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時間統計規律性促進時間感判斷：跨感官不對稱效果

Temporal Regularity Boosts Duration Judgement: Asymmetric Cross-modal Effect

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中文摘要

時間訊息使我們能整合各式各樣的事件並做出預測。前人探討“節奏時間知覺 (時間統計規律性)”以及“時距時間知覺 (時間感判斷)”間關係的研究中顯示請參與者做聽覺時間感判斷時，比起不規則的聲音，若將目標聲音區間接續在以固定時間間隔出現、具有時間規律性的喀噠聲之後播放，參與者的表現較好。越來越多的證據指出，知覺作業中若目標刺激接在時間間隔規律的事件之後出現，會使參與者更能偵測與分辨出該目標，且這可能是透過一種可影響多種感官的機制所達成。然而，目前尚不清楚時間統計規律性是否可透過類似的機制跨感官地影響其他感官的時間感，亦或此種促進效果僅侷限在單一感官中。更者，從時間解析度不同的感官訊息中所抽取出的時間統計規律性，是否會因此對於時間感有不同程度的影響(例如聽覺比視覺訊息的時間解析度好，是否因此聽覺統計規律性對時間感影響較大)，目前也尚待驗證。為探討上述議題，本研究共執行了五個實驗，其中實驗一使用純視覺刺激，其他實驗使用視覺與聽覺刺激。參與者須在時間間隔規律(具時間統計規律性)或不規律的刺激序列出現之後，比較隨後依序出現的兩個目標刺激何者呈現的時間較長(時間感判斷)。實驗結果顯示，規律的視覺刺激可以促進視覺時間感判斷(實驗一)，卻未能促進聽覺時間感判斷(實驗二)，即使以測驗要求參與者注意目標聲音出現前的視覺序列是否具有時間規律性，仍無跨感官的促進效果(實驗三)。相較之下，規律的聽覺刺激在參與者有特別注意其時間結構的規律性時，能夠跨感官地促進視覺的時間感判斷(實驗四)，而這樣的促進效果在參與者較不注意聽覺序列的時間結構時即消失(實驗五)。綜觀而言，本篇研究闡明了時間統計規律性可跨感官地促進時間感的判斷，而視覺與聽覺的時間統計規律性，對彼此感官時間感影響的不對稱性，更支持了時間解析度較好的感官(聽覺)所提供的訊息，對於時間估計的判斷也更為重要。

關鍵詞: 時間統計規律性；時間感；視覺規律性；聽覺規律性；跨感官效果

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Abstract

Temporal information enables us to integrate events and make predictions. By examining the relationship between beat-based timing (temporal regularity) and duration-based timing (duration judgement) mechanisms, previous research has shown better performance in auditory duration judgement when the target durations were preceded by a regular auditory click sequence than by an irregular one. Increasing evidence suggests that preceding rhythmic context makes sensory targets more detectable and discriminable, which may be mediated by a supramodal mechanism. Yet little is known about whether the facilitation effect of temporal regularity on duration judgment is supramodal or is constricted within a single modality. Moreover, whether rhythmic information extracted from different modalities with varied temporal resolutions is weighted differently (e.g., whether audition weights more since it has a better resolution than vision) also needs to be examined. To resolve this issue, the present study conducted five experiments using visual and/or auditory stimuli. Participants were required to compare two durations preceded by a regular or an irregular sequence. The results revealed that visual temporal regularity facilitated visual duration judgment (Experiment 1) but not auditory duration judgment (Experiment 2) even when participants explicitly paid attention to the rhythmic structures of the preceding sequences (Experiment 3). By contrast, auditory temporal regularity facilitated visual duration judgment with attention deployed to the temporal structure (Experiment 4) and this cross-modal effect vanished without attention (Experiment 5). Overall, the present study demonstrated that temporal regularity can cross-modally boost duration judgments, while the finding of the asymmetric audio-visual effect supports the view that information with better temporal precision is weighted more heavily in time estimation.

Keywords: temporal regularity; time perception; visual rhythms; auditory rhythms; cross-

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modal effect

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Introduction

Time perception is critical to our daily life. Only through deciphering temporal structures of events are we able to integrate perceptual or action sequences, to capture regularities from the information-bombarded environment, to predict future outcomes, and to make accurate movements.

Based on the rhythmic context of perceived stimuli, perceptual timing can be classified into beat-based timing and duration-based timing (Grube, Lee, Griffiths, Barker, & Woodruff, 2010; Keele, Nicoletti, Ivry, & Pokorny, 1989; Teki, Grube, & Griffiths, 2012; Teki, Grube, Kumar, & Griffiths, 2011). Beat-based timing refers to the timing mechanism used when people perceive rhythmic or temporally regular stimuli (*temporal regularity*), whereas duration-based timing is defined as the timing mechanism used when people estimate an absolute duration of discrete time intervals (*duration judgement*).

Not surprisingly, human daily life is full of scenarios involving these two timing mechanisms. One the one hand, for example, temporal regularity helps us make predictions in activities such as biological motion and speech production. Imagine that you are in a live music concert, trying to clap and sway to the music with others; the rhythmic beats from the music and other's movements offer a predictable pattern for you to follow up on the next beat. On the other hand, suppose you are making instant cup noodles, without duration-based timing you may not be able to time the "golden three minute" precisely, leading to overcooked noodles and thus spoiling your appetite (unless you use a countdown timer).

While these two perceptual timing mechanisms seem to be quite different from one another, both of them help us plan for an upcoming event. Thus how these two timing mechanisms interact with each other and whether they share a common underlying central mechanism is an intriguing issue. A previous fMRI study provided solid evidence, in

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auditory domain, for the interaction between these two timing mechanisms (Teki et al., 2011). Researchers used a paradigm embedding a duration comparison task at the end of an auditory sequence, which was composed of brief click sounds with either regular or irregular sub-second stimulus-onset asynchronies (SOAs). Participants were asked to compare the last SOA with the second-to-last SOA in each sequence. The behavioral results showed that the average reaction time was significantly facilitated and the accuracy rate was marginally better when participants' SOAs were preceded by a regular click sequence than by an irregular one. The finding suggests that temporal regularity might aid duration-based timing within the auditory modality. In the imaging results, Teki et al. (2011) revealed that the activity in striato-thalamo-cortical network was higher for beat-based timing, while the olivocerebellar network was involved more for duration-based timing.

