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Non-uniform transformation of subjective time during action preparation

Miho Iwasaki, Kodai Tomita, Yasuki Noguchi *

Department of Psychology, Graduate School of Humanities, Kobe University, 1-1 Rokkodai, Nada, Kobe 657-8501, Japan

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Although many studies have reported a distortion of subjective (internal) time during preparation and execution of actions, it is highly controversial whether actions cause a dilation or compression of time. In the present study, we tested a hypothesis that the previous controversy (dilation vs. compression) partly resulted from a mixture of two types of sensory inputs on which a time length was estimated; some studies asked subjects to measure the time of presentation for a single continuous stimulus (stimulus period, e.g. the duration of a long-lasting visual stimulus on a monitor) while others required estimation of a period without continuous stimulations (no-stimulus period, e.g. an inter-stimulus interval between two flashes). Results of our five experiments supported this hypothesis, showing that action preparation induced a dilation of a stimulus period, whereas a no-stimulus period was not subject to this dilation and sometimes can be compressed by action preparation. Those results provided a new insight into a previous view assuming a uniform dilation or compression of subjective time by actions. Our findings about the distinction between stimulus and no-stimulus periods also might contribute to a resolution of mixed results (action-induced dilation vs. compression) in a previous literature.

1. Introduction

Sensation of time is an essential ability for humans (Matell & Meck, 2004; Nobre & O'Reilly, 2004). Accurate estimation of the duration of a stimulus and an inter-stimulus interval (ISI) is necessary when we understand someone's speech and listen to music (Macar et al., 2002; Mauk & Buonomano, 2004). Time sensation also plays a critical role in a coordination of complex and rhythmic movements such as walking and dancing (Lewis & Miall, 2003). Despite this importance, our sensations and representations of time (subjective time) are not always accurate but influenced by various psychological factors, such as attention (Macar, Grondin, & Casini, 1994) and emotion (Droit-Volet & Meck, 2007). Of particular interest in these days is a distortion of time induced by an execution and observation of actions (Desantis, Waszak, Moutsopoulou, & Haggard, 2016; Haggard, Clark, & Kalogeras, 2002; Press & Cook, 2015; Watanabe, 2008; Yarrow, Haggard, Heal, Brown, & Rothwell, 2001).

This distortion of time can be typically seen when sensory stimuli are presented around the moment of actions. Some studies showed that subjective time for a visual event before (Hagura, Kanai, Orgs, & Haggard, 2012) and after (Park, Schlag-Rey, & Schlag, 2003) a voluntary manual movement was overestimated compared to actual duration of that event (action-related dilation of time). In contrast, others (Binda, Cicchini, Burr, & Morrone, 2009; Morrone, Ross, & Burr, 2005; Yokosaka, Kuroki, Nishida, & Watanabe, 2015) reported an underestimation of an interval between two visual stimuli at the time of hand movements and saccades (action-related compression of time). This inconsistency among researches (dilation vs. compression) is seen not only on visual but also on somatosensory stimuli. A recent study (Press, Berlot, Bird, Ivry, & Cook, 2014) reported that the vibrations applied to a moving finger were perceived to be longer than those to a stationary finger (dilation), while another (Tomassini, Gori, Baud-Bovy, Sandini, & Morrone, 2014) showed that an perceived interval between tactile taps was shorter when those taps were presented to moving than static hands (compression). Overall, there has been no unified view as to whether actions induce a dilation or compression of subjective time.

How can we resolve this inconsistency? One way is to examine differences in experimental designs and parameters among previous studies, thereby identifying critical factor(s) producing the mixed results. First possible factor would be a relative timing of stimuli to actions. In one study, target stimuli for estimation of time were presented before an execution of actions (Hagura

* Corresponding author.
E-mail address: ynoguchi@lit.kobe-u.ac.jp (Y. Noguchi).

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et al., 2012). In other words, they measured time sensations *before* action execution (pre-action design). Many other studies, however, did not use the pre-action design, giving target stimuli *during* (Yokosaka et al., 2015), *after* (Park et al., 2003), or around (Morrone et al., 2005; Press et al., 2014; Tomassini et al., 2014) the moment of actions. Since an action is a complex process involving a sequence of multiple stages (preparation, execution, and termination, etc.), this variability in relative timings of stimuli to actions (before, during, or after) might cause the mixed results in a previous literature. Another possible factor for the inconsistency would be differences in types of actions (motor effectors) in previous studies. One study reported an action-related compression of time induced by saccadic eye movements (Morrone et al., 2005), while others showed a time dilation by manual movements, such as reaching (Hagura et al., 2012), finger lifting (Press et al., 2014), and key pressing (Park et al., 2003). It might be thus possible that movements of eyes and hands induce compression and dilation of time, respectively. Recent studies, however, reported evidence against this view (time compression by hand movements (Tomassini & Morrone, 2016; Tomassini et al., 2014; Yokosaka et al., 2015)).

