; $***p < .001$; ns indicates not significant ($p > 0.05$). **b** I_2 Relative Duration effects for each participant and I_1 duration, with overlapping data points represented in shaded color, and with the diagonal line representing the identity line (accuracy in $I_2 < I_1$ trials = accuracy in $I_2 > I_1$ trials).

I_1 duration	$I_{2s} - I_{2l}$ estimate [%]	z_{ratio}	p	p_{FDR}
1.2 s	40.44 [27.66 53.22]	6.20	< .001	< .001
1.8 s	7.68 [-1.99 17.36]	1.56	.120	.120
2.4 s	-13.27 [-22.76 -3.81]	-2.75	.006	.007
3.0 s	-21.40 [-30.87 -11.93]	-4.43	< .001	< .001
3.6 s	-26.30 [-35.61 -16.98]	-5.53	< .001	< .001

Table 2 *Statistical analysis of simple effects of Exp. 2 (N=20).* Simple effects contrasting between I_2 relative duration (short minus long) for each I_1 interval. Model estimates were back-transformed to probability estimates for clarity, and are reported with 95% confidence interval. Reported statistics based on odds ratio with I_2 shorter in the nominator. Both uncorrected and FDR-corrected p values are reported. Significant contrasts are in blue. I_{2s} and I_{2l} stand for shorter and longer I_2 relative to I_1 trials, respectively.

Findings of Exp. 1 and 2 showed that the equilibrium point of the contraction bias effect was earlier than the objective distribution center. This may suggest that the perceived distribution center was earlier than the objective one. To support this hypothesis, we conducted an additional experiment, in which the distribution center was manipulated within participants. The procedure was identical to that of Exp. 2, except that participants performed the task in two separate sessions, and I_1 Duration distribution was manipulated between sessions to be either short (short-duration condition: 0.8-2.4 s in 0.4 s increments) or long (long-duration condition: 1.6-3.2 in 0.4 s increments). Results were analyzed similarly to the previous experiments, except that Distribution and its interaction terms were added as fixed factors to the model, while allowing for a random intercept, random slopes for Distribution and for I_2 Relative Duration, and a random I_2 Relative Duration X Distribution interaction slope by subject.

3.3 Experiment 3

Consistently with the previous experiments, we found a significant main effect for I_1 Duration ($\chi^2(6) = 129.33, p < .0001$), no effect for I_2 Relative Duration ($\chi^2(1) = 0.01, p = .929, BF_{01} = 125$), and a significant interaction between two factors ($\chi^2(6) = 1078.90, p < .0001$). Importantly, the results show that this interaction occurred in both the short-duration ($\chi^2(4) = 734.80, p < .0001$) and long-duration ($\chi^2(4) = 347.36, p < .0001$) conditions (in different sessions), with pattern supporting the existence of a contraction bias in both conditions (see **Fig. 5**). Simple effects analysis for I_2 relative duration with I_1 Duration as a modulator revealed significance differences in performance for all intervals except the 1.6 s interval of the short-duration condition, which corresponds to the objective center of that distribution (see **Table 3**).

Fig. 5 Performance in Exp. 3 ($N=20$). **a** Accuracy for Shorter ($I_2 < I_1$) and Longer ($I_2 > I_1$) trials for each I_1 duration of the Short- (above) and Long- (below) duration conditions. Error bars designate ± 1 standard error from the condition's mean, corrected for within-subject variability (Cousineau & O'Brien, 2014). Reported statistics based on odds ratio with I_2 shorter trials in the nominator (see Table 3) and are FDR-corrected. * $p < .05$; *** $p < .001$; ns indicates not significant ($p > .05$). **b** I_2 Relative Duration effects for each participant and I_1 duration of the Short- (left) and Long- (right) duration conditions, with overlapping data points represented in shaded color, and with the diagonal line representing the identity line (accuracy in $I_2 < I_1$ trials = accuracy in $I_2 > I_1$ trials).

263 According to the reversal in direction of I_2 effect between the 2 and 2.4 s intervals of the Long-
 264 duration condition, it is plausible to assume the perceived distribution center occurred between
 265 these intervals. Distribution significantly modulated I_1 Duration ($\chi^2(2) = 7.96$, $p = .019$),
 266 indicating that performance between the overlapping I_1 intervals differed between
 267 distributions, and likewise, Distribution significantly modulated I_2 Relative Duration ($\chi^2(1) =$
 268 24.00 , $p < .0001$), indicating that the size of the I_2 effect differed in magnitude between the
 269 two distributions. Despite not finding a significant 3-way interaction between the fixed terms
 270 ($\chi^2(2) = 2.94$, $p = .223$, $BF_{01} = 3673$), likely due to low power, we have followed the
 271 preregistered plan, to inspect the 2-way interactions of Distribution by I_2 Relative Duration,
 272 separately for each of the three overlapping I_1 intervals (1.6, 2.0, 2.4 s). This contrast of

I_1 duration	$I_{2s} - I_{2l}$ estimate [%]	z_{ratio}	p	p_{FDR}
Short distribution				
0.8 s	63.02 [48.13 77.90]	8.30	< .001	< .001
1.2 s	17.99 [9.15 26.83]	3.99	< .001	< .001
1.6 s	-1.90 [-9.05 5.24]	-0.52	.602	.602
2.0 s	-19.05 [-26.75 -11.35]	-4.85	< .001	< .001
2.4 s	-32.08 [-42.08 -22.08]	-6.29	< .001	< .001
Long distribution				
1.6 s	24.84 [15.91 33.77]	5.45	< .001	< .001
2.0 s	7.21 [0.94 13.47]	2.26	.024	.030
2.4 s	-5.766 [-0.20 -11.34]	-2.03	.042	.047
2.8 s	-17.10 [-24.86 -9.34]	-4.32	< .001	< .001
3.2 s	-23.78 [-33.17 -14.31]	-4.94	< .001	< .001

Table 3 Statistical analysis of simple effects of Exp. 3 ($N=20$). Simple effects contrasting between I_2 relative duration (short minus long) for each I_1 interval. Model estimates were back-transformed to probability estimates for clarity, and are reported with 95% confidence interval. Reported statistics based on odds ratio with I_2 shorter trials in the nominator. Both uncorrected and FDR-corrected p values are reported. Significant contrasts are in blue. I_{2s} and I_{2l} stand for shorter and longer I_2 relative to I_1 trials, respectively.

I_1 duration	Interaction estimate [%]	z_{ratio}	p	p_{FDR}
1.6 s	-21.17 [-29.43 -12.92]	-5.03	< .001	< .001
2.0 s	-22.25 [-30.07 -14.42]	-5.57	< .001	< .001
2.4 s	-20.93 [-28.51 -13.35]	-5.41	< .001	< .001

Table 4 *Statistical analysis of simple interaction effects of Exp. 3 ($N=20$).* Simple interaction effects for I_2 Relative Duration by Distribution for each of the overlapping I_1 durations. Contrasts were calculated by subtracting between I_2 relative duration (shorter minus longer) within each distribution, and then subtracting between distributions (short-duration condition minus long-duration condition). Model estimates were back-transformed to probability estimates for clarity, and are reported with 95% confidence interval. Reported statistics based on odds ratio [(short-duration condition (I_2 shorter / I_2 longer)) / ((long-duration condition (I_2 shorter / I_2 longer))]. Both uncorrected and FDR-corrected p values are reported. Significant contrasts are in blue.

contrasts analysis (see **Table 4**) revealed that the I_2 relative duration effect was significantly modulated by the distribution of the intervals, in each of the overlapping I_1 intervals. Overall, the results of Exp. 3 are consistent with the results of the other two experiments and further suggest that the shift in perceived distribution center occurs for duration estimation of long (1.6-3.2 ms) and not short (0.8-2.4 s) intervals.

