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Investigation of isochrony phenomenon based on the computational theory of human arm trajectory planning

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ABSTRACT

The isochrony principle is a well-known phenomenon whereby the speed of human arm movement is regulated to increase as its trajectory distance increases. However, the relationship between the trajectory planning and the isochrony phenomenon has never been sufficiently explained. One computational study derived the algorithm for estimating the optimal movement segmentation and its duration based on the framework of the minimum commanded torque change criterion. By extending this finding, we can consider the hypothesis that the human arm trajectory is generated based on the minimum commanded torque change criterion to ensure that the duration average of the commanded torque changes (DCTCs) are equivalent between certain movement segmentations, rather than to satisfy the isochrony phenomenon. To test this hypothesis, we measured the behavioral performance of hand movement tasks in which subjects write eight-shaped and double-elliptical-shaped trajectories including two similar shaped arcs of different sizes (hereafter called large and small loops). Our results indicate that the human arm movement is planned in such a manner that the DCTCs for the large and small loops are equivalent during writing of the double-elliptical-shaped trajectories regardless of the arc size. A similar tendency was also observed for the data during the eight-shaped movements, although the ratio of the DCTCs slightly changed depending on the arc size conditions. Thus, our study provides experimental evidence that the isochrony phenomenon is ensured through the computational process of trajectory planning.

1. Introduction

The isochrony principle (Viviani & McCollum, 1983; Viviani & Flash, 1995; Sartori, Camperio-Ciani, Bulgheroni, & Castiello, 2013; Flash, Meirovitch, & Barliya, 2013; Viviani & Terzuolo, 1982) is known as a specific phenomenon of motor control, whereby the speed of hand reaching movement is regulated to increase as its trajectory distance increases. For instance, when a subject draws the eight-shaped symbol shown in Fig. 1 by hand, the time required to write both arcs that form this symbol is approximately equivalent, and is independent of the difference in perimeter distance between each arc. Early studies of this phenomenon found experimental evidence that the movement speed increases relative to the movement size to ensure a stable movement time (Viviani & McCollum, 1983; Viviani & Flash, 1995). The latest studies on the isochrony principle (Flash et al., 2013) considered the computational relationship between changes in the movement speed and changes in the movement size to satisfy this principle. However, these studies did not include a detailed investigation of the computational process between trajectory planning and the isochrony principle, focusing instead on the geometrical relationship between movement speed and movement size (Flash et al., 2013). To

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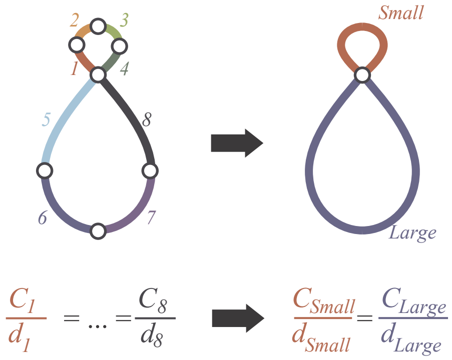

Fig. 1. Schematic view of our hypothesis. Considering that the movement time is adjusted to satisfy the constant DCTC for each via-point based on Eq. (5), this suggests that the DCTCs for the upper and lower arcs are modified to ensure that $C_{Large}/d_{Large} = C_{Small}/d_{Small}$.

account for the isochrony phenomenon in the motor control of human arm movement, there is a need to identify how the movement trajectory is generated while optimizing the movement time to ensure the isochrony phenomenon in association with the computational model of trajectory planning.

Various trajectory planning criteria have been proposed, such as the minimum jerk criterion (Flash & Hogan, 1985; Edelman & Flash, 1987; Kyriakopoulos & Saridis, 1988), minimum torque change criterion (Uno, Kawato, & Suzuki, 1989; Kawato, Maeda, Uno, & Suzuki, 1990), and the minimum muscle tension change criterion (Dornay, Kawato, & Suzuki, 1996; Kudo, Choi, Kagawa, & Uno, 2016). In general, when we apply these models to generate a simulated optimal trajectory of human hand-drawing, geometrical information about the start and end points is required as a boundary condition. Further, in the case of generating a complex trajectory, such models assume that the movement trajectory must pass from start to end through some specified points (so-called via-points) (Edelman & Flash, 1987); naturally, information of both the location and transit time of each via-point is also required for the boundary condition. Therefore, these conventional models cannot solve the issue of how the human brain plans an optimized trajectory and movement time in parallel to satisfy the isochrony phenomenon.

Certain computational studies on the trajectory planning for human arm movement (Wada & Kawato, 1993; Nakano et al., 1999; Wada, Kaneko, Nakano, Osu, & Kawato, 2001; Wada & Kawato, 2004) could be considered as a relevant solution to the above issue. On the basis of the framework of the minimum commanded torque change criterion, these authors (Wada & Kawato, 1993; Nakano et al., 1999; Wada et al., 2001; Wada & Kawato, 2004) provided an optimization algorithm for trajectory planning, which can coincidentally satisfy the following two problems: (1) estimation of some via-points to draw the optimal trajectory, and (2) derivation of the updated rule of the transit time of arm movement between each via-point to ensure a constant commanded torque change. Therefore, the proposed algorithm could estimate both the optimal via-point and via-to-via movement time during complex hand movement tasks based on the framework of the minimum commanded torque change criterion. In addition, this algorithm can generate a simulated trajectory so that the average duration of the commanded torque change (so-called DCTC) is equivalent in each via-to-via movement interval (these intervals are virtually partitioned by the via-points) (Wada & Kawato, 2004). By extending the above computational relationship to the DCTC condition and movement interval with the commanded torque change model, two previous studies (Saito, Tsubone, & Wada, 2006; Saito & Wada, 2006) suggested the possibility that the isochrony principle can be explained by computational theory based on the minimum commanded torque change model. Thus, the above mentioned algorithm (Wada & Kawato, 1993; Nakano et al., 1999; Wada et al., 2001; Wada & Kawato, 2004) could extend as the fundamental principle to understand how the isochrony phenomenon is ensured during human arm movement. However, experimental evidence is lacking to support this possible assumption.

In this paper, we address the issue of whether the isochrony principle can be explained by computational theory based on the minimum commanded torque change model (Wada & Kawato, 2004; Saito et al., 2006; Saito & Wada, 2006). We then hypothesize that the trajectory of human arm movement generates to satisfy the constant DCTC between large and small loops, rather than to ensure constant movement times (Wada & Kawato, 2004; Saito et al., 2006; Saito & Wada, 2006). To test this hypothesis with experimental data, we conduct two different hand reaching tasks (eight-shaped trajectory and double-elliptical-shaped trajectory) that were applied in previous isochrony studies (Viviani & McCollum, 1983; Flash et al., 2013). In the analysis, we first estimated the via-points and the time using the above-mentioned algorithm (Wada & Kawato, 2004) and separated the movement segments (i.e. different size of loops). Then we evaluated the DCTCs among different movement intervals to consider how the joint-torque changes are controlled during the hand movement tasks.

2. Relationship between via-point time optimization algorithm and isochrony phenomenon

The minimum commanded torque change criterion (Nakano et al., 1999; Wada et al., 2001) is defined as the following equation: