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A momentum effect in temporal arithmetic

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# Equal contribution

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A momentum effect in temporal arithmetic

The mental representation of brief temporal durations, when assessed in standard laboratory conditions, is highly accurate. Here we show that adding or subtracting temporal durations systematically results in strong and opposite biases, namely over-estimation for addition and under-estimation for subtraction. The difference with respect to a baseline temporal reproduction task changed across durations in an operation-specific way and survived correcting for the effect due to operation sign alone, indexing a reliable signature of arithmetic processing on time representation. A second experiment replicated these findings with a different set of stimuli. This novel behavioral marker conceptually mirrors in the time domain the representational momentum found with motion, whereby the estimated spatial position of a visual target is displaced in the direction of motion itself. This *momentum effect in temporal arithmetic* suggests a striking analogy between time processing and visuospatial processing, which might index the presence of common computational principles.

Introduction

How temporal duration is perceived and represented is the object of intense multidisciplinary investigation and theoretical debate (Drayton & Furman, 2018). Though subjective perception of temporal durations can be heavily distorted by cognitive and emotional factors (Droit-Volet 2018; Buhusi & Meck, 2009), the representation of brief temporal durations across heterogeneous laboratory tasks is highly accurate. In neutral settings the reproduction of short time durations – in the range of hundred milliseconds – is almost perfect (Wearden, 2003). Leading theories of time processing (Gibbon, 1977; Meck & Church, 1983) attributed this precision (systematically found across several animal species) to the regularity of a pace-maker which codes the perceived duration(s) as they enter an accumulator. Many investigators have postulated the existence of neuronal clocks in the brain; indeed, "time cells" in the hippocampus and enthorinal cortex appear to faithfully encode elapsed duration during a memory task (Eichenbaum, 2014). Moreover, neuronal tuning to duration has been recently observed in the human premotor cortex using fMRI (Protopapa et al., 2019).

However, the idea that time is encoded as an independent and abstract entity has been empirically challenged, and it has been argued that time cannot be disentangled from space at the neural level (Buzsáki & Llinás 2017), possibly because spatial and temporal processing are carried out by the same core mechanism (i.e., sequential activity of the hippocampus; Buzsáki & Tingley, 2018). Tight coupling between time and space, which is also manifest in the wealth of spatial words and metaphors that describe time concepts (e.g., Boroditzky, 2000), might stem from a common metric of representation and/or overlapping cognitive systems (Bonato et al., 2012, for review).

Here we investigated whether the mental manipulation of temporal durations generates a "momentum-like" effect (Hubbard, 2015, for review), a directional bias observed both in physical and representational spaces. When asked to indicate the last spatial position occupied by a moving object that suddenly disappears participants show systematic overestimation in the direction of its trajectory (Hubbard, 2015). Attention shifts are also thought to imply a momentum that hampers a change of direction (e.g., Pratt et al., 1999). McCrink et al. (2007) extended this idea to the number domain, which is not intrinsically spatial but is known to have tight links with space (Zorzi et al., 2002). In the context of non-symbolic arithmetic, adding two quantities typically leads to overestimation, whereas subtraction leads to underestimation ("operational momentum"; also see Knops et al., 2009, 2014). We predicted a similar phenomenon for the time domain. That is, adding two temporal durations should produce overestimation (i.e., time dilation), whereas subtracting them should produce underestimation (i.e., time compression). This would suggest that the operational momentum is a general signature of magnitude processing.

Previous research suggests that our hypothesis is not far-fetched. For instance, questionnaire-based ratings of temporal proximity across past or future events unveil an "asymmetric" (called Doppler-like) compression (Caruso et al., 2013). Imagined equidistant events are rated closer in time when they are about to happen than when they had already happened. Takahashi and Watanabe (2015) found that summation of temporal durations led to overestimation, regardless of the sensory modality of the stimuli. Fortin and Breton (1995) and Fortin and Massé (2000) reported that, all other parameters being equal, a larger number of temporal durations to be added furthere increases the pattern of overestimation. However, none of these studies tested the possibility of a momentum-like effect, i.e. they did not contrast addition and subtraction. Therefore, it remains unknown whether the overestimation described for addition is an operation-specific effect or whether it simply is a general consequence of time manipulation. Moreover, to the best of our knowledge, subtraction of temporal duration has never been investigated. While addition of two durations is straightforward in terms of the accumulator mechanism, subtraction can be thought of as de-accumulation of the second duration from the first. Although the latter appears as a much less “natural” operation there is no a-priori reason for predicting the opposite pattern with respect to addition. According to the momentum hypothesis, however, predictions are clear-cut: the bias should be operation-specific, leading to underestimation for subtraction and overestimation for addition with respect to a baseline reproduction task. The direct comparison between addition and subtraction is also important to rule out any confound due to the different nature of the task (vs reproduction) as well crucial to exclude any unspecific effect due to task difficulty (i.e., cognitive load; Block et al., 2010). We tested our hypothesis by comparing time addition and subtraction in two experiments based on a “temporal arithmetic” task, in which two temporal durations were conveyed by auditory stimuli and the response was delivered by pressing a button for the duration corresponding to their sum or difference. Both the stimuli and the response were devoid of any lateralized component to exclude contamination by spatial compatibility effects.