3.4 Sequential analysis

In experiments 1-3 we tested how the relation between I_1 , I_2 , and the distribution center affected performance. In an exploratory analysis, which was not preregistered, we sought to determine whether the preceding trial's I_2 affected the representation of the current trial's I_1 . This analysis is reported in the **Online Supplementary Material S1**.

4. Discussion

In this study, we examined whether judgment about time intervals is subject to a contraction bias toward the center. Using a 2AFC interval comparison task, we demonstrated in three separate experiments substantial contraction bias effects. A second finding of the present study is that when longer interval ranges were used (1-3 s in Exp. 1, 1.2-3.6 s in Exp. 2 and 1.6-3.2 s in Exp. 3): contraction converged toward a point that deviated leftward from the objective

center of the distribution, indicating that the subjective center was underestimated. However, when shorter intervals (0.8 – 2.4 s) were used in Exp. 3, no such asymmetry was found, suggesting that the leftward shift is contingent on the range of intervals.

4.1. Contraction bias in duration comparison

Most of the earlier studies employed a design in which there was a standard “anchor” interval that was repeated at every trial (e.g., Hellström, 1977; Stott, 1935; Woodrow, 1935). With this kind of design, the effect may be attributed to the repeated activation of memory representation of the standard interval, rather than to perceptual processes. The purpose of the present study was to examine perceptual processes irrespective of memory and, therefore, we randomly varied the pairs of intervals so that there was no repeating standard. One early study, which applied a similar approach to ours and used varied pairs of intervals, has demonstrated contraction bias effects that are consistent with our findings (Allan, 1977). However, that study was different than the present one in a few respects: a. it employed fewer intervals and therefore there were fewer pairing options; consequently, reliance on memory was not fully excluded; b. the timed stimuli appeared at different spatial locations, thereby dependencies between time and space were not eliminated; and c. participants received no trial-by-trial feedback. This last point is important because previous studies have suggested that the use of feedback eliminates the TOE (Jamieson & Petrusic, 1976, 1978). Here we show that in our hands, this is not the case, as the effect was robustly observed in all three experiments.

4.2 The equilibrium point

The equilibrium point is defined as the point where the contraction bias does not affect performance. In many studies of the contraction bias this equilibrium point is found at the objective center of the distribution. For example, Lieder et al. (2019) examined the contraction bias in pitch discrimination, and found that the equilibrium point was the center of the pitch distribution. However, other studies found the equilibrium point to be shifted from center. For

example, Sapey-Triomphe et al. (2021) found a leftwards shifted equilibrium point when participants were asked to compare the sizes of two visual stimuli. Similarly, in the present study, the equilibrium point was shifted leftward for long, supra-second, intervals; but in our study there was no such shift for shorter, sub-second, intervals.

Such asymmetries in the equilibrium point may reflect that perceptual contraction is not towards the center of the distribution but towards another point on the distribution (e.g., the lower third point in our case). According to this interpretation, the asymmetry does not reflect a bias away from the center, but simply reflects the contraction goal. However, considering that previous studies using a duration reproduction task, have demonstrated a robust perceptual attraction to the center of the distribution (Cicchini et al., 2012; Coull et al., 2013; Gu et al., 2015; Jazayeri & Shadlen, 2010), these asymmetries may reflect a bias away from this basic center-attraction. Two different biases may explain this phenomenon: a reporting bias – the tendency of participants to consistently provide one response more than the other; and a perceptual bias – their tendency to underestimate the center of the distribution.

