



## OPEN Studying the aftereffect and changes in sensitivity to physical and mental time references using a time adaptation paradigm

Wang On Li<sup>1✉</sup>, Kenneth Sung Lai Yuen<sup>2,3</sup>, Dorita Hue-fung Chang<sup>4</sup> & Calvin Kai-Ching Yu<sup>1</sup>

Time adaptation aftereffects occur following repeated presentation of stimuli with similar durations. This study tested whether time adaptation mechanisms align with other sensory adaptations by examining whether subsequent temporal percepts are repelled from adapted durations while demonstrating improved sensitivity. Alternative averaging hypotheses derived from Bayesian and central tendency frameworks were also investigated. Beyond the commonly employed time bisection task, this study incorporated a time production task to evaluate whether adaptation influences mental time references or remains limited to perceptual processing. Results showed that adapting to longer durations significantly reduced point of subjective equality (PSEs) in shorter-duration tasks, but not vice versa, with no consistent improvements in sensitivity observed. Support for the classical perceptual adaptation model was therefore limited. Conversely, aftereffects in the 500 ms production task shifted toward adapted durations, aligning with averaging predictions. These findings indicate that time adaptation exerts differential effects on physical versus mental time references. Moreover, temporal adaptation differs from other sensory adaptations in that it represents an integration of multimodal information rather than a modality-specific process.

**Keywords** Subjective time perception, Time adaptation, Time bisection task, Time production task

Perceptual adaptation is a fundamental phenomenon across sensory domains, characterized by systematic shifts in perception following prolonged exposure to specific stimuli. This perceptual process has been extensively documented in vision research. Gibson (1933)<sup>1</sup> demonstrated that adapting to curved lines causes straight lines to appear curved in the opposite direction, while Blakemore and Campbell (1969)<sup>2</sup> showed that exposure to tilted orientations biases the perception of subsequent lines away from the adapted orientation. Motion adaptation produces similar aftereffects (Anstis, Verstraten, & Mather, 1998)<sup>3</sup>. These adaptations are not merely the result of neural fatigue but serve essential functional purposes, particularly the recalibration of perceptual norms to enhance sensitivity and discriminability (Chopin & Mamassian, 2012<sup>4</sup>; Stocker & Simoncelli, 2005<sup>5</sup>; Thompson & Burr, 2009<sup>6</sup>).

The neural mechanisms underlying perceptual adaptation involve changes in the responsiveness of sensory neurons. Neurons that are band-pass tuned to specific stimulus features (such as orientation) show altered activity patterns following prolonged exposure, either through reduced responsiveness or modified gain control (Kohn & Movshon, 2003<sup>7</sup>; Müller, Metha, Krauskopf, & Lennie, 1999<sup>8</sup>). This neural adaptation exhibits two key characteristics: a repulsion effect, where subsequent perceptions are biased away from the adapted stimulus, and improved discriminability around the adapted value.

Recent research has extended adaptation phenomena to temporal perception. Heron et al. (2012)<sup>9</sup> demonstrated that repeated exposure to stimuli of specific durations biases subsequent time judgments, proposing a channel-based model in which duration-tuned mechanisms undergo adaptation similar to those in other sensory channels. Shima et al. (2016)<sup>10</sup> further showed that adaptation effects can cross temporal boundaries, with sub-second adaptations influencing supra-second perception. However, time adaptation exhibits unique characteristics that distinguish it from traditional sensory adaptations, particularly its cross-

<sup>1</sup>Department of Counselling and Psychology, Hong Kong Shue Yan University, Braemar Hill, North Point, Hong Kong, China. <sup>2</sup>Neuroimaging Center (NIC), Focus Program Translational Neuroscience (FTN), Johannes Gutenberg University Medical Center Mainz, Mainz, Germany. <sup>3</sup>Leibniz Institute for Resilience Research (LIR), Mainz, Germany. <sup>4</sup>Department of Psychology, The University of Hong Kong, Hong Kong, China. ✉email: woli@hksyu.edu

modal nature (Heron, Hotchkiss, Aaen-Stockdale, Roach, & Whitaker, 2013)<sup>11</sup>; Roseboom, Linares, & Nishida, 2015<sup>12</sup>.

The cross-modal properties of time adaptation raise fundamental questions about whether temporal adaptation follows the same principles as visual or auditory adaptation. Classical sensory adaptations are typically modality-specific and produce consistent repulsion effects, accompanied by enhanced sensitivity. However, time perception involves distributed neural networks rather than dedicated sensory channels, and temporal information is processed across multiple modalities simultaneously. This suggests that time adaptation might operate through different mechanisms than traditional perceptual adaptations.

Competing models of temporal processing further complicate the argument. Vierordt's Law describes how short durations are systematically overestimated while long durations are underestimated—a pattern that could reflect either adaptation-like processes or alternative mechanisms. Lewis and Miall (2003)<sup>13</sup> proposed distinct systems for sub-second (automatic, motor-based) versus supra-second (cognitive, attention-dependent) timing after reviewing 35 imaging studies, including PET and fMRI studies. Others have argued for unified 'memory-mixing' mechanisms involving working memory interference (Gu & Meck, 2011)<sup>14</sup> or Bayesian central tendency effects (Lejeune & Wearden, 2009<sup>15</sup>; Shi et al., 2013)<sup>16</sup>. These hypotheses predict an averaging mechanism that perceptions shift toward the average of recently experienced durations—an aftereffect opposite to classical adaptation's repulsion effects.