Experiment 1

Method

A “temporal arithmetic” task was devised. In both experiment 1 and 2 participants had to press the space bar of the computer keyboard with their right index finger to play white noise for a duration corresponding to the sum or to the difference of two, auditorily presented, white noise stimuli. Before and after this arithmetic task, a reproduction task of single durations (baseline Task) corresponding to correct outcomes of the “temporal arithmetic” task was performed.

Participants & Apparatus

The experiments described in the present manuscript have been approved by the Ethical committee of the Faculty of Psychology of Ghent University and were implemented using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) on a computer with a 15.4 inches monitor. The sound (intensity approx. 60 dB) was binaurally presented via professional over-ear Sennheiser headphones and consisted in white noise sampled at 44.1 kHz with a resolution of 16 bit. 20 participants (14 females, mean age 19 years) gave written consent to take part in Experiment 1. Sample size was decided by significantly increasing the sample (n = 12) tested in the first Operational momentum study McCrink, Dehaene, & Dehaene-Lambertz, (2007).

Task and Stimuli

Temporal Arithmetic Task

Trial structure is shown in Figure 1. After a fixation dot (1000 ms) a first stimulus (white noise) was played (duration: 600 ms for addition or 1200 ms for subtraction). Then the "+" sign (perform addition) or the "-" sign (perform subtraction) appeared for a random interval (range: from 600 ms to 1000 ms) which did not allow participants to use any heuristic based on the total duration of the stimuli (Takahashi & Watanabe, 2015). After its disappearance, a second sound (150, 300 or 450 ms long) was played. A fixation point was presented again (600 ms) and participants were prompted (go screen) to press the space bar for a duration corresponding to the sum/difference of the two operands, according to the identity of the previously presented arithmetic sign. The button press made the go-screen disappear and played white noise, which lasted until the key was released. With such press/release response modality time performance is less variable than with alternative methods (see Mioni, Stablum, McClintock & Grondin, 2014, for review).
In +/- “zero" conditions no second operand was presented after an interval of 600ms or 1200ms and participants were asked to “add” or “subtract” a duration of zero to the first operand. This “internal” control condition, (as opposed to the “external” baseline provided by the baseline reproduction task) was meant to test for operation-induced biases (Pinhas & Fischer, 2008). The five target durations (750 ms, 900 ms and 1050 ms, with 600 ms & 1200 ms in the +/- 0 conditions)

corresponded to the correct outcome of addition/subtraction problems (e.g. 750ms = 600 ms + 150 ms vs. 1200 ms - 450 ms) and matched those of the reproduction task (see Figure 1). Addition and subtraction problems were presented in alternated blocks; order was counterbalanced across participants. Within each block, every arithmetic problem was randomly presented 8 times for a total of 240 trials (120 for each operation) across 6 blocks. Each block was preceded by eight practice trials.