The first, criterion-based, explanation was suggested by Sapey-Triomphe et al., (2021) as an interpretation of a similar leftward shift in the equilibrium point observed when participants were asked to compare the size of two discs. According to this interpretation, participants of our experiment tended to choose the second stimulus as the longer more often than the first one, but only when the intervals were relatively long. For shorter intervals, there was no such report bias. Importantly, changes in the criterion can explain the shift in the equilibrium point as described here but they cannot explain the contraction bias per se; i.e., how responses are modulated not only by the relation between I1 and I2 but also by their magnitudes. The second, perceptual, explanation suggests that participants tended to underestimate the center of the interval distribution. According to this interpretation, the finding of different biases for different interval duration suggests that there are different levels

of estimation accuracies for different magnitudes of the stimulus. For example, in the temporal domain this finding may reflect a mechanistic difference between temporal estimation of supra- and sub-second intervals. Evidence suggests that, whereas the supra-second time perception is more cognitively mediated through attention, working memory and counting strategies (Grondin et al., 1999, 2004); sub-second time perception is more automatic and motor-related (Lewis & Miall, 2003b). This is also consistent with findings of brain imaging studies showing dissociable brain areas that are activated for each category (Hayashi et al., 2014; Lewis & Miall, 2003a; Murai & Yotsumoto, 2016; Wiener et al., 2010). Consistently with its more automatic and motor-related nature, it could be hypothesized that time estimation at the sub-second range is more susceptible to the contraction bias, leading to a larger effect for the shorter relative to longer I_1 s. More generally, this could also suggest that the contraction bias affects automatic and motor processes to a larger degree than cognitive processes. Future studies could compare between these competing hypotheses by employing interval distributions which are exclusively within the sub-second ranges.

4.3 Bayesian inference and the contraction bias

Findings of the present study can be explained by a Bayesian framework (Ashourian & Loewenstein, 2011), that is, by the integration between the currently-presented interval and prior knowledge regarding its distribution. Indeed, previous studies have demonstrated that time perception may be governed by a Bayesian process (Burr et al., 2013; Cicchini et al., 2012; Gu et al., 2015; Jazayeri & Shadlen, 2010; Shi et al., 2013). There is an open discussion regarding the temporal locus of Bayesian integration: whereas most models imply that the influence of prior knowledge is post-perceptual, i.e., that the working memory representation is being modulated by prior information, a recent study claimed that the effect of prior information occurs earlier – at the perceptual stage (Damsma et al., 2021). Findings that demonstrated the contraction bias in serial displays, such as in the present study, are consistent

with the earlier account. When two stimuli are presented serially, it could be hypothesized that the working memory representation of the first stimulus would be weaker than that of the second stimulus. According to this view, the contraction bias – a stronger pull to the distribution center for the first compared to the second stimulus – is the result of this bias in working memory representation. This bias, arguably, leads participants to rely more strongly on the prior when judging the first stimulus and on the likelihood (the sensory representation) when judging the second (Ashourian & Loewenstein, 2011), as is the case in the present study.

This hypothesis, suggesting that the contraction bias is due to the deterioration of the working memory representation of the first stimulus, leads to the prediction that any interference between S1 and S2 should enhance the effect. However, existing evidence regarding the effect of such interference is inconclusive. For example, studies who manipulated the interstimulus intervals between S1 and S2, assuming that longer intervals would lead to larger interference, showed ambiguous results. While some studies provided evidence supporting the hypothesis by showing that longer ISI (i.e. more interference) led to larger contraction bias effects (Preuschhof et al., 2010; Sinclair & Burton, 1996), one other study showed the opposite effect in the tactile domain using shorter ISIs than the previous studies (Karim et al., 2013). This suggests that there are other, yet unknown, factors that influence the contraction bias, and that some of these factors cannot be explained solely by the Bayesian account. Moreover, it suggests that different perceptual domains (e.g., the tactile modality and the temporal domain) may show different types of modulations of the contraction bias effects.