An observation in previous time adaptation studies notes a potential confounding of perceptual and decisional processes. Both Heron et al. (2012)<sup>9</sup> and Shima et al. (2016)<sup>10</sup> employed tasks that required comparison with physical reference durations, making it impossible to determine whether adaptation affects only perceptual encoding or also the internal temporal references used for decision-making. This distinction is crucial for the attentional gate model of subjective time perception (Gibbon, Malapani, Dale, & Gallistel, 1997<sup>17</sup>; Treisman, 1963<sup>18</sup>; Zakay & Block, 1997)<sup>19</sup>, which proposes that temporal judgments involve comparing accumulated pulses with stored reference memories. Although the model has been relatively successful in generating research hypotheses to explain subjective time perception in relation to attention, arousal, and working memory (Coull, Cheng, & Meck, 2011)<sup>20</sup>, there is a lack of a coherent description of mental time reference.

If time adaptation operates purely at the perceptual level—similar to visual adaptations—then only the encoding of new temporal information should be affected, leaving internal reference memories intact. However, the cross-modal nature of temporal processing and the potential for averaging suggest that adaptation might also modify the mental time reference standards themselves. This possibility has profound implications for understanding whether time adaptation represents a recalibration of temporal sensitivity or a more fundamental alteration of internal timing mechanisms.

To address these questions, the present study employed both time bisection tasks (which rely on physical references) and time production tasks (which depend on internal temporal references) to disentangle perceptual and decisional components of time adaptation. This approach allows us to determine whether adaptation effects are consistent with classical sensory adaptation principles or reflect alternative mechanisms specific to temporal cognition. Additionally, the results will provide insight into the mental representations of time.

## Methodology

### Power analysis

The planned analyses emphasised group comparisons among adaptation and task duration conditions. Previous studies have primarily employed small-sample psychophysics methods; direct group comparisons have been used infrequently (e.g., Heron et al., 2012<sup>9</sup>; Li et al., 2015<sup>21</sup>; Shima et al., 2016)<sup>10</sup>. Bruno, Segala, and Baker (2023)<sup>22</sup> studied how perceived durations were influenced by visual motion adaptation with  $n = 20$ . Power analyses were conducted according to Li et al. (2015)<sup>21</sup>, who used one-sample  $t$ -tests to compare the adaptation effect in the same visual field and different visual fields. The effect sizes of the time adaptation effect in the same visual field were between *Cohen's*  $d = 1.62$  and  $2.43$ . Using G\*Power 3.1 ( $\alpha = 0.05$ , Power  $[1 - \beta] = 0.95$ ), the required sample size for a mixed-design 3 (adaptation)  $\times$  2 (pre-post) ANOVA is a total  $n = 12 - 24$ . Taking these studies into account, the target *sample size* ( $n$ ) in each condition was 30.

## Participants

Ninety participants with normal or corrected-to-normal vision (female: 45; mean age = 20.8; SD = 1.8) were divided into three groups. Participants in each group adapted to different time durations, while the grouping was governed by a Latin square design. All participants were naive to the research hypotheses. The experimental sessions lasted no longer than 60 min, which included practice, pre-adaptation tasks, an adaptation phase, and post-adaptation tasks. The experimental procedures were reviewed and approved by the Human Research Ethics Committee (HREC) of the Hong Kong Shue Yan University (Ref# HREC 20–05 [FF03]). All procedures were conducted in accordance with the HREC guidelines and regulations. Informed consent was obtained from all participants prior to data collection, and they received monetary compensation upon completion of the study.

## Procedures

Participants sat 70 cm away from a 19" LCD monitor. At the beginning of the experiment, they signed an informed consent form detailing their rights. Then, they completed practice trials composed of three trials of a time bisection task and a time production task. The tasks were block designed so that participants completed all the trials of a task of a specific duration before moving on to another block. Then, the participants completed pre-adaptation tasks, which were followed by an adaptation phase. After the adaptation phase, the participants completed post-adaptation tests, which included repeats of the time production and time bisection tasks. The only difference was that there was a refreshing phase before every trial. All participants underwent the adaptation

phase of one duration (i.e., 500, 1000, or 2000 ms) only, whereas the time production and time bisection tasks included measurements of all tested durations (i.e., 500, 1000, and 2000 ms). Figure 1 illustrates the procedures for the respective tasks and phases, as well as their arrangement in the study.

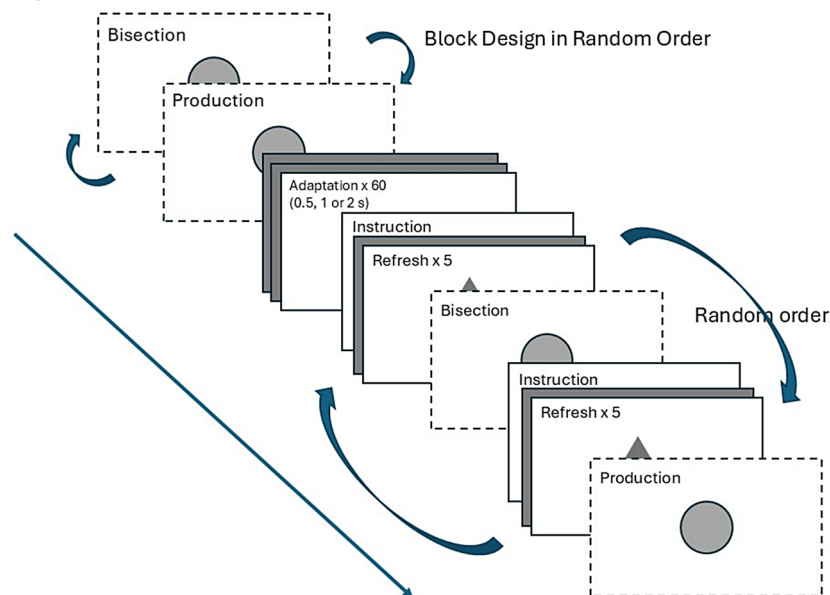
### Adaptation phase

The screen presented a series of random polygons (triangles, squares, pentagons, and hexagons) repeatedly according to the adaptation conditions (500, 1000, and 2000 ms). The Inter-Stimuli Intervals (ISIs) were randomized from 800 to 1000 ms.