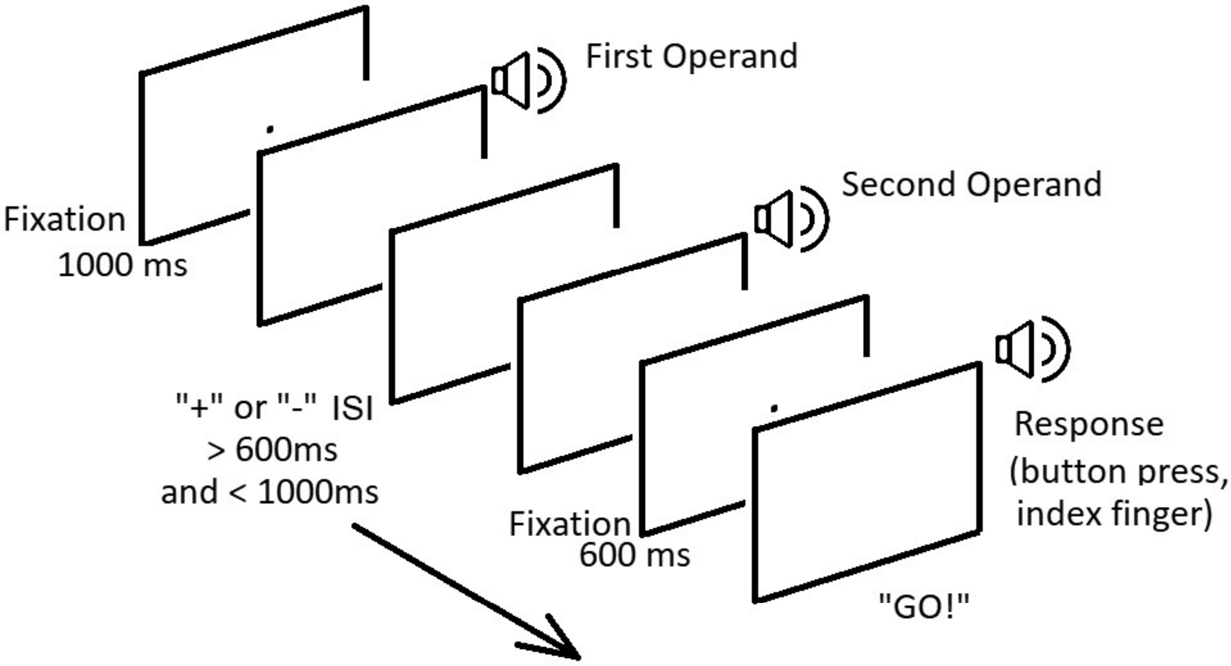

Figure 1. A representative trial of the arithmetic task is shown. The loudspeaker symbol indicates that white noise was played. In the baseline reproduction task no operation had to be performed: the arithmetic symbol was replaced by a dot and a single duration was presented.

ADDITION				SUBTRACTION		
FIRST OPERAND	SECOND OPERAND	Total		FIRST OPERAND	SECOND OPERAND	Total
600	150	750		1200	450	750
600	300	900		1200	300	900
600	450	1050		1200	150	1050
600	0	600		600	0	600
1200	0	1200		1200	0	1200

Table 1. The different durations (in ms) tested in Experiment 1 are reported. Durations to be reproduced in the baseline task matched the correct outcomes of the arithmetic task.

Temporal Reproduction Task (baseline task)
After a first fixation screen (1000 ms) white noise was presented for 600, 750, 900, 1050 or 1200 ms, corresponding to the five correct outcomes of the arithmetic task. After a second fixation screen (random duration from 600 ms to 1000 ms), a go-sign prompted participants to reproduce the duration they had been presented (with same response modality as in the arithmetic task). Each target duration was presented/reproduced four times across three consecutive blocks for a total of 120 trials (2 runs (one before and one after the temporal arithmetic task) X 3 blocks X 4 trials X 5 target durations).

Results

The data of one participant were partially corrupted and therefore the participant was excluded from further analysis. Trials falling two SD outside the individual average for each condition and target duration/outcome were discarded (4.02 % of the total). A repeated measures ANOVA was performed on mean estimates using Condition (3 levels: addition, subtraction, and reproduction) and Duration (5 levels: 600 ms, 750 ms, 900 ms, 1050 ms, and 1200 ms) as factors. A main effect of Condition emerged $F(2, 36) = 34.7$, $p < .001$, $\eta^2 = .66$, indicating that the produced durations differed across operations. Addition (954ms) resulted in significantly longer estimates than subtraction (799ms) ($p < .001$). Simple reproduction (859ms) resulted in intermediate durations which were significantly shorter than addition ($p < .001$) and longer than subtraction ($p < .05$) (Paired t-test Bonferroni adjusted). A momentum-like, operation-specific, bias was therefore present. As expected, estimates significantly differed across target durations [$F(4, 72) = 200$, $p < .001$, $\eta^2 = .92$], whereas the significant interaction with Condition [$F(8, 144) = 17.49$, $p < .001$, $\eta^2 = .49$] reveals that the pattern of under- / over-estimation was not constant across the different durations (see Figure 2).

Next, we directly compared addition and subtraction performance (Bonferroni corrected t-tests for $n = 3$ comparisons). For the three non-zero operand durations addition led to significantly longer estimates than subtraction across all durations [750ms: $t(18)= 6.7$, $p < .001$, difference = 207ms; 900ms: $t(18)= 7.02$, $p < .001$, difference = 234ms; 1050ms: $t(18)= 8.2$, $p < .001$, difference = 260ms]. In the +/- 0 conditions the difference between addition and subtraction albeit significant was much smaller [38 ms for the 600ms duration: $t(18)= 3.3$, $p < .05$; 39 ms for the 1200ms duration, $t(18)= 2.34$, $p < .05$]. Importantly, the difference between addition and subtraction was still present, across all target durations, after subtracting, for each participant, the individual bias present in the +/- 0 conditions (Bonferroni corrected t-tests for n=3 comparisons, $t(18)= -5.03$; -5.73 and -6.73 respectively, all ps < .01).