4.4 The contraction bias – a polyonymous phenomenon

Studies from as early as the 19th century have noticed the phenomenon that stimuli of relatively large magnitude tend to be perceived as smaller and stimuli of relatively small magnitude tend to be perceived as larger. Over the years this phenomenon received a few different definitions by different studies. These definitions were based on the observation that perception of

magnitudes tends to be attracted to the “center” but they varied in how they interpreted this center and what domains they focused on. A known error in temporal perception is *Vierordt's law* (Vierordt, 1868), which is the tendency to overestimate short intervals and underestimate long ones. The center in this case is defined experimentally – as the duration of the interval that is accurately perceived, not overestimated and not underestimated (the “point of indifference”). The *central tendency of judgment* (Hollingworth, 1910), also called the *regression effect* or *regression to the mean* (Burr et al., 2013; Petzschner et al., 2015; Stevens & Greenbaum, 1966), describes a similar phenomenon that is not specific to the temporal domain, and defines the center statistically – as the mean magnitude of recently experienced stimuli. Vierordt’s law is often referred to as a specific case of the central tendency in the temporal domain (Karaminis et al., 2016; Schlichting et al., 2018; Shi et al., 2013). Finally, the term *contraction bias* was used to describe the over- and underestimation of stimuli relative to their expected size (Ashourian & Loewenstein, 2011; Lieder et al., 2019; Sapey-Triomphe et al., 2021), with expectations being often pulled toward the mean (Poulton, 1979).

A specific case of this polyonymous phenomenon is the TOE (Allan, 1977; Fechner, 1860; Fraisse, 1948; Hellström, 1977, 1985), also referred to as a *sequential contraction bias* (Poulton, 1979) or the *sequential effect* (Petzschner et al., 2015). TOE is the manifestation of the perceptual pull towards the center in sequential stimuli presentations. It is important to note, however, that a few recent studies have used the term *contraction bias* to describe the same effect of sequential stimuli that earlier studies have called TOE (Ashourian & Loewenstein, 2011; Lieder et al., 2019; Raviv et al., 2012). Future studies are encouraged to note these terminological inconsistencies and be cautious when interpreting findings based on these terms.

4.5 Methodological implication of the temporal contraction bias

Studies of time perception often make use of interval comparison tasks, where two intervals are serially presented and participants are requested to judge which was longer (e.g., Lapid et

al., 2008; Merchant et al., 2008; Piras & Coull, 2011; Stauffer et al., 2012; Toplak et al., 2003). In many of these studies, one of the two intervals remains constant while the other varies, with order changing between trials (e.g., Smith et al., 2002). In another design, called a roving-referent bisection task, two different standards are presented, followed by a probe. In this task, participants are asked to judge which of the two standards is more similar in its duration to the probe (e.g., Allan, 2002). The present findings highlight that in all these cases a contraction bias might be present, with the duration judgement being affected by both the order of the stimuli, and by their relation to the overall distribution (i.e., whether they are shorter or longer than the average stimulus). Furthermore, with longer interval durations (supra-second) this bias is asymmetrical, introducing a further potential confound. Therefore, to avoid undesired effects of the contraction bias, interval order and durations should always be fully balanced through design or controlled-for through appropriate statistical methods. Moreover, when modelling behavior, researchers are encouraged to add the relevant variables to their models to capture the relatively large variance the contraction bias explains, in order to make sure any effect they observe is not already explained or partly explained by it.

4.6 Conclusions

Here we showed, for the first time, that the contraction bias, the systematic bias to over- and under-estimate stimuli according to their presentation order and their relation to their underlying distribution's center, distorts time estimation. The findings demonstrate that duration – a supramodal psychophysical feature with no sensory magnitude – ‘behaves’ in this respect very similar to other psychophysical features such as loudness, size, or brightness. Despite being independent of sensory input (i.e., duration can be measured even without sensory input), a basic perceptual property such as the contraction bias exists. This is a demonstration that different brain mechanisms, which are conceptually and physiologically distinct, nevertheless function according to similar mutual psychophysical principles.

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Data availability. The preregistration forms, the datasets for Exp. 1-3, as well as R-markdown files that reproduces all the reported statistical analyses and bar graphs within the paper, are uploaded to the project's Open Science Foundation repository (<https://osf.io/t3kb7>).

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