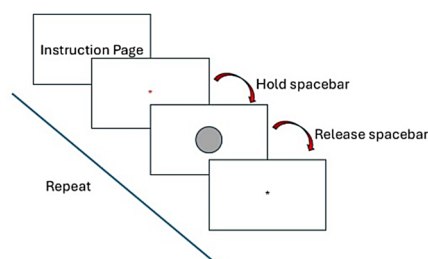
### Time bisection task

A time-bisection task (Droit-Volet, Brunot, & Niedenthal, 2004<sup>23</sup>; Li & Yuen, 2015)<sup>24</sup> provided a contrast of the effect of time adaptation to mental and perceptual references. The screen showed an instruction page that informed the participants of the task procedures and indicated that the current block was a time bisection task. Neutral oval stimuli, subtending a visual angle of  $3.7^\circ \times 3.8^\circ$ , were then presented to the participants. These stimuli were presented in temporal pairs, consisting of a reference and a target interval. Similarly, a block design was used. There was only one reference interval in all the trials of one block. The reference intervals were either 500, 1000, or 2000 ms. Target intervals were plus or minus the relative differences from the reference durations. The step sizes for 500, 1000, and 2000ms were 100, 200, and 400 ms, respectively. In other words, the seven intervals of 500ms are 200, 300, 400, 500, 600, 700, and 800ms. The intervals of 1000ms were 400, 600, 800, 1000, 1200, 1400, and 1600ms, while those of 2000ms were 800, 1200, 1600, 2000, 2400, 2800, 3200 ms. Each comparison was repeated a total of eight times, with the presentation sequence of reference and target

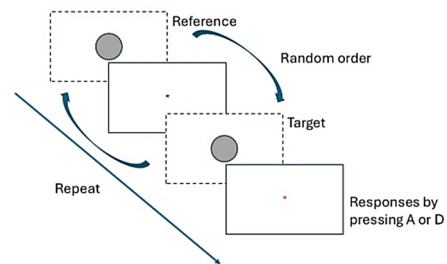
#### a. Experiment Flow



#### b. Production Task



#### c. Bisection Task



**Fig. 1.** A schematic diagram of the experiment procedures. All adaptation and task durations included 500, 1000, and 2000 ms conditions. Each participant completed (a) one adaptation duration and (b) all task durations in a random order in a block design. The oval-shaped stimuli were only used in tasks, while other polygons (i.e., a triangle, a square, a pentagon, or a hexagon) were used in the adaptation phase. Red fixation crosses were used to prompt participants' responses.

randomized. Participants' task is to indicate whether the first or second interval is longer in duration. Pilot tests showed that absolute differences in the range of 100 ms would be too difficult for a 2000 ms reference duration, since the relative difference was too small. The time bisection task in the post-adaptation test also included a refreshing phase between trials.

Participants' responses to specific stimuli in different conditions were collated. The data were recoded as the proportion of LONG responses of the target interval with respect to the reference interval. A cumulative Gaussian psychophysics curve was fitted into individual participant data to estimate their perceived subjective equivalent (PSE), which was the point at which participants perceived the stimulus as being the same as the reference. Having poor fit conditions ( $R^2 < 0.6$ ) in more than three conditions indicated a participant's incapability in performing the bisection task. They were excluded from the analyses. Other PSEs with  $R^2 < 0.6$  were replaced by condition means. Additionally, the Standard Error Mean (SEM) of the PSE provided an estimate of participants' sensitivity to the task.

### Time production task

The screen displayed instructions informing participants of the required durations (i.e., 500, 1000, or 2000 ms). Similar to the bisection task, the production task was a block design based on duration to reduce confusion. A red fixation appeared on the screen to prompt the participants to press the computer mouse. A circle subtended at a visual angle of  $3.7^\circ \times 3.8^\circ$  appeared on the screen and remained there for as long as the participant held the mouse button. This duration was recorded as the produced duration. Another fixation appeared after a randomized ISI duration (0.8 to 1 s) was used to minimize the time cue provided. The participants repeated six trials of the duration production task. Then, a new instruction page was shown on the screen to prompt the participants to begin the next production task. The time production task in the post-adaptation test included a refreshing phase between trials.

The produced durations were averaged to provide an estimate of the participants' mental reference to specific durations, while their SDs helped to estimate their sensitivity. Produced durations beyond two SDs of a participant's average, which, in most cases, represented finger errors, were discarded. Further, participants who produced durations beyond three SDs of the overall mean were excluded. Participants who produced contradictory durations were also excluded (e.g., their produced 500ms was longer than the 1000ms they produced).

### Time adaptation phase

Participants were randomly assigned to one of three adaptation durations (i.e., 500 ms, 1000 ms, or 2000 ms). The screen repeatedly presented polygons (a triangle, a square, a pentagon, or a hexagon) for specific durations according to the adaptation duration. Each presentation was separated by a fixation cross with an ISI randomly ranging from 800 to 1000 ms. The presentations were repeated 60 times.

### Refreshing phase

A refreshing phase was inserted between sets of trials to maintain the adaptation effects during the time production and bisection tasks. Its setup was the same as the adaptation phase, except that the presentation was only repeated five times.

### Hypotheses and planned analyses

The bisection and production data were analyzed separately for group comparison after curve fitting and cleaning. The task durations were also separated, as they fell into different ranges (500, 1000, and 2000 ms). The comparisons included an analysis of the computed PSEs and their SDs from the time bisection task, alongside similar analyses comparing the average produced durations and their SDs among different conditions in the time production task. A 2 (pre-post adaptation)  $\times$  3 (adapted duration) mixed-design ANOVA was conducted to examine potential main and interaction effects. We used the notation 'task duration (adaptation duration)' to denote conditions; for example, 500 (1000) represented a task condition of 500 ms with an adaptation duration of 1000 ms.