Individual reproduction durations for each target in the non-zero arithmetic problems were then used as a baseline to compute an index of temporal bias related to the effective durations reproduced by each participant in the "baseline" conditions, when no operations had to be performed (for addition: result duration - baseline duration; for subtraction: baseline duration - result duration). ANOVA on temporal bias values with Condition (addition vs. subtraction) and Duration (750 ms, 900 ms, and 1050 ms) as factors revealed a significant two-way interaction $F(2, 36) = 10.46$, $p < .001$, $\eta^2 = .37$ and no main effects (both Fs < 2, ns). The interaction was due to the opposite effects of duration length on addition and subtraction. For subtraction, underestimation (signed values are now reported for the sake of clarity) significantly increased with target duration [between 750ms (-61ms) and 1050 ms (-173 ms), $t(18) =2.98$, $p <.01$]. For addition the opposite pattern emerged [significant decrease in overestimation between 750ms (145ms difference) and 1050 ms (87ms), $t(18)= 3.3$, $p < .01$].

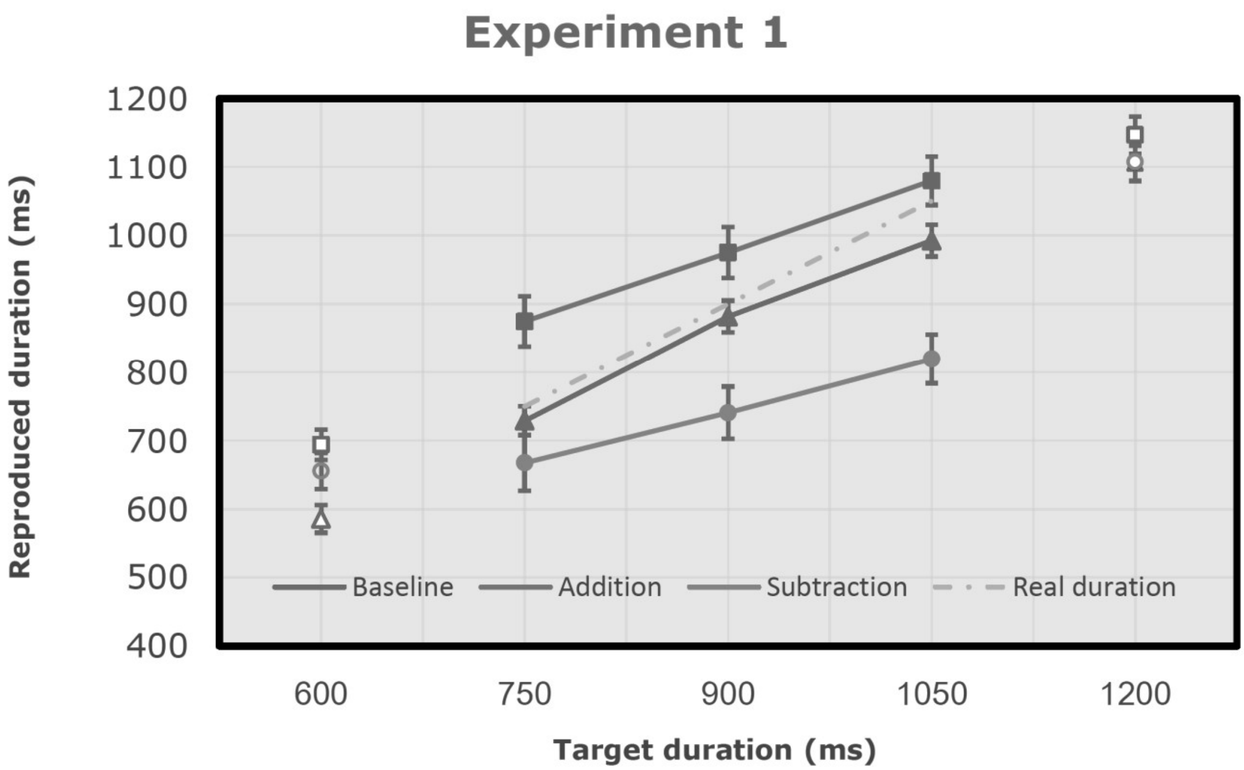

Figure 2. Mean reproduced durations (in milliseconds) for each condition and target duration in Experiment 1. Blue squares represent addition, green circles represent subtraction and red triangles represent reproduced durations in the baseline condition (no arithmetic). The dash-dotted grey line represents the objective target duration. Empty symbols represent "control" conditions in which the second operand was not presented (+/- 0 operations). They allow estimating the impact of arithmetic sign alone. Error bars represent SEM.