Based on their results and other neurophysiological, neuroanatomical, and clinical studies, Teki et al. (2012) proposed a unified model of time perception by incorporating these two timing mechanisms. In this model, relative timing mechanism mediated by striatum serves as the default timing mode, which encodes a duration through learning temporal regularity. On top of this baseline, duration-based timing mechanism that involves olivocerebellar network accounts for the error prediction, which is especially useful in scenarios lacking clear rhythmic context. Consistent with the prediction model, recent research has shown that in participants with transient or chronic cerebellar disruption, the beat-based timing was spared despite impairment in duration estimation (Grube, Cooper, Chinnery, & Griffiths, 2010; Grube et al., 2010; Teki et al., 2012). In contrast, patients with hereditary basal ganglia degeneration (Huntington's disease) tend to have severe impairment in both beat-based and duration-based timing (Cope, Grube, Singh, Burn, & Griffiths, 2014), which is also predicted by this unified model.

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Although it has been established that temporally regular context helps duration judgement within a single modality (audition) and also these two timing mechanisms were proposed to be in a unified timing system, little has been explored about whether this facilitation can also extend to vision or cross-modality.

Increasing evidence revealed that rhythmic context benefits perceptual detection and discrimination (attentional entrainment). For example, while following temporally regular tones, the auditory pitch of last tone was judged more accurately when the target tone occurred at the expected beat (Jones, Moynihan, MacKenzie, & Puente, 2002). Moreover, a masked visual target appearing at the isochronous moments to the preceding visual entertainers was also detected better than at the asynchronous moments (Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Mathewson et al., 2012). To explain the phenomena, it was proposed that after we perceive temporal regularity, a supra-modal mechanism increases perceptual performance by reallocating attention periodically at the anticipated time to synchronize to the temporal regularity (Jones & Boltz, 1989; Jones et al., 2002).

Recently a study further showed a cross-modal perceptual benefit from temporal regularity (Miller, Carlson, & McAuley, 2013). In this eye-tracking research, participants were asked to fixate at a central dot, and after a regular sequence of auditory tones, the fixation dot changed location as a visual target to be detected. The dot would change location at the time either synchronous or asynchronous to the auditory regular tones. A shorter saccade latencies were observed in the synchronous conditions in comparison to the asynchronous conditions. The finding supports a supramodal mechanism, in which general attention is entrained by temporal regularity and contributes to perceptual benefits in another modality.

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In the same vein, it is possible that temporal regularity benefits duration judgment through a similar supramodal mechanism by allocating attention to the expected time. In agreement with the perspective of rhythmic entrainment, prior research showed that auditory duration judgments improved with valid induction regular sequences (Barnes & Jones, 2000). In this study, an auditory sequence composing of brief tones was presented steadily in a regular induction interval (e.g., 300 ms), and a successive interval as a standard duration was either an integer multiple of the induction interval (e.g. 600 ms) or not (e.g. 524 ms). A comparison duration was presented seconds later, and participants performed better when the standard duration was a multiple of induction interval. Their findings support that rhythmic context may aid subsequent duration judgment through this waxing and waning attention as a consequence of rhythmic entrainment. Accordingly, it is possible that temporal regularity extracted from rhythmic stimuli in one modality may facilitate duration judgments in another modality via a similar mechanism.

Since a cross-modal influence on duration judgment is possible, the next question is whether the temporal regularity extracted from modalities with different temporal resolution contributes differently to duration judgment. It has long been proposed that human beings tend to integrate information in a statistically optimal fashion (Ernst & Banks, 2002), as is the case in integrating information for calculating an uncertain duration (Freestone & Church, 2016; Hartcher-O'Brien, Di Luca, & Ernst, 2014; see also Jazayeri & Shadlen, 2010; Shi, Church, & Meck, 2013). According to the Bayesian brain theory, our brain, as a Bayesian optimization machine, would integrate prior knowledge and available sensory evidence from different sources to optimize estimation of unknown information (Hartcher-O'Brien, Di Luca, & Ernst, 2014; for reviews, see Knill & Pouget, 2004). Importantly, the best estimation is the weighted-sum of each evidence based on their precision. That is, the more precise the information is, the greater it weights in the

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final estimation. Auditory events usually offer better temporal acuity than visual events (Burr, Banks, & Morrone, 2009; Chen & Yeh, 2009; Welch & Warren, 1980). For example, auditory durations were judged as longer with less variation in comparison to visual durations (Wearden, Edwards, Fakhri, & Percival, 1998), and auditory intervals or filled durations were discriminated better than visual ones (Rammsayer, 2014). Therefore, it can be inferred from the Bayesian brain theory that auditory temporal regularity would contribute to the influence on duration judgments more than visual temporal regularity.

Thus our research aim is twofold: (1) to examine whether the facilitation effect of temporal regularity on duration judgment is a supramodal or is constricted within a single modality, and (2) to explore whether rhythmic information extracted from different modalities with varied temporal resolutions is weighted differently (e.g., audition has a better resolution than vision).

In this study, we conducted five experiments with visual and/or auditory stimuli to probe our research questions. To briefly explain our paradigm, we presented a sequence of stimuli, in which the last two stimuli were targets for participants to compare their presenting durations. As a within-subject factor, the temporal regularity of the sequences was either regular or irregular, that is, with fixed or jittered interstimulus intervals (ISIs). Before we tested the cross-modal influence, we examined the within-modality influence in visual modality. The preceding sequence and the targets were both composed of visual disks in Experiment 1. Then in the subsequent 4 experiments, the preceding sequence was paired with cross-modal targets, composing visual-auditory sequences (VA) in Experiment 2 and 3, instead auditory-visual sequences (AV) in Experiment 4 and 5.

Three hypotheses arose from the research questions to be tested:

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1. *Supramodal* hypothesis: Temporal regularity can facilitate duration judgment via a *supramodal* mechanism, such as attentional entrainment. Therefore, a better performance in duration judgment should be observed in both VA and AV sequences.

2. *Optimization* hypothesis: Though beat-based timing and duration-based timing might cooperate with each other in a unified model, an optimization mechanism, as suggested in the Bayesian brain theory, might tune the weight of temporal information from each modality differently according to its precision. Then we could predict that auditory and visual temporal regularity should weight differently in each cross-modal pair, and thus causing different results in duration judgments. According to this hypothesis the temporal regularity from auditory sequence (more precise) is predicted to help visual duration (less precise) judgments, but not vice versa.