To address whether time adaptation aligns with classical sensory adaptation principles, the analysis first tested the repulsion hypothesis, predicting that adaptation would bias subsequent temporal judgments away from the adapted duration. Specifically, we hypothesized that adapting to shorter durations would lead to overestimation of test intervals (conditions 1000(500), 2000(500), and 2000(1000)), while adapting to longer durations would produce underestimation (conditions 500(1000), 1000(2000), and 500(2000)). This pattern would demonstrate the characteristic repulsion effect observed in visual and auditory adaptation paradigms. The alternative hypothesis is the averaging based on the central tendency or Bayesian frameworks, which predicts that temporal judgments would shift toward the adapted duration rather than away from it. This would manifest as attraction effects opposite to classical sensory adaptation patterns.

Additionally, the sensitivity enhancement hypothesis predicts that time adaptation would improve temporal discriminability, as evidenced by reduced standard errors of PSEs in bisection tasks and decreased variability in production tasks following adaptation. This improvement should manifest regardless of adaptation duration if time adaptation operates through mechanisms similar to other sensory adaptations.

The channel-based specificity hypothesis, derived from duration channel models, further refines predictions that adaptation effects would be strongest when the adapted and test durations were most similar. This was assessed by computing aftereffect magnitudes (post-adaptation minus pre-adaptation values) and conducting one-way ANOVAs comparing conditions with the same task duration but different adaptation durations (such as 500(500) versus 500(1000) versus 500(2000)).

To determine whether time adaptation affects internal temporal representations beyond perceptual processing, we employed a differential task approach comparing bisection and production tasks. The bisection task relies on comparison with externally presented physical references, while the production task depends primarily on internal temporal standards stored in memory. In contrast, if time adaptation operates purely at the perceptual level—similar to other sensory adaptations—then bisection tasks would show adaptation effects while production tasks would remain unaffected. This pattern would indicate that adaptation influences only the encoding of incoming temporal information without altering the mental time reference standards used for temporal judgments.

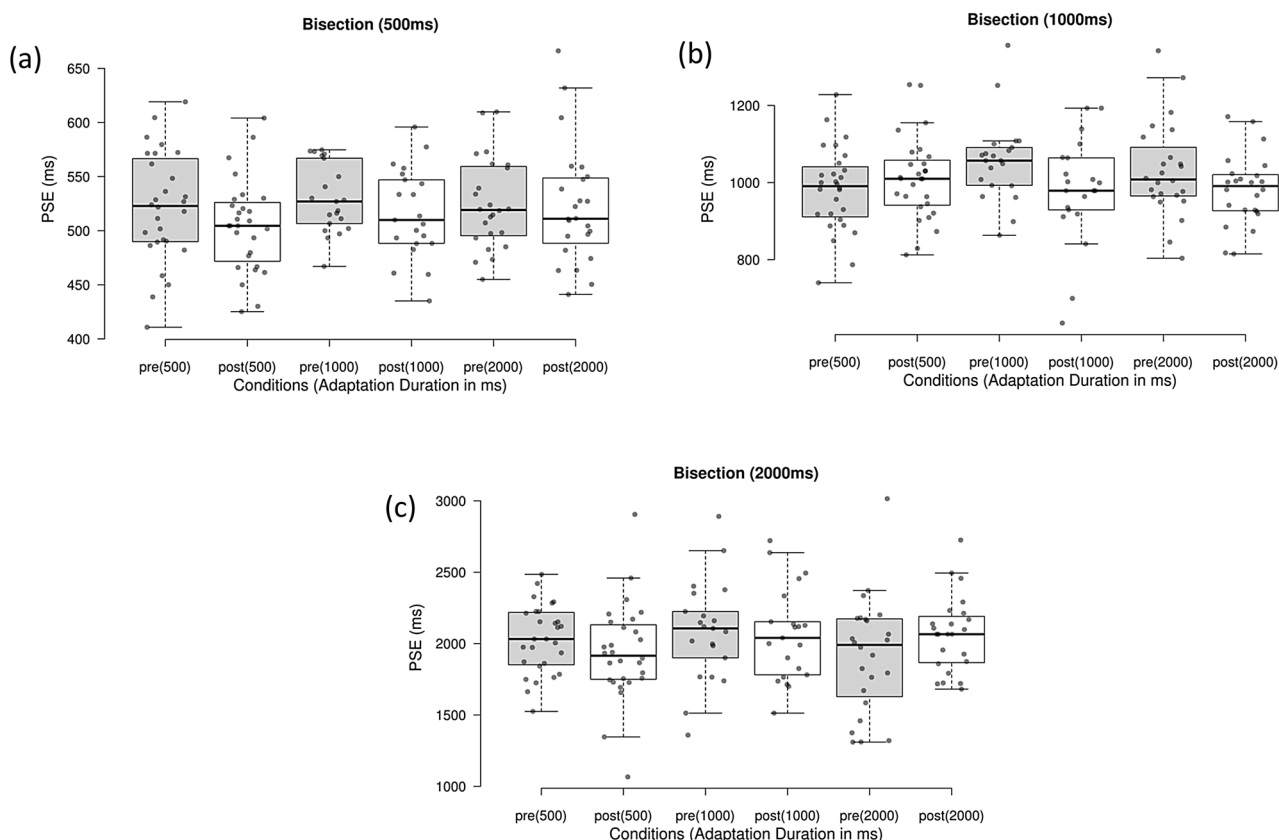
## Results

### Time bisection task

The valid  $n$  for the time bisection task analysis was 73 across the three adaptation conditions (500 ms:  $n=28$ , 1000 ms:  $n=21$ , 2000 ms:  $n=24$ ). A  $3 \times 3$  Mixed ANOVA was conducted to ensure the baseline of the three groups of participants did not differ significantly ( $F_{(2, 70)}=1.94$ ,  $p=.15$ ,  $\eta^2<0.01$ ). Figure 2 presents the PSEs under different experimental conditions. Figure 3 presents samples of mixed-level psychometric curves of the three adaptation conditions.