Discussion

Arithmetic on durations induced a systematic, operation-specific, bias. Across all the considered durations, estimates for addition outcomes were longer than for subtraction outcomes. This effect was present also after controlling for the bias triggered by operation signs alone which was visible in the +/- conditions along with a difference with respect to baseline reproduction (emerging for the shortest interval) which we attribute to an anchoring effect. To test the generalizability of our findings we performed a second experiment with a different range of durations. In Experiment 1 participants could in principle have ignored the first operand, which did not vary within condition, to categorize the second operands as "short" "medium" or "long". The first operand was always longer than the second one and it is therefore possible that the outcomes were influenced by the "decreasing" stimulus order. Considering that when second operands were longer performance was closer to the control task the effects could have been due to the relative size of the second operand with respect to the control. Experiment 2 was designed to prevent any of these strategies.

Experiment 2

Method

Experiment 2 differed from Experiment 1 only for the set of stimuli adopted. The +/- zero conditions were not presented because the (limited) impact of operation sign alone in the context of this specific task has been already quantified in Experiment 1.

Participants

A total of 24 participants (14 females, mean age 24 years) gave written consensus to take part in the experiment.

Stimuli

A larger set of durations with respect to Experiment 1 was adopted (see Table 2). Temporal arithmetic problems were again matched in terms of correct operation outcomes (600, 750, 900 or 1050 ms). Eight different operations-combinations concurred to each outcome. In the addition condition, half of the problems had a shorter first operand and the other half had a longer first operand.

ADDITION				SUBTRACTION		
FIRST OPERAND	SECOND OPERAND	Total		FIRST OPERAND	SECOND OPERAND	Total
450	150	600		750	150	600
150	450	600		900	300	600
400	200	600		1050	450	600
200	400	600		1200	600	600
150	600	750		900	150	750
600	150	750		1050	300	750
300	450	750		1200	450	750
450	300	750		1350	600	750
150	750	900		1050	150	900
750	150	900		1200	300	900
300	600	900		1500	600	900
600	300	900		1650	750	900
300	750	1050		1200	150	1050
750	300	1050		1350	300	1050
600	450	1050		1500	450	1050
450	600	1050		1650	600	1050

Table2. The different durations (in ms) for addition (Left) and subtraction (Right) presented in Experiment 2.

Results

4.06 % of the trials were removed according to the previously described two SD trimming criterion. The repeated measures ANOVA on mean estimates highlighted significant main effects of target Duration [$F(3, 69) = 195.7$, $p < .001$, $\eta^2 = .90$, and Condition [$F(2, 46) = 13.7$, $p < .001$, $\eta^2 = .37$]. Mean estimates were longer for addition (938 ms) compared to both subtraction (764ms, $t(23) = 4.25$, $p < .001$) and reproduction (792ms, $t(23) = 3.89$, $p < .001$), while there was no significant difference between subtraction and reproduction ($t(23) = 1.03$, $p = .325$, ns). The two factors interacted significantly, $F(6, 138) = 19.95$, $p < .001$, $\eta^2 = .46$. Addition estimates were significantly longer than subtraction estimates across all durations [600ms: $t(23)= 4.1$, $p <$ 001, difference = 165ms; 750ms: $t(23)= 4.2$, $p < .001$, difference = 176ms; 900ms: $t(23)= 4.0$, $p < .001$, difference = 168ms; 1050ms: $t(23)= 4.05$, $p < .001$, difference = 228ms].

As in Experiment 1 an index of temporal bias was computed by taking individual reproductions for each target problem as a baseline. ANOVA on bias values with Condition (addition vs subtraction) and Duration (600ms, 750 ms, 900 ms, and 1050 ms) revealed a main effect of Operation, $F(3, 69) = 5.2$, $p < .05$, $\eta^2 = .18$ and a significant interaction, $F(3, 69) = 54.9$, $p < .001$, $\eta^2 = .71$. As in Experiment 1 the latter was due to the opposite effects duration had on addition and subtraction. As in Experiment 1, when taking reproduction as baseline, the underestimation characterizing subtraction increased with duration [e.g., between 600ms (+61ms) and 1050 ms (-110ms), $t(23) = 6.9$, $p < .001$]. For addition the pattern was reversed [significant decrease in overestimation between 600ms (226ms) and 1050 ms (77ms), $t(23) = 7.98$, $p <.001$].

