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Entropy of space–time outcome in a movement speed–accuracy task

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ABSTRACT

The experiment reported was set-up to investigate the space–time entropy of movement outcome as a function of a range of spatial (10, 20 and 30 cm) and temporal (250–2500 ms) criteria in a discrete aiming task. The variability and information entropy of the movement spatial and temporal errors considered separately increased and decreased on the respective dimension as a function of an increment of movement velocity. However, the *joint* space–time entropy was lowest when the relative contribution of spatial and temporal task criteria was comparable (i.e., mid-range of space–time constraints), and it increased with a greater trade-off between spatial or temporal task demands, revealing a U-shaped function across space–time task criteria. The traditional speed–accuracy functions of spatial error and temporal error considered independently mapped to this joint space–time U-shaped entropy function. The trade-off in movement tasks with joint space–time criteria is between spatial error and timing error, rather than movement speed and accuracy.

1. Introduction

The relation between movement speed and accuracy is one of the most robust phenomena in human movement performance. The essence of the speed–accuracy relation is that with an increase in movement speed there is concomitant decrease in movement spatial accuracy. The speed–accuracy relation has been an important topic in the field of motor control that has led to many theoretical accounts and empirical findings (Crossman & Goodeve, 1983; Elliott et al., 2010; Fitts, 1954; Hancock & Newell, 1985; Meyer, Smith, Kornblum, Abrams, & Wright, 1990; Plamondon & Alimi, 1997; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Woodworth, 1899).

Movement in the service of action, however, takes place in both space and time. It follows, therefore, that there is potential for both spatial error and temporal error in motor tasks. For example, it has been shown that increasing movement velocity within the same criterion movement time results in a decrease of movement timing error, rather than an increase in error as in a movement spatial accuracy task (Ellis, Schmidt, & Wade, 1968; Kim, Carlton, Liu, & Newell, 1999; Newell, Carlton, Carlton, & Halbert, 1980; Newell, Hoshizaki, Carlton, & Halbert, 1979). Thus, the directional effect of the relation of movement speed and accuracy is a function of whether spatial or temporal accuracy in the outcome is being measured (Newell, 1980). Indeed, several studies have shown an inverse relation between the variability of spatial and temporal errors in aiming movements (Brouwer, Smeets, & Brenner, 2005; Danion, Bongers, & Bootsma, 2014; Hancock & Newell, 1985;

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Hsieh, Liu, Mayer-Kress, & Newell, 2013; Kim et al., 1999). In reciprocal aiming tasks, moreover, Danion et al. (2014) found that this inverse relation in movement outcome variability was not present in the spatial and temporal variability of the separate acceleration and deceleration sub-phases of the movements.

Hancock and Newell (1985) proposed a space–time framework of the movement speed–accuracy relation that is based on the space–time principle that the spatial component of movement is always measured with respect to time and that the temporal component of movement is always measured with respect to space (Minkowski, 1908). When movement tasks determine that the temporal and spatial errors are in the same plane of motion, the error distributions in both dimensions affected by movement speed are consonant. The space–time account of movement accuracy is most strongly relevant in tasks where both spatial and temporal dimensions of movement are task criteria (e.g., Danion et al., 2014; Hsieh et al., 2013; Kim et al., 1999; Newell, 1980; Zelaznik, McCabe, Mone, & Thaman, 1988). The variability of movement error considered in the separate dimensions of space and time has been shown to map to the rate of force production and the temporal properties of the impulse (Carlton & Newell, 1993; Kim et al., 1999; Schmidt et al., 1979).

The space–time framework led to the proposition that a measure of movement error in the joint dimensions of space and time is required rather than only a measure of spatial error or temporal error independently (Hancock & Newell, 1985; Newell, 1980). In this regard, Hsieh et al. (2013) created a performance score as feedback that was an integrated and weighted product of spatial and temporal movement criteria. This measurement approach revealed a new U-shaped function for movement speed and accuracy in contrast to the traditional accounts of the effect of movement speed on either spatial error or temporal error. However, this approach used weightings in the integrated performance score feedback of spatial error and movement time to investigate how performance was influenced under the different combinations of space and time task conditions. It is possible that the particular performance score feedback manipulation used may have driven the aiming task outcome to produce the observed function.

Here we investigated the construct of joint information entropy as another candidate approach to unifying the space–time variability of the movement speed and accuracy relation. This approach focuses on the actual probabilities of the spatial and temporal movement outcome without manipulation into a weighted performance score as in Hsieh et al. (2013). The use of entropy (Cover & Thomas, 1991; Shannon, 1948) as a reflection of variability in the motor system has, however, not been applied broadly in the motor control domain and tended to focus on movement outcome error in a single dimension (Lai, Mayer-Kress, & Newell, 2006; Lai, Mayer-Kress, Sosnoff, & Newell, 2005).

Lai, Hsieh, and Newell (2015) investigated an unified spatial and temporal error measurement of the probabilistic estimates of movement outcomes that can be implemented even though the units for assessing movement error in spatial and temporal error are different. The measure is an unified space–time entropy because it considers the *joint* probability structure of spatial and temporal movement error (Scott, 1992; Williams, 1997). It is anticipated that the movement variability in terms of a probabilistic two dimensional space–time approach would be different from the variability measured in the traditional single dimension distribution analysis of spatial or temporal error because it captures a unified index of the collective spatial and temporal uncertainty. Lai et al. (2015) showed that *joint* space–time entropy was sensitive to different speed–accuracy manipulations but did not investigate the speed–accuracy function for *joint* space–time entropy.

In the experiment reported here we investigate the *joint* entropy of spatial and temporal error in a discrete aiming task over a range of amplitude and time criteria. Given the preliminary studies reported above it was hypothesized that movement velocity in the mid parameter range of spatial–temporal constraints will lead to the minimum of a *joint* entropy of the space–time outcome (Hsieh et al., 2013). The finding of a U-shaped function for entropy of the space–time outcome would contrast with the speed–accuracy functions of the movement outcome measured independently in either the space or time dimension (Fitts, 1954; Plamondon & Alimi, 1997; Schmidt et al., 1979; Woodworth, 1899). It is anticipated, however, that the traditional speed–accuracy functions for spatial error and temporal error considered independently can be mapped to this space–time U-shaped function.

2. Methods

2.1. Participants

The participants were 12 right-handed healthy young adults who volunteered for the experiment. The mean age of the participants was 28.17 (range ± 3.58) years. Participants provided informed consent and the experimental procedures were approved through the policies of the Institutional Review Board of Penn State University.

2.2. Apparatus

A Wacom Cintiq 21UX digital tablet (Model DTZ-2100D, 561 × 421 × 61.3 mm with an active surface area of 432 mm × 324 mm) was connected to a PC computer (the pixel range was set at 800 × 600) and used for data collection (see Fig. 1). A handheld, cordless stylus (Model ZP-501E) with a weight of 18 g was used with the digital graphic tablet. A custom computer discrete aiming program was used to preset different movement time goals and different amplitudes in space–time and calculate the spatial error and temporal error for the participants immediately after each discrete aiming