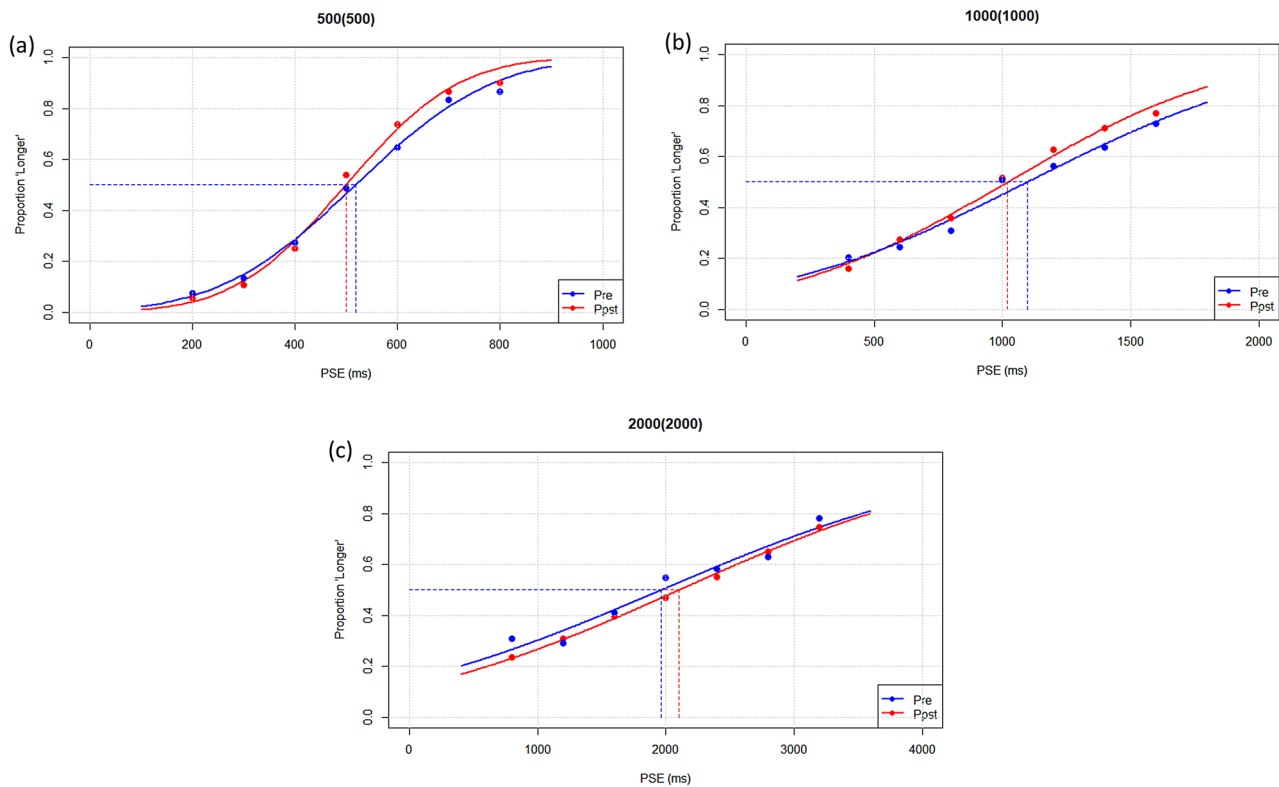
A mixed 2 (pre-post adaptation)  $\times$  3 (adapted duration) ANOVA conducted on the PSEs of the 500 ms time bisection task showed no significant main effects (pre-post:  $F_{(1, 70)}=2.37$ ,  $p=.13$ ,  $\eta^2=0.02$ ; adapted duration:  $F_{(2, 70)}=0.83$ ,  $p=.44$ ,  $\eta^2=0.01$ ) or interaction effects ( $F_{(2, 70)}=0.41$ ,  $p=.66$ ,  $\eta^2=0.01$ ). The results of the 1000 ms time bisection task were similar (pre-post:  $F_{(1, 70)}=0.03$ ,  $p=.86$ ,  $\eta^2<0.01$ ; adapted duration:  $F_{(2, 70)}=1.08$ ,  $p=.35$ ,  $\eta^2=0.01$ ; interaction:  $F_{(2, 70)}=1.72$ ,  $p=.19$ ,  $\eta^2=0.03$ ). The main pre-post effects of the 1000 ms time bisection task were marginally significant (pre-post:  $F_{(1, 70)}=3.12$ ,  $p=.08$ ,  $\eta^2=0.02$ ), while the adapted duration was not ( $F_{(2, 70)}=0.46$ ,  $p=.63$ ,  $\eta^2=0.01$ ). Its interaction effect was marginally significant ( $F_{(2, 70)}=2.9$ ,  $p=.06$ ,  $\eta^2=0.04$ ). PSEs increased after adapting to 500 ms, while the other two durations reduced.

Only adapting to 1000 ms duration showed a significant main effect of adaptation on SEMs ( $F_{(1, 70)}=4.29$ ,  $p=.04$ ,  $\eta^2=0.03$ ): that is, the sensitivity was improved. Adapting to 500 and 2000 ms resulted in significant interaction effects: that is, in comparison to other longer durations, adapting to 500 ms appeared to reduce sensitivity (500 ms:  $F_{(2, 70)}=4.35$ ,  $p=.02$ ,  $\eta^2=0.5$ ; 2000 ms:  $F_{(2, 70)}=3.0$ ,  $p=.05$ ,  $\eta^2=0.04$ ). The analyses of the SEM of the PSEs did not provide sufficient support for the hypothesis that sensitivities increase after adaptation. Table 1 summarizes the PSEs and SEM analyses.