Operation bias. The difference between addition and subtraction was still present across all target durations after correcting for the average bias present in the two +/- 0 conditions of Experiment 1 (38.6 ms). Bonferroni-corrected t-tests (for $n = 4$ comparisons) yielded significant results for all comparisons [600 ms: $t(23)= 3.1$, $p < .01$; 750ms: $t(23)= 3.2$, $p < .01$; 900ms: $t(23)= 3.1$, $p < .01$; 1050ms: $t(23)= 4.05$, $p < .001$].

Operand order. Addition in Experiment 2 included trials in which the first operand was the longer duration (long + short) or the shorter duration (short + long). We assessed whether operand order had an effect on addition estimates in a repeated measures ANOVA with Operand Order (Short-Long vs. Long-Short) and Duration (600, 750, 900 or 1050ms) as factors. The effect of Operand Order was significant [$F(1, 23) = 63.1$, $p < .001$, Short-Long = 963 ms, SD = 138 , Long-Short = 913 ms, SD = 138], with Short-Long problems yielding longer estimates than Long-Short problems ($t(95) = 9.04$, $p < .001$). The main effect of Duration was also significant [$F(3, 69) = 62.9$; $p < .001$], whereas the interaction was not significant [$F(3, 69) = .71$; $p = .54$. Pairwise comparisons confirmed that the difference between the two operand orders was present across each of the four target durations (all *p*s <. 05, Supplementary Figure 1). Thus, overestimation was present for both types of trials but presenting a longer duration as second operand further increased the temporal bias. This additional bias might be due to anchoring effects (LeBoeuf & Shafir, 2006; also see Blini, Pitteri & Zorzi, 2018). Increasing vs decreasing duration has an impact on time perception (Binetti et al., 2012). However, these order effects cannot explain the overall pattern of findings, because in Experiment 1 the first operand was always longer than the second for both addition and subtraction. Moreover, in Experiment 2 the same pattern of under- vs. over- estimation emerged despite the presence of balanced operands for addition.

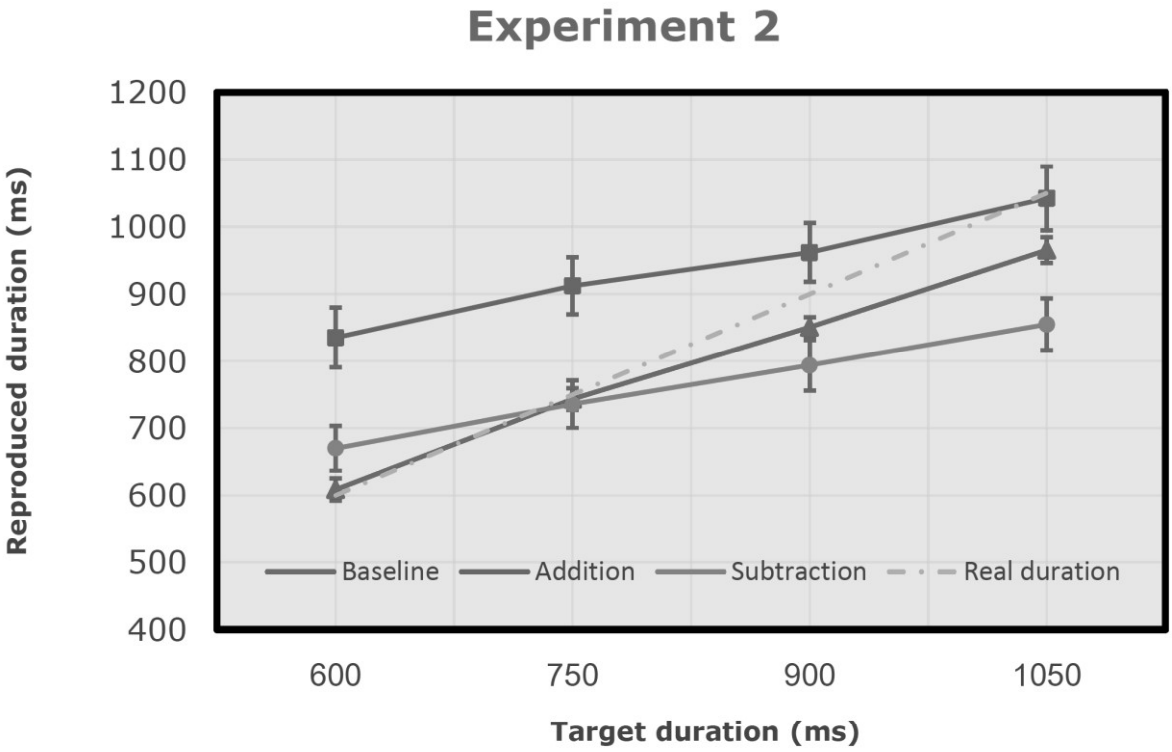

Figure 3. Mean reproduced durations (in milliseconds) for each condition and target duration in Experiment 2. Blue squares represent addition, green circles represent subtraction, and red triangles represent reproduced durations in the baseline condition (no arithmetic). The dash-dotted grey line represents the objective target duration. Error bars represent SEM.