3. *Mechanism-specific* hypothesis: Though adaptation for frequency of temporal beats can transfer across modalities, adaptation for durations has a modality-specific feature (Levitan, Ban, Stiles, and Shimojo, 2015; Li, Yuan, & Huang, 2015, Heron *et al.*, 2012; for a review, see Murai, Whitaker, & Yotsumoto, 2016). Thus it seems that these two timing mechanisms work differently in how temporal information is utilized among modalities. Besides, current evidence only showed temporal regularity affected duration judgment within a single modality, so temporal information probably may not be integrated and benefit duration judgment in another modality. In this case, nonsignificant results should be observed in both VA and AV cross-modal experiments.

General Methods

Stimuli and experimental paradigm

Stimuli and apparatus.

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Each trial contained a sequence of stimuli and the two last stimuli were targets to be compared by participants. The stimulus immediately before the two targets (i.e., the third-to-last stimuli) was an oddball to allow participants to prepare for the task instead of having to memorize all individual durations. We used disks as visual stimuli and beep tone sounds as auditory stimuli. All the visual disks were black with 50% general transparency and were presented on a gray background. The standard disks were 2° in visual angle, and the oddball disk was composed of a disk (diameter 2°) with a surrounding concentric circle (diameter 2.2°). One disk was presented at the center of the screen each time. All the standard auditory beep sounds were 800 Hz pure tone, and the oddball beep sounds were 830 Hz pure tone, generated with Matlab (Mathworks, USA) and Psychtoolbox-3 (http://psychtoolbox.org). The volume of beep sounds was on average 52db SPL measured at the chin rest, which was used to stabilize the participant's head position. Words of instructions were presented in black color on a gray background. Visual stimuli and auditory stimuli were respectively presented on a 21" cathode ray tube monitor and 2.0 channel desktop speakers (one speaker at each side of the monitor) which were on the depth plane of 92 cm from the participant, and were driven by an Apple Mac Mini desktop computer running Mac OS 10.10.5. Stimuli presentation and the collection of participant's responses were controlled via Matlab with Psychtoolbox-3.

Design and paradigm.

In each trial, 8-11 stimuli were sequentially presented. Participants were required to compare the durations of the last two stimuli (the standard target, Ts, and the deviant target, Td) and judge which one had longer duration (i.e., *duration comparison task*). An oddball was presented immediately before the two targets to enable participants to respond quickly in the subsequent task. Participants were instructed to gaze at the center

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of the screen, pay attention to all stimuli, and press the corresponding key as soon and accurately as possible right after the presentation of the last stimulus ended. For example, participants were asked to press their right index finger on the comma key (with symbols "," and "<") when Ts was longer and right middle finger on the period key (with symbols "." and ">") when Td was longer (*Figure 1*). The regularity of ISIs was a within-subject factor: the ISIs in each sequence were either regular or irregular. An instruction "Please press the space bar to proceed" would show up on the screen as a feedback to ensure the response was being recorded. After participants pressed the space bar, the next trial began after a random interval ranging from 1 to 2 seconds. All of the combinations of durations and stimuli numbers were balanced between regular and irregular conditions. Participants were informed that the number of stimuli varied for each sequence but they were naïve about the exact range of the numbers.

While all the stimulus durations remain unchanged (standard duration: either 400 ms or 600 ms) for each trial, the duration of the last one, as a deviant target (Td), was either longer or shorter than that of the second-to-last stimulus (a standard target with the standard duration, Ts). The percentage of the duration difference between Td and Ts was adjusted before the formal testing according to an individualized threshold obtained from a pretest to prevent ceiling or floor effects. The interstimulus intervals (ISIs) in regular sequences were kept constant in 500 ms (standard ISI). In irregular sequences, ISIs ranged from 20% to 60 % from the standard ISI (i.e., 200 to 400 ms or 600 to 800 ms) except that the ISI between Ts and Td was fixed at 500 ms. Therefore, the stimuli at the duration comparison stage in the irregular sequences were identical to that in the regular ones. Rather than asking participants to compare a standard ISI to a deviant one with the standard ISI only repeating in regular preceding sequences but not in irregular ones as in Teki et al. (2011), we asked participants to compare target durations. While the duration

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of Ts was always identical to the standard durations, the standard duration was repeated equally in both regular and irregular sequences. Therefore, if participants had better performance with the regular sequences, the effect should not be derived from unequal exposure to the standard duration.

There were six blocks in each experiment and each block was composed of 24 trials with randomly assigned temporal regularity (regular or irregular) in each trial. After completing each block, participants were asked to rest for at least 5 seconds. Before starting the formal experiment, participants were required to complete 16 to 40 practice trials until they were familiar with the task demand. The experiment would be terminated if the accuracy rate for each condition was lower than 60%. Tapping and (explicit or implicit) counting were not allowed during all experiments to prevent target duration from being divided into various smaller units.

Paradigm difference among experiments.

In Experiment 1, we aimed to test whether temporally regular visual stimuli could facilitate visual duration judgement. That is, both targets and the stimuli preceding targets were visual disks (Visual). Participants were asked to observe all visual disks and to detect the oddball stimuli (just before the two targets) in order to make quick and accurate responses after the last target disappeared (*Figure 1*).

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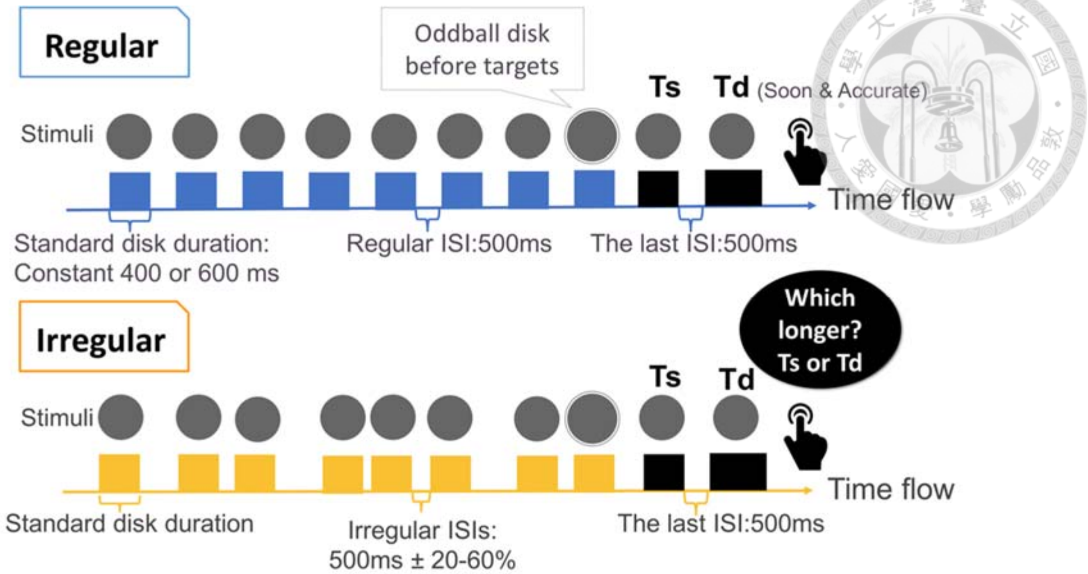

*Figure 1***.** Procedure of Experiment 1 (Visual).