**Fig. 2.** Boxplots of PSEs in bisection tasks using the BoxPlotR tool (Spitzer, Wildenhain, Rappsilber & Tyers, 2014 [25]). Center lines indicate the medians, while box limits denote the 25th and 75th percentiles, as determined by the R software. Error bars denote the 5–95% percentiles. The panels indicate the results of the (a) 500, (b) 1000, and (c) 2000 ms time bisection tasks.





**Fig. 3.** Plots of psychometric curves based on average data in conditions where the adaptation and task duration are the same, using RStudio (<https://posit.co/download/rstudio-desktop/>) and R version 4.5.1 (<https://cran.rstudio.com/>). The panels display the curves for bisection task conditions: (a) 500 (500) [ $n=28$ ], (b) 1000 (1000) [ $n=21$ ], and (c) 2000 (2000) [ $n=24$ ].

Task	500			1000			2000		
PSE	<i>F</i>	<i>p</i>	$\eta^2$	<i>F</i>	<i>p</i>	$\eta^2$	<i>F</i>	<i>p</i>	$\eta^2$
<i>Adapt</i>	2.37	0.13	<0.01	3.12	0.08	0.02	<0.01	0.86	<0.01
<i>Duration</i>	0.83	0.44	0.01	0.46	0.63	0.01	1.08	0.35	0.01
<i>Interaction</i>	0.41	0.66	0.01	2.9	0.01**	0.04	1.72	0.19	0.03
<i>SEM</i>	<i>F</i>	<i>p</i>	$\eta^2$	<i>F</i>	<i>p</i>	$\eta^2$	<i>F</i>	<i>p</i>	$\eta^2$
<i>Adapt</i>	<0.01	0.99	<0.01	4.29	0.04*	0.03	1.45	0.23	0.01
<i>Duration</i>	1.84	0.17	0.03	0.55	0.58	0.01	0.43	0.65	0.01
<i>Interaction</i>	4.35	0.02	0.05	0.57	0.57	0.01	3.04	0.05	0.04

**Table 1.** Summary of planned analyses of bisection tasks.

Two exploratory  $2 \times 2 \times 2$  mixed ANOVAs were conducted to test the repulsion hypothesis. To test whether adapting to a longer duration would lead to a reduction of the PSEs, a mixed 2 (pre-post adaptation)  $\times$  2 (adapted duration: 500 and 1000)  $\times$  2 (task duration: 1000 and 2000) ANOVA was conducted (Table 2). Another mixed 2 (pre-post adaptation)  $\times$  2 (adapted duration: 1000 and 2000)  $\times$  2 (task duration: 500 and 1000) was conducted to test whether adapting to a shorter duration would lead to an extension of the PSEs. Adapting to longer duration significantly reduced the PSEs ( $F_{(1,43)}=7.12, p=.01, \eta^2=0.14$ ), while adapting to short duration did not significantly increase the PSEs ( $F_{(1,47)}=1.19, p=.28, \eta^2=0.03$ ).

**Time production task**

The valid  $n$  for this analysis was 77 (0.5s:  $n=24$ , 1s:  $n=27$ , 2s:  $n=26$ ). A  $3 \times 3$  Mixed ANOVA was conducted to ensure the baseline of the three groups did not differ significantly ( $F_{2,74}=0.28, p=.76, \eta^2<0.01$ ). Table 3 presents the test statistics. Mixed 2 (pre-post adaptation)  $\times$  3 (adapted duration) ANOVAs were conducted separately for the three production durations. Only 500 ms showed a significant main effect on pre-post adaptation ( $F_{1,74}=7.60, p=.01, \eta^2=0.01$ ), while the produced durations of 1000 ms ( $F_{1,74}=0.11, p=.74, \eta^2<0.01$ ) and 2000 ms ( $F_{1,74}=1.16, p=.28, \eta^2<0.01$ ) were not significant. The 500 ms productions were significantly underestimated after adaptation. The adapted durations did not have any statistically significant main effect, indicating that adapting to different

a) 2 (adaptation) x 2 (duration: 1000 and 2000) x 2 (task: 500 and 1000)							
Main	F	p	$\eta^2$	Interaction	F	p	$\eta^2$
Adapt(A)	7.12	0.01*	0.14	A x D	0.56	0.46	0.01
Duration(D)	0.18	0.68	< 0.01	D x T	0.19	0.66	< 0.01
Task(T)	1344.27	< 0.01**	0.97	A x D x T	0.11	0.74	< 0.01
b) 2 (adaptation) x 2 (duration: 500 and 1000) x 2 (task: 1000 and 2000)							
Main	F	p	$\eta^2$	Interaction	F	p	$\eta^2$
Adapt(A)	1.19	0.28	0.03	A x D	0.05	0.82	< 0.01
Duration(D)	4.26	0.05*	0.08	D x T	1.07	0.31	0.02
Task(T)	1051.32	< 0.01**	0.96	A x D x T	1.29	0.26	0.03

**Table 2.** Summary of exploratory analyses of bisection tasks (a) adapting to duration longer than or equal to the tasks and (b) adapting to duration shorter than or equal to the tasks.

Task	500			1000			2000		
Average	F	p	$\eta^2$	F	p	$\eta^2$	F	p	$\eta^2$
Adapt	7.60	< 0.01	0.01	0.11	0.74	< 0.01	1.16	0.28	< 0.01
Duration	0.14	0.87	< 0.01	0.01	0.995	< 0.01	0.23	0.80	0.01
Interaction	0.54	0.58	< 0.01	0.04	0.96	< 0.01	1.24	0.30	0.01
SD	F	p	$\eta^2$	F	p	$\eta^2$	F	p	$\eta^2$
Adapt	8.09	< 0.01**	0.03	5.13	0.03*	0.02	2.19	0.14	0.01
Duration	0.19	0.83	< 0.01	0.34	0.71	0.01	0.08	0.92	< 0.01
Interaction	0.32	0.73	< 0.01	0.65	0.52	0.01	0.77	0.47	0.01

**Table 3.** Summary of planned analyses of production tasks.

durations (i.e. 500, 1000, and 2000 ms) does not produce differentiated adaptation effects ( $F_{2,74} = 0.01\text{--}0.23$ ,  $p = .80\text{--}1.0$ ,  $\eta^2 < 0.01$ ). The interaction effects were also not statistically significant ( $F_{2,74} = 0.04\text{--}0.54$ ,  $p = .58\text{--}0.96$ ,  $\eta^2 < 0.01$ ). Figure 4 illustrates the descriptive data in boxplots.