Those differences among previous studies suggest several factors affecting a direction (dilation vs. compression) of action-related distortion of time. In the present study, we focused on a new parameter that has received little attention so far; the presence of continuous inputs during a period to be estimated. In some studies, subjects measured the *duration* of a single continuous stimulus (stimulus period). The action-related dilation was reported in all those studies (Hagura et al., 2012; Park et al., 2003; Press et al., 2014). In another group of studies, subjects estimated an *interval* between two brief stimuli (ISI, no-stimulus period), most of which reported the action-related compression (Morrone et al., 2005; Tomassini et al., 2014; Yokosaka et al., 2015). Those results suggest that the presence/absence of continuous inputs (duration vs. ISI) might be a key factor modulating a direction and a magnitude of time distortion.

2. Experiment 1

Based on an idea above, we first compared action-related time distortions under two conditions (Fig. 1). In one condition, subjects viewed a single continuous stimulus (a white disk of 950–1450 ms), performing key-pressing movements as soon as it disappeared from a screen. They then judged the duration of the white disk by comparing it with a reference stimulus (1200 ms) presented after the key-pressing movements (duration condition, Fig. 1A). In another condition (interval condition, Fig. 1B), one trial involved four brief (17 ms) flashes of a white disk, two in a pre-action period and two in a post-action period. After performing the key-press actions to the 2nd flash, subjects compared an ISI between the 1st and 2nd flashes (950–1450 ms) with that between the 3rd and 4th flashes (1200 ms). If the factor we assumed above (the presence/absence of continuous inputs) is critical, those two conditions (duration vs. interval) would produce different patterns of time distortions induced by the same actions.

As shown in Fig. 1, we presently used the pre-action design in which target stimuli for time estimation were presented before actions. This was based on the following two reasons. First, Hagura et al. (2012) used the pre-action design and showed an action-related dilation of visual events induced by manual movements. Importantly, they demonstrated this effect by excluding contributions of any non-action factors, such as attention and an elevation of arousal level accompanying action preparation. Furthermore, their results (action-related dilation) were supported not only by a subjective measure (a perceived length of time) but also by objective measures such as detection rates of rapidly-presented visual stimuli. Those solid results acquired through the pre-action design would provide a firm basis to test an effect of stimulus continuity (duration vs. ISI) in the present study. Second, the pre-action design can avoid a possible influence of somatosensory inputs caused by action execution. Since time estimation for the 1st target (duration or ISI, Fig. 1) was made before action execution, it was unlikely in the present study that peripheral sensor changes induced by action execution affected a subjective length of the target (pre-action) stimuli. Any effect on subjective duration (or ISI) can be thus attributed to the central processing (action preparation), which would make it easy to interpret the present data.

2.1. Methods

2.1.1. Subjects

Eighteen subjects participated in Experiment 1. This number of participants per experiment is equivalent to or larger than previous studies investigating an effect of actions on time sensation (Hagura et al., 2012; Press et al., 2014; Tomassini et al., 2014; Yokosaka et al., 2015). Most of those subjects were collected through a recruitment system in Kobe University, Japan. All had normal or corrected-to-normal vision. Informed consent was received from each subject after the nature of the study had been explained. All experiments were carried out in accordance with guidelines and regulations approved by the ethics committee of Kobe University.

2.1.2. Stimuli and task

All visual stimuli were generated using the MATLAB Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and presented on a CRT monitor (resolution: 1024×768 pixels) at a refresh rate of 60 Hz. In the duration condition (Fig. 1A), each trial started with an instruction screen indicating key-press actions required in that trial. A message on the instruction screen was "Release and Repress" (action trial) or "Keep Pressing" (no-action trial), and it was placed at a position slightly above a white fixation point ($0.19 \times 0.19°$) on a gray background. When subjects read the message and pressed a key with their right hand, the message went off and a color of the fixation changed into black. After a random delay of 1000–1900 ms (during which subjects kept pressing the key), a white disk (1st target, $3.13 \times 3.13°$) appeared over the fixation for 950, 1050, 1150, 1250, 1350, or 1450 ms (variable across trials), which was followed by a fixation-only screen for 1500 ms. In the action trials ("Release and Repress"), subjects had to release the key when the 1st target went off, and press it again. Importantly, both of those "release" and "repress" actions should be performed as quickly as possible, within 500 ms from an offset of the 1st target. Otherwise, they saw an error message informing an abortion of a current trial (the aborted trial was repeated later in the same experimental session). In the no-action trials ("Keep Pressing"), on the other hand, subjects had to keep pressing the key even after an offset of the 1st target (an error message was shown when they released the key). Subjects then saw the 2nd target (white disk) presented at the same position as the 1st target (note that the key was being pressed both in the action and no-action trials during this 2nd-target period). The duration of the 2nd target was 1200 ms in every trial, although this information was unknown to subjects. Finally, a task screen was presented on the screen that allowed subjects to release the key and prompted them to perform a temporal judgment task. In this task, subjects compared the duration of the 1st target (950–1450 ms) with that of the 2nd target (1200 ms). They pressed one key when they felt the 1st target was longer than the 2nd, and pressed another to indicate the reverse (those keys for the temporal judgment task were different