After viewing the serially presented 8 to 11 disks (see Stimuli and apparatus for details), participants were required to compare the presenting duration of the last two disks (their durations were represented by the black squares) and choose the longer duration by pressing the corresponding key as soon and accurately as possible right after the whole sequence ended. The duration of disks in each trial was kept constant at either 400 ms or 600 ms, while the duration of the last disk was jittered as a deviant target (Td) to be compared with the second last target (Ts). Each trial was randomly assigned with either regular or irregular ISIs. The upper panel showed a regular sequence, in which the ISIs were fixed at 500ms. The lower panel showed an irregular sequence, in which the ISIs were roved 20 to 60 % from the standard ISI (i.e. 500 ms ± 20 to 60 %).

To the extent that the facilitation effect of temporal regularity on the performance of duration judgement could extend to visual modality (Experiment 1), we conducted cross-modal experiments to examine whether a rhythmic context from one modality could be

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maintained and later on facilitated the performance of duration judgement in the other modality.

Visual-auditory sequences (VA) were presented in Experiment 2 and 3: two auditory beep sounds as targets were preceded by a visual sequence of disks in each trial. Then auditory-visual sequences (AV) were presented in Experiment 4 and 5: two targets were visual disks and were preceded by an auditory sequence of beep sounds (*Figure 2*).

Owing to the non-significant results in Experiment 2, a regularity check was added in a trial-by-trial manner after the duration comparison task in Experiment 3 and 4, as a control of attention on the preceding sequences in that information from different modalities may need amplification by attention to be integrated (Baars, Franklin, & Ramsoy, 2013). Therefore, by adding regularity checks, participants were required to additionally pay attention on rhythmic context of the preceding cross-modal stimuli in order to classify whether the intervals in the preceding sequence was in regular or irregular temporal structure by pressing the corresponding key ("r" key: regular; "e" key: irregular) (*Figure 2*).

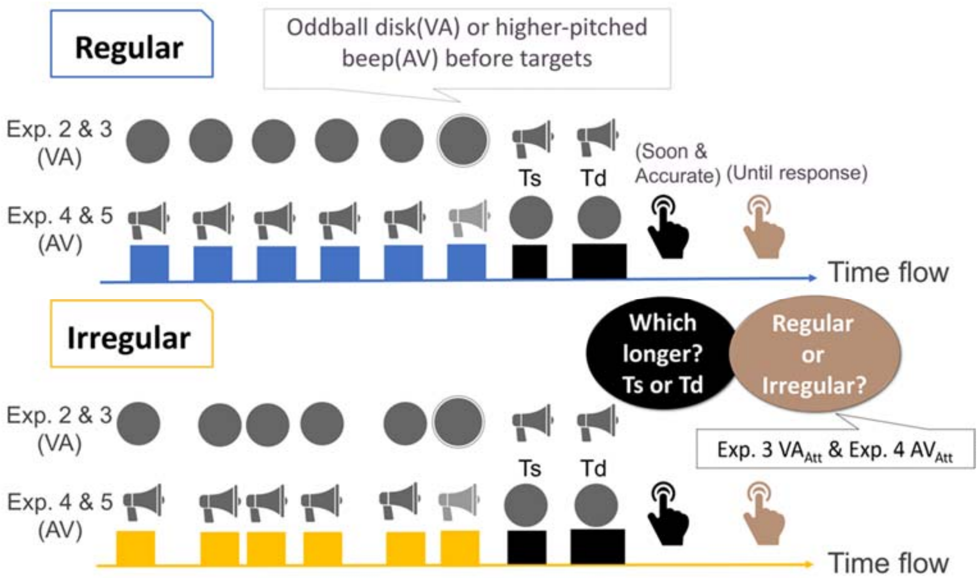

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Figure 2. Procedure of Experiment 2 to 3 (Visual preceding sequence–Auditory targets, VA) and Experiment 4 to 5 (Auditory preceding sequence–Visual targets, AV). The paradigm of Experiment 2 to 5 was similar to Experiment 1, except that we combined stimuli from two modalities in these experiments, and added regularity checks in Experiment 3 and 4. The stimuli types pairs of the preceding sequence and the targets were respectively VA and AV in Experiment 2 to 3 and Experiment 4 to 5. To enable participants to pay attention on the rhythmic context of each preceding sequence, we added a trial-by-trial regularity check in Experiment 3 (VA_{Att}) and Experiment 4 (AV_{Att}): after the duration comparison task, a question, "Regular or Irregular?" would be shown on the screen to require participants to answer the regularity of the preceding sequence by pressing the corresponding key (until response). Att: with additional attention by task demand.

Analysis.

Reaction times (RTs) in the duration comparison task were excluded from the analysis if they were shorter than 250 ms or longer than 3000 ms. The mean RT from correct trials (correct RTs) and accuracy rate were obtained for each participant per condition. Two-tailed paired t-tests were performed to compare the dependent variables between regular and irregular sequences after exclusion of data of outliers of correct RTs and accuracy rates. In Experiment 3 and 4, in which regularity check was performed, the rejection criteria for the accuracy rate of regularity checks was set closer to chance level (i.e. rejected if accuracy rate of regularity check < 60%).

Experiment 1

Previous research has shown that regularities of beat-based timing facilitated the duration-based timing within the auditory modality (Barnes & Jones, 2000; Teki et al.,

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2011). Before examining whether temporal regularities can benefit duration judgment via a supramodal mechanism using non-concurrent visual and auditory stimuli, we aimed to confirm whether temporal regularities have an effect on time judgement in visual modality, which is known as the most dominant modality for humans (Posner, Nissen, & Klein, 1976).

Method

Participants.

Eighteen healthy adults (8 females, M = 24.56 years, SD = 3.62 years), who were naïve about the purpose of the experiment, gave informed consent before the experiment and were financially compensated for their participation.

Design and paradigm.

A sequence of visual disks was serially presented in each trial and participants were asked to compare the presenting duration of the last two disks (Ts and Td; *Figure 1*) by pressing the corresponding key as soon and accurately as possible after each sequence ended (for details, please see General Methods and *Figure 1*).