Mixed  $2 \times 3$  ANOVAs were conducted on the SDs of the respective produced durations. There appeared to be a general adaptation effect: that is, sensitivity increased in producing 500 ms ( $F_{2,74} = 8.09$ ,  $p = .01$ ,  $\eta^2 = 0.03$ ) and 1000 ms ( $F_{2,74} = 5.13$ ,  $p = .03$ ,  $\eta^2 = 0.02$ ) after adaptation. The time production of 2000 ms showed a similar trend, but this was not statistically significant ( $F_{2,74} = 7.60$ ,  $p = .14$ ,  $\eta^2 = 0.01$ ). The main effect of adapted duration and interactions was not significant ( $F_{2,74} = 0.08\text{--}0.77$ ,  $p = .47\text{--}0.92$ ,  $\eta^2 < 0.01$ ).

Discussion

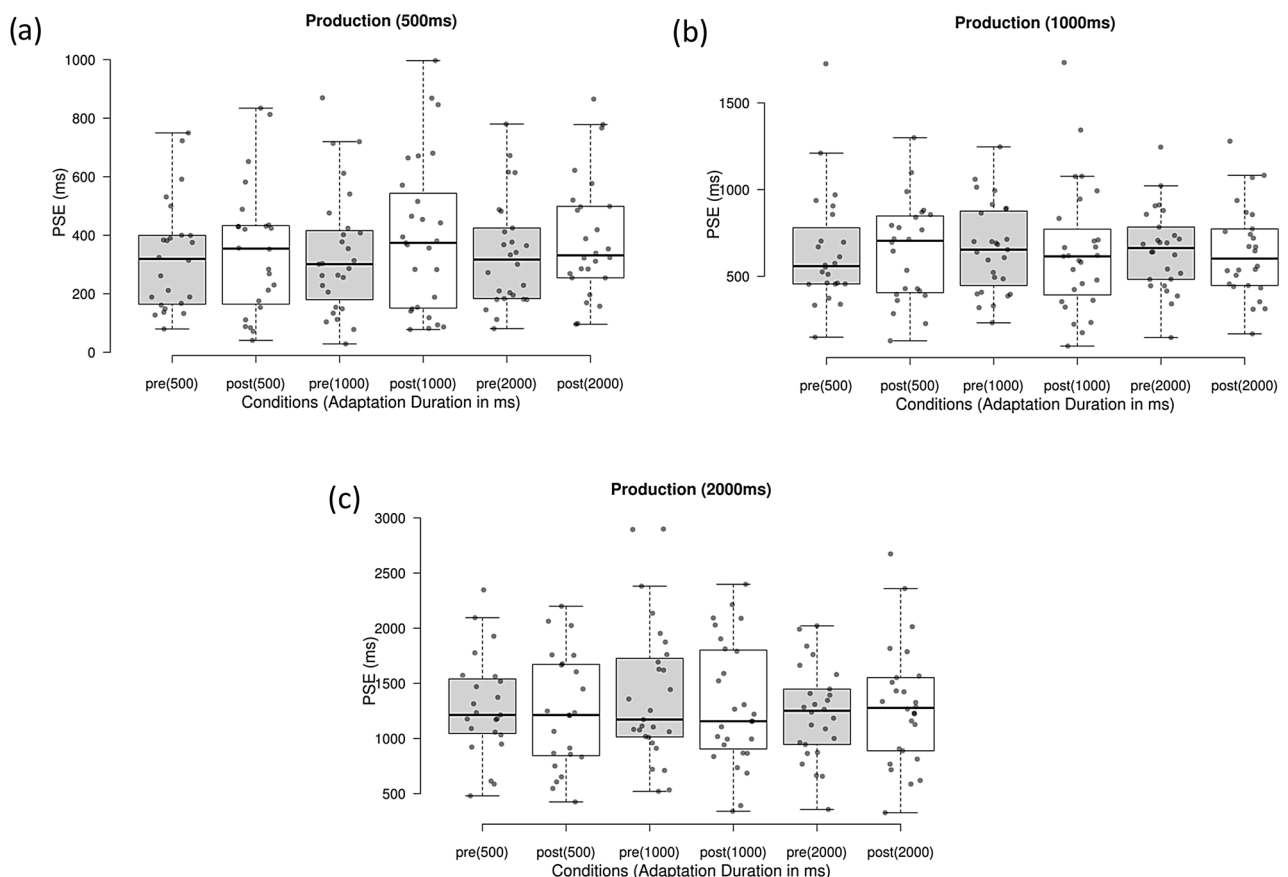
The present study employed bisection and production tasks to address two fundamental research questions regarding time adaptation mechanisms. The first question examined whether time adaptation operates similarly to classical sensory adaptations, while the second investigated whether adaptation affects internal temporal reference standards beyond perceptual processing.

The planned  $2 \times 3$  ANOVA of bisection tasks provide limited evidence for the classical sensory adaptation model in terms of the repulsion hypothesis. The 1000 ms bisection task demonstrated weak but directionally consistent adaptation effects, with adapting to 500 ms inducing relative increases in perceived subjective equivalents (PSEs). In contrast, reductions followed adaptation to durations of 1000 and 2000 ms. This bidirectional pattern aligns with the repulsion hypothesis, where post-adaptation perception deviates away from the adapted duration. Exploratory additional analyses reveal that adaptation to longer durations significantly reduces PSEs, further supporting this repulsion effect. However, the asymmetric nature of these effects suggests that temporal adaptation may not fully mirror visual or auditory adaptations.