Regression modeling

The wider set of stimuli adopted in Experiment 2 allowed to empirically test the potential contribution of several factors, including relative operand size. This was not possible in Experiment 1 due to the very limited set of stimuli and to the lack of multiple operand durations leading to the same target duration. We used regression modeling to predict average duration (across participants) for each of the 32 operations included in Experiment 2 (16 additions and 16 subtractions, see Table 2). We evaluated the contribution of different predictors using an incremental procedure, with a single predictor added at each step. Model fitness was evaluated in terms of adjusted r-squared. Scatter plots (see Figure 4) contrast model predictions with the empirical data for each of the 32 operations; therefore, alignment of the points to the diagonal provides a visual index of model fitness.

Model 1: Target duration. As a first step we included objective target duration as predictor of the subjective estimates. The effect of target duration was significant (β=0.42758, t(30)= 4.2097, p< 0.001), with the model yielding an adjusted R-squared of 0.35. However, as clearly visible in the upper left panel of Figure 4, the model did not capture the difference between addition (circles) and subtraction (crosses). Moreover, it also failed in capturing the variability across items that shared type of operation (addition or subtraction) and target duration, thereby suggesting that duration of the individual operands needs to be taken into account.

Model 2: Model 1 + Operand duration. Including duration of the second operand as predictor increased the fit of the model (adjusted R-squared) to 0.409 (β-target=0.38; t(29)=3.81, p< 0.001; β-operand=0.17; t(29)=1.99, p=0.056). Importantly, as visible in the upper right panel of Figure 4, the model captured much of the within-operation variability, both for addition and subtraction. This suggests an anchoring effect: participants increase or decrease their estimates of the result based on the length of the second operand. Nevertheless, the model still fails to capture the overall pattern because it is underestimating addition and overestimating subtraction.

Model 3: Model 2 + Operation type. As a final step we included operation type (binary coded with +1 for addition and -1 for subtraction) in the model, which yielded an adjusted R-squared of 0.975. The effect of operation type (across durations) is expressed by the large regression coefficient (β-operation=85.8, t(28)=25.39, p< 0.001). Moreover, including operation type in the model had little effect on the other regression coefficients, which remained substantially unchanged (β-target=0.39; t(29)=18.67, p< 0.001; β-operand=0.15; t(29)=8.33, p< 0.001). As visible in the lower panel of Figure 4, the final model fully explains the pattern of temporal arithmetic data and it accounts for nearly all of the variance across the 32 operations.