Results

The average correct RT in the regular sequences was significantly faster than that in the irregular sequences ($t(17) = -2.22$, $p<.05$, two-tailed paired t-test, see *Figure 3*; regular: M = 531.99 ms, SD = 85.70 ms; irregular: M = 552.56 ms, SD = 99.33 ms). There was no significant difference in average accuracy rate between regular and irregular conditions ($t(17) = 1.76$, $p>.05$, two-tailed paired t-test; regular: M = 77.85 %, SD = 7.53 %, irregular: M = 75.59%, SD = 8.39 %).

Among the post-experiment subjective reports from 18 participants, 14 participants noticed that the regularity of disk sequences had changed during the experiment, yet most

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of them reported that the regularity of sequence did not have any impact on their performance of duration judgement. Four participants reported that all the sequences were perceived regularly, but the overall speed had changed over trials. Three in these four participants reacted faster in regular sequences than in irregular sequences.

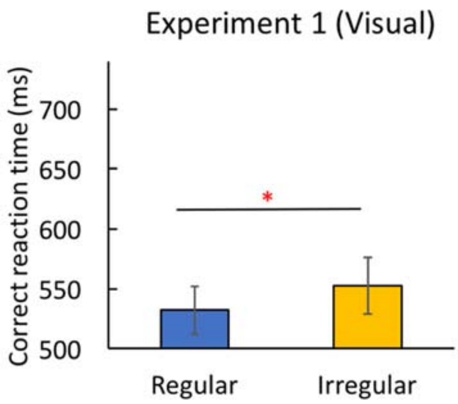

Figure 3. Results of Experiment 1 (Visual). The average correct RT was significantly faster in regular sequences rather than in irregular ones, which indicated that visual temporal regularity also benefited time judgement of visual events in spite of poor temporal resolution.

Discussion

The shorter correct RTs in the regular condition in Experiment 1 indicates that within a single modality (vision), temporal regularity also benefits time judgement. On the ground that temporal information extracted from temporal regularity can be used to facilitate time estimation within visual (Experiment 1) and auditory modality itself (Barnes & Jones, 2000; Teki et al., 2011), an emerging question is whether this information can be generalized and thus enhance the performance of duration judgement in other modalities. In the next experiment, we tested whether visual rhythmic context would have a cross-modal influence on duration judgment.

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Experiment 2

In Experiment 1, temporal regularity aids duration judgment within a single modality. In the following four experiments, we aimed to test (1) whether the benefits from the temporal regularity extracted from one modality can facilitate subsequent duration judgment in the other modality, that is, whether this facilitation effect is supramodal or constrained in the single modality; and (2) given that audition is temporally more precise than vision, whether the temporal regularity provided by visual modality weights differently from the weight of auditory temporal regularity. Overall, we used a similar paradigm as Experiment 1 with non-concurrent cross-modal stimuli (a visual sequence followed by two auditory target durations) to examine whether the regular temporal structure obtained from visual temporal regularity can be transferred to auditory modality and help subsequent duration judgments in the auditory domain (for details, please see General Methods and *Figure 2*).

Method

Participants.

Twenty-three healthy adults (15 females, M = 24.39 years, SD = 4.02 years), who were naïve about the purpose of the experiment, gave informed consent before the experiment and were financially compensated for their participation.

Results

The average correct RT in the regular sequences was not significantly different from the irregular sequences ($t(22) = -.42$, $p>.05$, two-tailed paired t-test, see *Figure 4*; regular: M = 572.85 ms, SD = 176.68 ms, irregular: M = 576.49 ms, SD = 175.09 ms). There was no significant difference in the average accuracy rate between regular and irregular conditions ($t(22) = -.90$, $p>.05$, two-tailed paired t-test; regular: M = 71.92%, SD = 6.92%, irregular: M = 73.33%, SD = 7.84 %).

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Among the post-experiment subjective reports from 23 participants, 15 participants noticed the regularity of disk sequences had changed over trials, but most of them regarded the regularity of sequence had little impact on their performance of duration judgement. Eight participants reported that all the sequences were perceived regularly, but the overall speed had changed over trials. Among those who thought that their performances were influenced by temporal regularities, the reported influences were also inconsistent: one participant reported more difficult in irregular sequences, and three reported more difficult in regular sequences.

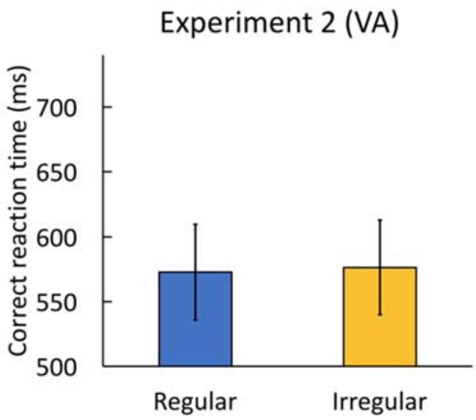

Figure 4. Results of Experiment 2 (VA): Visual preceding sequence–Auditory duration comparison task without attention demanded by task. There was no significant difference in correct RTs between regular and irregular sequences in this VA cross-modal experiment.

Discussion

In Experiment 2, no cross-modal facilitation was found in the setting of auditory duration comparison task preceded by temporally regular visual sequences.

The lack of attention on the rhythmic structure may account for the non-significant results in VA sequences. Proposed with a framework describing how signals bound and

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integrated in a directional flow through amplification by attention, the global workspace theory highlights an important role of attention in composing a unified conscious percept: through propagation by attention, local information (e.g., multimodal perceptions) gets access into a global workspace, which integrates relevant information together and broadcasts it back to local processors (Baars, Franklin, & Ramsoy, 2013; Dehaene & Changeux, 2011; Dehaene, Changeux, & Naccache, 2011; Dehaene & Naccache, 2001; Newman & Baars, 1993). In Experiment 2, the auditory targets did not share the same modality with the preceding visual stimuli, so that the cross-modal target could be relatively easier for participants to detect without the need to pay much attention to the preceding visual stimuli nor to their temporal regularities. Thus in the following experiment, we controlled this factor of voluntary attention on the temporal structure of preceding cross-modal stimuli by including a second task.

Experiment 3

In Experiment 3, the paradigm was similar to Experiment 2. However, participants were asked to pay attention to the temporal regularity of the preceding visual stimuli by an additional task demand in order to examine whether a cross-modal facilitation effect by visual temporal regularities on auditory duration judgement can happen with the assistance of voluntary attention. Different from Experiment 2, participants were required to report the regularity of the preceding sequence (regularity check) in a trial-by-trial manner after the duration comparison task (see General Methods and *Figure 2* for details).