The channel-based specificity hypothesis received limited support, with only marginal interaction effects observed in the 1000 ms bisection task. The absence of robust duration-specific adaptation patterns challenges the notion that temporal processing relies on discrete duration-tuned channels analogous to orientation or spatial frequency channels in vision.

The results also diverge from classical sensory adaptation predictions regarding the enhancement of sensitivity. While the 1000 ms bisection task showed significantly improved sensitivity following adaptation, the 500 ms bisection task demonstrated slight reductions in sensitivity, and the 2000 ms condition showed no consistent pattern. This inconsistent sensitivity profile contrasts sharply with the reliable discriminability improvements characteristic of visual and auditory adaptations (Chopin & Mamassian, 2012<sup>4</sup>; Thompson & Burr, 2009)<sup>6</sup>.

These findings suggest that time adaptation operates through fundamentally different mechanisms than classical sensory adaptations. Unlike modality-specific visual or auditory adaptations, temporal processing involves vast distributed neural networks (Wiener, Turkeltaub & Coslett, 2010)<sup>26</sup>. The cross-modal nature of



**Fig. 4.** Boxplots of PSEs in production tasks using the BoxPlotR tool (Spitzer, Wildenhain, Rappsilber & Tyers, 2014 [25]). Center lines indicate the medians, while box limits denote the 25th and 75th percentiles, as determined by R software. Error bars denote the 5–95th percentiles. The panels indicate the results of the (a) 500, (b) 1000, and (c) 2000 ms time bisection tasks..

time adaptation, as demonstrated by Li et al. (2015)<sup>21</sup> and Heron et al. (2012)<sup>9</sup>, indicates that temporal adaptation represents an integrated process combining multiple factors rather than a single-modality phenomenon.

Adaptation effects in the 1000 ms and 2000 ms production tasks are not statistically significant, whereas the 500 ms task exhibited a significant shift toward the adapted duration. At baseline, production tasks also displayed an overall reduction in produced durations. In contrast, the bisection tasks exhibited asymmetrical repulsion effects, with judgments biased away from the adapted duration. These opposing patterns support an averaging mechanism in production tasks and a repulsion mechanism in bisection tasks, indicating that adaptation differentially influences mental and physical time references. Unlike bisection, production tasks rely mainly on internal temporal standards during the post-adaptation phase, suggesting that adaptation modifies mental time references in accordance with the Bayesian or central-tendency models (Lejeune & Wearden, 2009<sup>15</sup>; Shi et al., 2013)<sup>16</sup>. Mental time reference—shaped by cumulative exposure to temporal events—appears more susceptible to adaptation in sub-second regimes, which operate automatically, than in supra-second regimes, which involve cognitive control (Koch et al., 2007<sup>27</sup>; Lewis & Miall, 2006)<sup>28</sup>. Although one might argue that production still entails implicit physical referencing when the stimuli are shown while participants hold the key, this cannot account for the directional differences observed. Overall, the dissociation between bisection and production results indicates that time adaptation engages multiple processing levels, affecting both perceptual encoding and decision-making standards.

The enhanced sensitivity observed in production tasks, particularly the general reduction in variability across 500 ms and 1000 ms conditions, likely reflects practice effects rather than adaptation-induced improvements in discriminability. Given that production tasks exhibited larger inherent variability than bisection tasks, the reduction in standard deviations following repeated trials appears more consistent with familiarization than with the theoretical sensitivity enhancements predicted by classical adaptation models.

The observed adaptation effects among bisection tasks in this study aligned in the same direction as those documented in prior research. The effects were notably smaller despite using a much larger sample size in each condition (Heron et al., 2012<sup>9</sup>; Li et al., 2015<sup>21</sup>; Shima et al., 2016<sup>10</sup>). This discrepancy may stem from methodological differences, including the concurrent use of bisection and production tasks alongside a broad duration range (300–3200 ms). Although block designs and inter-block instructions were implemented, participants potentially struggled with task-switching demands, which could have attenuated the adaptations.



Repeated exposure across tasks may have further confounded aftereffects. Crucially, all participants were naïve to the research objectives, contrasting with prior studies that occasionally employed experienced psychophysics observers. This inexperience likely contributed to the elevated proportion of poor-fitting data despite pre-collection practice blocks. Future investigations could mitigate these issues by extending practice protocols and distributing tasks across multiple sessions, as demonstrated by Li et al. (2015)<sup>21</sup>.

The present study provides evidence regarding time adaptation mechanisms through concurrent bisection and production tasks. While adaptation effects were weaker among naïve participants compared to previous research, the directional patterns offer important theoretical insights. Adapting to longer durations demonstrated limited support for classical sensory adaptation, with post-adaptation perception deviating away from adapted durations in a pattern consistent with repulsion effects. However, time adaptation differs fundamentally from visual and auditory adaptations, as it lacks a channel-based effect and exhibits inconsistent sensitivity improvements. Production tasks revealed contrasting patterns, with 500 ms conditions showing attraction toward adapted durations consistent with Bayesian and central tendency models. This dissociation between bisection and production demonstrates that adaptation operates at multiple processing levels, affecting both perceptual encoding and mental temporal reference. These findings suggest that temporal adaptation represents an integrated, multi-modal process distinct from classical sensory adaptations, highlighting the complex nature of time perception mechanisms.

## Data availability

The datasets generated and analyzed during the current study are available as supplementary materials.

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## Author contributions

W. O. Li was the project manager responsible for funding acquisition, project administration, data analyses and writing the original draft. K. S. L. Yuen contributed to the conceptualization, methodology, and data analyses. D. H. F. Chang designed the protocols and procedures. C. K. C. Yu supervised the data collection. All authors reviewed the manuscript.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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**Correspondence** and requests for materials should be addressed to W.O.L.

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