Acta Psychologica 182 (2018) 9–20

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Search strategies in practice: Influence of information and task constraints

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ARTICLE INFO

Keywords:
Search-strategies
Knowledge of results
Learning
Constraints

ABSTRACT

The practice of a motor task has been conceptualized as a process of search through a perceptual-motor workspace. The present study investigated the influence of information and task constraints on the search strategy as reflected in the sequential relations of the outcome in a discrete movement virtual projectile task. The results showed that the relation between the changes of trial-to-trial movement outcome to performance level was dependent on the landscape of the task dynamics and the influence of inherent variability. Furthermore, the search was in a constrained parameter region of the perceptual-motor workspace that depended on the task constraints. These findings show that there is not a single function of trial-to-trial change over practice but rather that local search strategies (proportional, discontinuous, constant) adapt to the level of performance and the confluence of constraints to action.

1. Introduction

Bernstein (1967) postulated that practice was not a simple repetition of the means of a solution of a given motor problem but rather it is the process of change in each repetition that leads to a task solution. In this view, practice is the search for a solution to specific perceptual-motor task demands (Connolly, 1977). Thus, the 'degrees of freedom problem' (Bernstein, 1967), and the change over time in motor learning and development, can be viewed as the search for a solution in a problem of many variables (Gel'fand & Tsetlin, 1962).

From a dynamical systems perspective, the search can be understood as the motion through an evolving perceptual-motor workspace (Fowler & Turvey, 1978; Newell, Kugler, Emmerik, & McDonald, 1989; Newell & McDonald, 1992; Newell, McDonald, & Kugler, 1991). A way to visualize this workspace is to consider a landscape that the learner (searcher) moves through in order to achieve the goal (find a region in this landscape that maps to the task goal). This landscape can be characterized in terms of the variables that the learner can act/perceive in the task (see Fig. 1.a and 1.c). It has a given topology (shape) that leads some regions to be easier to access than others. This shape is a result of the tendencies of learner to act in given ways rather than others, interacting with what the task requires the individual to perform. In studying learning as a search, the emphasis is on how to describe the perceptual-motor workspace and the ways by which the learner moves through the space.

In the language of dynamical systems, this workspace is conceptualized as the dynamical state space arising from the interaction of organism, task and environmental constraints (Newell, 1986) that channels the search and provides information of the topology of the workspace. The learner has tendencies for stable modes of movement in action (Kugler, Kelso, & Turvey, 1980; Newell et al., 1991), and it has been hypothesized that these modes constrain the search to occur in a lower dimensional space than that afforded by all the degrees-of-freedom of the system (e.g., joints, muscles, etc.). That is, if the space is characterized by n variables, the tendencies of the system would reduce the search to occur in $m < n$ dimensions (see Fig. 1.b). The search along this low dimensional space in practice would be maintained as long it is still efficient in terms of realizing the task demands (Gel'fand & Tsetlin, 1962).

Considering that the search is constrained in the low-dimensional space, information about performance in the task (knowledge of results – KR) would guide the motion of the learner in the perceptual-motor workspace, showing a simple relation between KR and the change in movement performed (Fowler & Turvey, 1978). The relation between KR and behavioral change from trial-to-trial has been assumed to be proportional to the level of error in KR (Dingwell, Smallwood, & Cusumano, 2013; Newell, Liu, & Mayer-Kress, 1997; van Beers, 2009); that is, the greater the performance outcome error (i.e., difference between movement outcome from the goal), the greater the absolute change from one to the next trial. This relation is consistent with the principles of attractor dynamics where motion to a fixed point occurs as a function of the distance to it, leading to proportional change over time (Newell, Liu, & Mayer-Kress, 2001, see Fig. 1.c and 1.d). However, the evidence for this proportional relation between KR and

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[1] This work was supported by National Council for Scientific and Technological Development (CNPq) – Brazil [grant number 211487/2013-9].

http://dx.doi.org/10.1016/j.actpsy.2017.11.004
Received 23 August 2016; Received in revised form 6 August 2017; Accepted 5 November 2017