Method

Participants.

Eighteen healthy adults (7 females, M = 23.11 years, SD = 3.62 years), who were naïve about the purpose of the experiment, gave informed consent before the experiment and were financially compensated for their participation.

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Results

There was no significant difference between the average correct RTs of regular and irregular sequences ($t(17) = .36$, $p>.05$, two-tailed paired t-test, see *Figure 5*; regular: M= 701.39, SD = 199.30ms, irregular: M = 695.33, SD = 206.83ms). There was no significant difference in the average accuracy rate between regular and irregular conditions ($t(17) = .08$, $p>.05$, two-tailed paired t-test; regular: M = 76.16%, SD = 6.03%, irregular: M = 76.30%, SD = 6.12 %).

The average accuracy rate of regularity checks was 90.01± 8.51% with all individual points above 60%. Four of the 18 participants reported subjective impact by the regularity in the post-experiment interview, yet among these feedbacks, both positive and negative influences were reported.

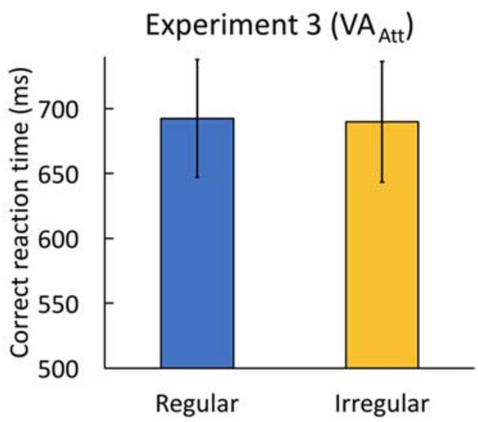

Figure 5. Results of Experiment 3 (VA$_{Att}$): Visual preceding sequence–Auditory duration comparison task with attention demanded by task. Despite that we added a trial-by-trial regularity check after each duration comparison task to make participants pay attention on the visual preceding sequences, there was still no significant difference in correct RTs between regular and irregular sequences.

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Discussion

Even though participants had paid attention (explicitly as required to perform the second, regularity check, task) to the temporal structure of the preceding sequence in Experiment 3, we still did not find any differences between regularities with visual preceding sequences followed by auditory duration comparison task.

One possible reason was that the facilitation effect of temporal regularity on duration-based timing may be modality-specific, yet another possible reason was that visual events weight differently from the weighting of auditory events in this estimation.

According to the Bayesian inference of time perception, our brain tends to make an optimal estimation by combining current observation with the previously obtained signals (Jazayeri & Shadlen, 2010). As a result, the more precise information tends to weight more in the final estimation. If temporal regularities extracted from one modality can facilitate duration judgement via a supramodal mechanism, we would predict that auditory preceding sequences, which are temporally more precise than visual events, may positively influence the duration judgement of visual targets.

Experiment 4

To examine whether the facilitation effect of temporal regularities on duration judgment was supramodal and whether the rhythmic information extracted from auditory modality may behaviorally aid visual duration judgement since the auditory preceding events provide more precise temporal information than visual events, we performed a cross-modal experiment with a similar paradigm as Experiment 3 except that we used auditory preceding sequences and visual targets in Experiment 4 (see General Methods and *Figure 2* for details).

Method

Participants.

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Twenty healthy adults (12 females, M = 22.90 years, SD = 3.52 years) gave informed consent before the experiment and were financially compensated for their participation. All, except one participant, were naïve about the purpose of the experiment. Removal of his data did not affect the results.

Results

The average correct RTs of regular sequences was significantly faster than the irregular sequences ($t(19) = -2.20$, $p<.05$, two-tailed paired t-test, see *Figure 6*; regular: M = 580.46 ms, SD = 108.81ms, irregular: M = 602.33 ms, SD = 124.51 ms) with auditory beep sounds preceding visual duration comparison task.

There was no significant difference in the average accuracy rate between regular and irregular conditions ($t(19) = .27$, $p>.05$, two-tailed paired t-test; regular: M =78.43%, SD = 8.69%, irregular: M = 78.00%, SD = 9.52%). The average accuracy rate of regularity checks was 88.99% (SD = 9.52%) with all individual accuracies above 60%. Eight of the 20 participants reported subjective impact by the regularity in the post-experiment interview, yet among these feedbacks, both positive and negative biases were reported. However, one in four participants reported regularity aided duration judgments but the individual data showed longer correct RTs in the regular sequences.

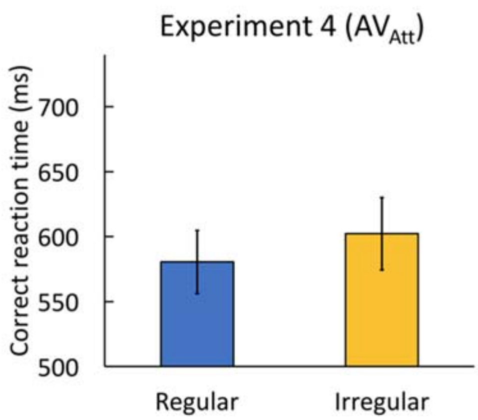

Figure 6. Results of Experiment 4 (AV_{Att}): Auditory preceding sequence–Visual

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duration comparison task with attention demanded by task. We kept trial-by-trial regularity checks to make participants pay attention on the auditory preceding sequences in this AV cross-modal experiment. The average correct RT was significantly faster in the regular sequences than that in the irregular sequences.

Discussion

With additional task to require attention, the preceding regular sequences of auditory events successfully facilitated the performance in the subsequent visual duration judgements in Experiment 4. Rather than an effect restricted within single modality, the results suggests the benefit from temporal regularity may be mediated by a supramodal mechanism. By considering the difference in temporal precision from visual and auditory modalities, the non-significant results in the VA experiments (Experiment 2 and 3) and the significant results observed in this AV experiment implicate that the temporal contexts provided from these visual and auditory modalities may weight differently in the supramodal mechanism according to their precision toward the task-related information (i.e., temporal precision in the current study). This asymmetry supported the Bayesian inference of time perception that when estimating the most likely elapsed period of time, our brain tends to integrate relevant information from previous experience (prior) with the current signals discriminated from noise (likelihood) in order to make the optimal estimation (posterior). As a result, estimation tends to bias toward the more precise distribution between the prior and likelihood. Therefore, different priors provided by sequences from the two modalities with different level of temporal precision may explain the asymmetric results: as the prior from the preceding visual events should contribute less to the final estimation in comparison to the auditory targets themselves, and thus there was no significant facilitation in duration comparison task in VA experiments.