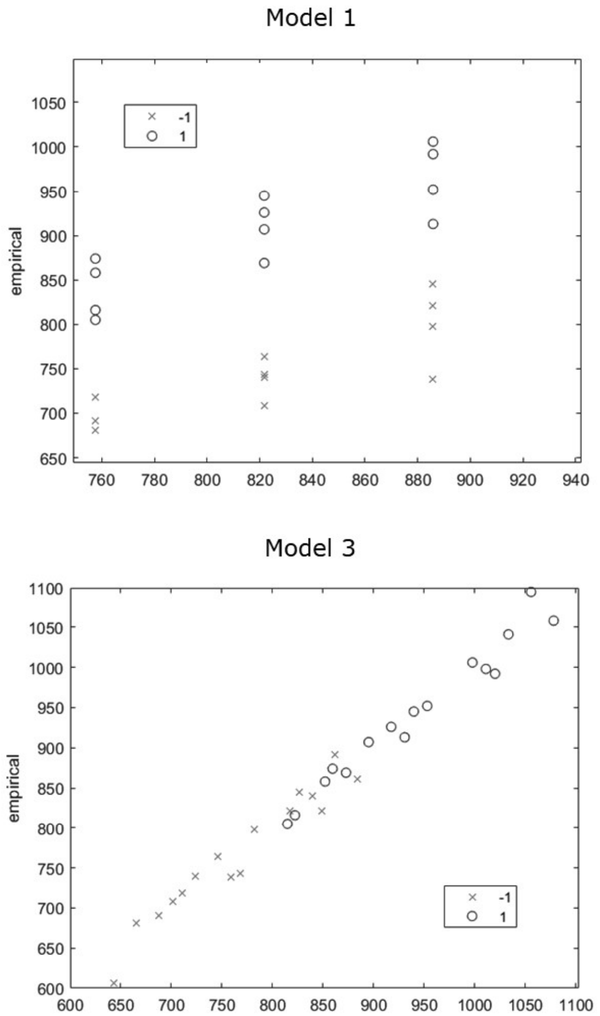

Figure 4. Scatter plots contrasting empirical (participants' average) vs predicted (model) estimates from regression modeling of the temporal arithmetic data. Each of the 32 points represents an individual operation. Note that alignment of the points to the diagonal is an index of model fitness. Model 1 (upper left panel) includes only target duration, Model 2 (upper right panel) adds the duration of the second operand, and Model 3 (bottom panel) also includes type of operation. The latter model shows that including an "operation-specific bias" allows to capture nearly all the variance (about 98%) in the temporal arithmetic data.

Discussion

Experiment 2 replicated the systematic pattern of overestimation for addition and underestimation for subtraction described for Experiment 1, using stimuli that made the implementation of strategies very hard if not impossible. The presence of different operands resulting in the same target duration also allowed to unveil an anchoring effect. That is, problems with longer second operands led to longer estimates compared to problems with shorter second operand. This violation of commutativity mirrors recent findings by Shaki et al. (2015), who showed that a line is reproduced as longer when it follows the presentation of an addition with increasing operand size with respect to when operands are presented in a decreasing order. Regression modeling further demonstrated that only including a momentum-like effect based on type of operation allows to fully capture the pattern of estimates in temporal arithmetic at the item level.

Conclusions

Across two experiments and two different sets of stimuli we observed operation-specific time mis-reproduction when participants added or subtracted brief time durations. In a task lacking any lateralized component, addition and subtraction induced systematic over- and under-estimation, respectively. Importantly, the temporal bias was much larger than the one induced by the operation sign alone, as measured in zero-operand trials. Estimates were also modulated by the duration of the addend/subtrahend. The difference across operations was reliable also with respect to a reproduction-only condition used as baseline. This comparison showed that the temporal bias was modulated by duration in an operation-specific direction. With longer durations subtraction bias become larger while addition bias become smaller. This finding fits with the hypothesis that this momentum-like effect is generated by the mechanism encoding temporal duration rather than by domain-general or strategic factors. Experiment 2 replicated these results using a wider range of operands, thereby ruling out alternative, stimulus-specific, explanations.

In summary, we described for the first time that arithmetic operations on temporal durations produce systematic estimation errors that primarily depend on the type of operation (and to a smaller extent by the size of the operands). Our results show that the over-reproduction found in a multisensory task (Takahashi & Watanabe, 2015) is only one side of the coin. The (opposite) effect for subtraction is crucially present and allows us to cast the overall pattern within the broader theoretical framework of representational momentum. Note that the task did not allow to perform any accuracy check/outcome adjustment nor to employ counting strategies. We can also unambiguously exclude that the momentum effect was induced by the response modality, which also lacked any spatial connotation. The hypothesis that the momentum effect in temporal arithmetic reflects a genuinely intrinsic spatial component is consistent with previous results showing that temporal duration processing can be affected by a variety of visuospatial manipulations, including prismatic adaptation (Frassinetti et al., 2009), reverse reading (Casasanto & Bottini, 2014), and visuospatial priming (Di Bono et al., 2012). Furthermore, neuropsychological studies on patients affected by contralesional space disorders reveal a systematic association between pathological visuospatial processing and conceptual time in the form of ordered events processing (Antoine et al., 2019; Bonato et al., 2016, see Rinaldi et al., 2018 on the impact of purely visual impairment). Both lines of evidence (normal and pathological) therefore converge in suggesting that some aspects of time representation (either sensory or conceptual) are spatial in nature.

Our findings suggest that accurate internal estimates of time duration (Wearden, 2003; Wearden & Jones 2007) turn into a systematic bias when the same durations (which are accurately represented according to the reproduction task) are to be manipulated. Models of time representation might therefore need to include an intrinsic spatial component to account for the present findings. Future studies need to better isolate the cognitive stage at which the distortion takes place and to verify the existence of a single mechanism for manipulating quantities, whether numerosity of visual items or auditory durations. It would be also possible to test whether this effect is reflected in the chronotopic areas identified by Protopapa et al. (2019). Regardless of future perspectives, this novel effect makes time representation much closer to the way we process space than what was previously thought, as already revealed from the way we speak.

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Supplementay materials

The data have been made available on a permanent third-party archive (**https://osf.io/kvdux/?view_only=2a6c36b5828640c6aa7ba7a49ca53671**).

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