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Yet previous research has suggested that auditory beat perception for simple rhythm may be processed automatically (Bouwer, Van Zuijen, & Honing, 2014). Miller et al. (2013) used *task-irrelevant* isochronous auditory stimuli and also found a facilitation effect in the following change detection of visual targets. Thus, it is still possible that the auditory temporal regularity could be obtained without attention to amplify it to a global workspace, and still aided the performance in visual duration judgements. In the next experiment, we removed the regularity checks to examine whether the supramodal facilitation effect can happen in the circumstances with a decreasing level of attention to the preceding auditory sequences.

Experiment 5

To test whether the facilitation effect we observed in Experiment 4 (AVAtt) could remain with decreased attention to the temporal regularity, we used a similar paradigm as Experiment 4 except that there were no regularity checks in Experiment 5 (see General Methods and *Figure 2* for details).

Method

Participants.

22 healthy adults (13 females, M = 22.90 years, SD = 3.52 years), who were naïve about the purpose of the experiment, gave informed consent before the experiment and were financially compensated for their participation.

Results

There were no significant differences in the correct RTs between the regular and the irregular sequences ($t(21) = -1.19$, $p>.05$, two-tailed paired t-test, see *Figure 7*; regular: M = 596.39 ms, SD = 149.19 ms, irregular: M = 606.94 ms, SD = 177.3 ms) with auditory beep sounds preceding visual duration comparison task. There was no significant difference in the average accuracy rate between regular and irregular conditions ($t(21)$ =

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-.74, *p*>.05, two-tailed paired t-test; regular: M =74.79%, SD = 8.63%, irregular: M = 76.02%, SD = 6.56%). Among the post-experiment subjective reports from 22 participants, 16 participants noticed the regularity of disk sequences had changed, six participants regarded the sequences stayed regular during the experiment but had changed in speed, yet again most of them subjectively reported no impact from temporal regularities.

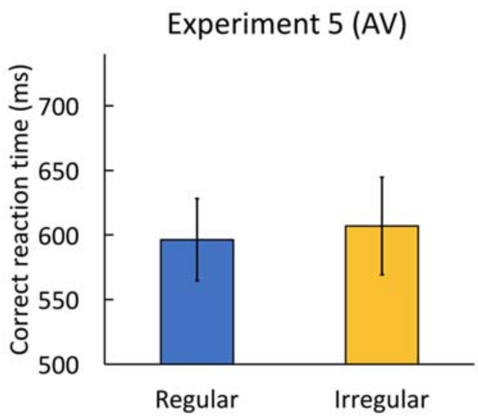

Figure 7. Results of Experiment 5 (AV): Auditory preceding sequence–Visual duration comparison task without attention demanded by task. After removal of trial-by-trial regularity checks, participants paid less attention on the preceding auditory sequences in this AV cross-modal experiment. The cross-modal facilitation effect observed in the Experiment 4 disappeared. There was no significant difference in the average correct RTs between regular and irregular sequences.

Discussion

In Experiment 5, we removed the regularity checks and thus participants were not required to pay attention to the temporal structures of each preceding sequence during the whole experiment. The non-significant results did not support that auditory temporal

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regularities can enhance the visual duration judgements without voluntary attention. Attention involvement in this task would be discussed below in the General Discussion.

General Discussion

We conducted five experiments with visual and/or auditory stimuli to examine whether the temporal information extracted from temporal regularity can facilitate duration judgment in other modalities, rather than merely within auditory modality, and furthermore, whether the temporal regularity provided by modalities with different temporal resolutions weights differently.

To control the difficulty level in prevention of a ceiling effect or a floor effect, an individualized threshold that obtained from a pretest was used to adjust the range Td jittered from Ts. The accuracy rates in our experiments were within 72.82 to 78.37 %, reflecting a fair control of difficulty level by the pretests. In Experiment 1, we found visual temporal regularity facilitated visual duration judgment as a faster average correct RT was observed in regular sequences than in an irregular one. The results suggest that temporal regular context aid duration judgment not only within auditory modality but also within visual modality (*Figure 3*).

In Experiment 2 and 3, using VA sequence-target stimuli pair, we found that visual temporal regularity did not benefit auditory duration judgments (*Figure 4*), even though we added a trial-by-trial regularity check to force participants additionally pay attention to the regularity of each preceding sequence in Experiment 3 (VA_{Att}) (*Figure 5*). Regarding the results in Experiment 2 (VA) and Experiment 3 (VA_{Att}), a supramodal mechanism with equal weight in audition and vision was less preferred. We further tested the influence of auditory temporal regularity on visual duration judgments in Experiment

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4 (AV_{Att}) by using a similar paradigm with Experiment 3 except that the sequence-target pair was changed from VA into AV.

In Experiment 4, in comparison to the irregular sequences, auditory temporal regularity successfully enhanced visual duration judgments (*Figure 6*). However, the impact became non-significant after we removed the task demand (regularity checks) so that the participants did not necessarily need to pay attention to the rhythmic context offered by the preceding sequences in Experiment 5 (AV) (*Figure 7*). Compatible with the optimization hypothesis, we found an asymmetric cross-modal effect. Our results support that temporal regularity enhanced duration judgment in another modality with a weighting difference when the regularities were provided from modalities with different temporal precision. From the perspective of Bayesian timing (Freestone & Church, 2016; Hartcher-O'Brien, Di Luca, & Ernst, 2014; see also Jazayeri & Shadlen, 2010; Shi, Church, & Meck, 2013), our brain integrates the received uncertain durations (noisy likelihood) with the temporal information provided from the preceding sequence (prior) in a statistically optimal way. Given that vision is relatively less precise in temporal resolution than audition, if there is a cross-modal integration mechanism favoring statistical optimization, then asymmetric cross-modal effect should be observed, which is consistent with our results.

One may propose another explanation on our results from the point of view that duration-based timing serves as baseline and help constitute beats. In this way, when being exposed to a temporally regular preceding sequence, participants may gain from repetitively memorizing an embedding duration that is similar to the standard target duration, and thus discriminate the standard duration from the deviated duration more easily in the following temporal comparison task. In previous auditory studies, participants were required to observe durations of intervals which repeated for many

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times in the regular sequences but not in irregular sequences, and thus the effect of temporal regularity may be confounded with the repetition effect unless further analysis is conducted to dissect these two (Barnes & Jones, 2000; Teki et al., 2011). Therefore, in this study, we used filled durations as targets, while the regularity was manipulated by controlling ISIs in preceding sequences to prevent this possible confounding factor. Hence, participants were exposed to equal numbers of standard durations in both regular and irregular sequences because all the presenting durations of stimuli in each preceding sequence were equal, and stimulus numbers were also equivalent between regular and irregular conditions. On the other hand, despite that the exposure to the standard ISI (500 ms in our study) were unequal between regular and irregular sequences, the standard target was either 400 or 600 ms, which was different from the standard ISI. Also, the temporal representation of a filled duration could be different from an empty interval. Previous studies showed that these two types of durations (filled durations V.S. empty intervals) were estimated differently according to the duration range and stimulus modalities (Horr & Di Luca, 2015; Rammsayer, 2014). Therefore, the results should be genuine from the effect of temporal regularity but not repetition of subpart durations.

Consistent with the global workspace theory, which suggests that attention plays an important role in amplify local information and enable it to enter a global workspace so as to be integrated with other relevant information and be broadcasted to a wide range of local processors (Baars et al., 2013; Dehaene & Changeux, 2011; Dehaene et al., 2011; Dehaene & Naccache, 2001), our results showed that the cross-modal facilitation effect provided by the auditory temporal regularity lost its power when we removed the task demand requiring attention on the rhythmic context. Whether attention is needed for extracting temporal regularities from sensory events to induce the facilitation? Miller et al. (2013) showed that though with a preceding auditory sequence of *task-irrelevant*

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sounds, participants had shorter saccade latency to move their eyes to the changed location of the target when the onset of changing location was on sync with the preceding sequence rather that out of sync. However, there are some exceptions that information integration may bypass global workspace: through repetitive learning, a task could be gradually approaching automaticity so that it no longer requires the processing in a global workspace (Baars et al., 2013). Different from the task in our study, the task in Miller et al. (2013) was a change detection task, while duration judgment requires higher level processing than detection. In our daily life, we frequently use a cross-modal rhythmic cue to expect and detect an upcoming object, such as early detecting someone's presence by hearing the footsteps, yet it is not the case for cross-modal rhythmic context in duration comparison task. The difference in processing level and automaticity is a possible reason that accounts for why attention seems to be required in our cross-modal study but not required in Miller et al. (2013).

As for the role of attention in Experiment 1 (Visual), on the one hand, the internal pattern of facilitated correct RTs in regular sequences was quite consistent, and most participants (14 of 18) reported having noticed the change in regularity. On the other hand, the preceding sequence shared the same modality with the targets, and thus the participants needed to detect the oddball disk on the screen in case they missed the following visual targets and not able to make quick response after each sequence ended. However, in the cross-modal experiments, the targets were from a different modality, and thus were relatively salient in comparison to the preceding sequences. This could be a reason why in Experiment 5, the AV cross-modal influence became nonsignificant without control of voluntary attention by task demand. After all, to further elucidate what role attention plays in modulating the cross-modal facilitation effect induced by rhythmic context, further studies with a systemic control of attention levels are needed.

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Gaining interests are arising in the interrelationship between the beat-based timing and the duration-based timing (Hartcher-O'Brien, Brighouse, & Levitan, 2016), and also their multisensory interaction. Recently, Levitan, Ban, Stiles, and Shimojo (2015) found that adaptation of rate perception was able to transfer symmetrically across auditory and visual modalities, suggesting a supramodal beat-based timing. On the ground that the rate perception provided from regular beats (beat-based timing information) can pass across auditory and visual modalities (Levitan et al., 2015), and beat-based timing information can aid duration judgment within a single modality (Barnes & Jones, 2000), if these two timing mechanisms are within one unified system and share information without an optimization mechanism, we could predict the information obtained from beat-based timing should equally contribute to visual and auditory duration judgment. However, in contrary to this prediction, we found an asymmetric influence on duration judgment between visual and auditory temporal regularity. Considering Bayesian optimization in a framework of the global workspace theory, it is plausible that temporal information from local processors (i.e. both temporal regularity and durations in this study) were integrated in a central hub, in which an optimization mechanism tuned the information according to task demand and the precision of each information source. Eventually along the signal flow, the integrated information was broadcasted back to local executive processors (e.g. a local clock, or motor preparation region). Nevertheless, it is also possible that the optimization mechanism actually works in local processors instead of in a central hub. Previous research has revealed that, in duration-based timing, the cross-modal integration is also asymmetric with greater weight of audition than vision (Chen and Yeh, 2009; Kanai, Lloyd, Bueti, & Walsh, 2011; Rammsayer, Buttkus, & Altenmüller, 2012). Chen and Yeh (2009) showed a concurrent auditory sound extended the perceived duration of a visual oddball, yet a concurrent visual object did not affect an auditory oddball's

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duration. A consistent evidence also showed that transcranial magnetic stimulation over primary auditory cortex impaired both auditory and visual time estimation, while stimulation over primary visual cortex only impaired visual time estimation (Kanai et al., 2011). Thus a local optimization mechanism may explain the auditory dominance on duration-based timing. As yet, we admit it is not possible to decipher the whole complex system merely through behavioral research. Further studies combining behavioral data, modeling, and electrophysiological evidence should shed light on the currently obscure pipeline of human timing perception, and especially how cross-modal temporal information is transferred between beat-based timing and duration-based timing.

Temporally regular stimuli help build temporal expectancy, yet temporal expectancy is not necessarily induced by temporal regularity. For instance, temporal orienting cues can also elicit temporal expectancy (for a review, see Nobre, 2001; Correa, Lupiáñez, Milliken, & Tudela, 2004). However, temporal orienting cues may elicit a relatively short temporal expectancy, while the temporal expectancy built by temporal regularity should fluctuate rhythmically rather than just peak once at a certain time after each event. Supporting the periodicity of temporal expectancies induced by rhythm, previous studies showed periodically enhanced detection of masked visual targets and also likely in duration judgments by using temporally regular entrainers (Barnes & Jones, 2000; Mathewson et al., 2012). Nonetheless, we could not rule out the possibility that using temporal orienting cue could elicit a similar asymmetric cross-modal enhancement in duration judgments using the current experimental setting, and more studies involving further time domain analysis should be required in the future to examine at what level does this interaction between timing mechanisms happen, and for how long it could last.

In conclusion, our results supported a supramodal mechanism in mediating the cross-modal influence across these two timing mechanisms by revealing that auditory temporal

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regularity boosted visual duration judgments, but not vice versa. An optimization mechanism that weight information differently according to their temporal precision can account for the asymmetric effect we observed.

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