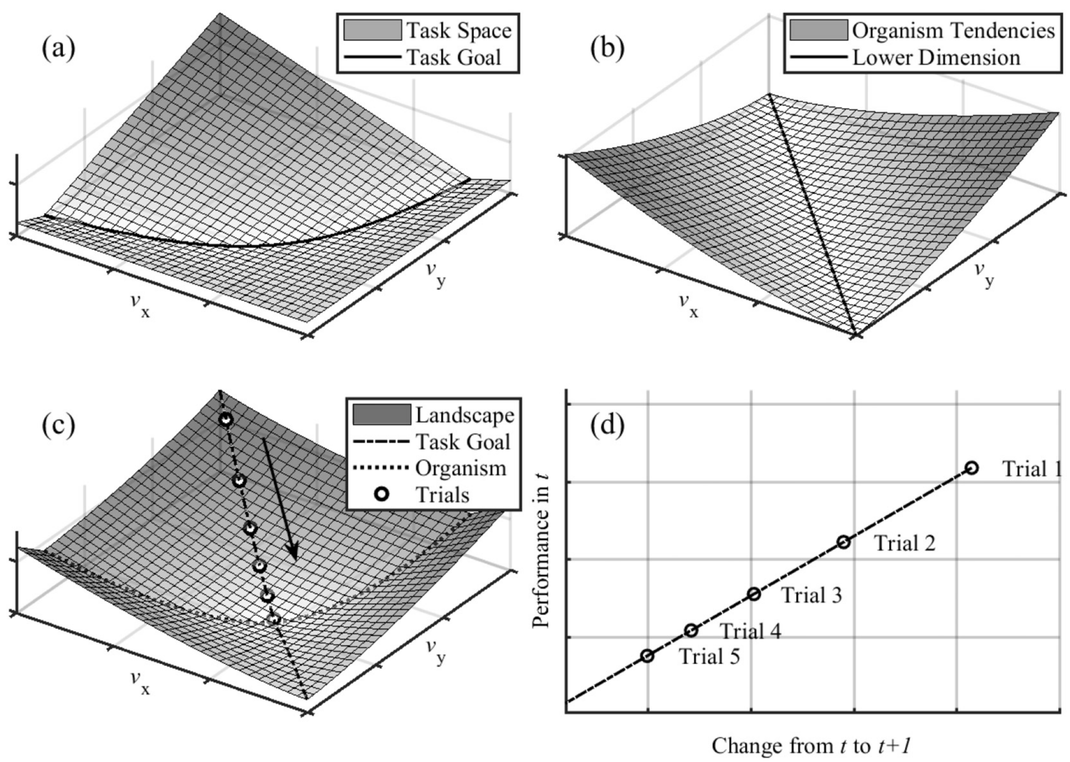

Fig. 1. (a) Schematic of the present experiment task space (see the Methods section). v_x and v_y are the variables that are modulated to achieve a given distance. The z dimension is the performance error. For any combination of vx and vy performed, a given performance results which (if the error is not zero – at the task goal line) individuals must act in accordance to achieve the task goal. (b) Schematic of a hypothetical intrinsic tendency of the organism in acting. The tendency makes the search at the bottom of the valley easier (the attracting low-dimensional space) than on different regions. (c) Superimposed task and intrinsic tendencies with hypothetical trials. Note that the individual is acting in terms of its intrinsic tendencies and changing in a proportional way to the performance outcome observed. (d) The proportional relation plotted in (c) in terms of trials, performance in trial *t* (*y* axis) and change from trial *t* to trial *t + 1*.

change in the movement outcome is limited and there are empirical and theoretical reasons for it.

Schmidt (1991) proposed that correcting small values of error might be maladaptive when the inherent variability (noise) of the system and motor commands are confounded; that is, an attempt to correct inherent variability (when the motor command was "appropriate") would cause the error to increase rather than decrease. Although other approaches also assume such a *signal plus noise* characterization of the motor output (e.g., Müller & Sternad, 2004; van Beers, 2012), there has been no attempt to deepen the discussion on the range of conditions in which the proportional relation of the change and KR would be maintained. This is relevant because tasks in which the inherent variability of the system is relatively high in terms of the required change might qualitatively alter the way the system acts in search.

Indeed, the early literature showed that individuals might not correct for small errors (Blackwell & Newell, 1996; Wolpert, Miall, Winter, & Stein, 1992) resulting in a non-proportional relation between change and KR. Recent studies have investigated the relation using autocorrelation techniques (e.g., Abe & Sternad, 2013; Dingwell et al., 2013) and the results vary from persistent change (positive autocorrelation) to no relation at all (Newell et al., 1997). A limitation is that these techniques assume that the same search strategy is maintained over the whole block of trials analyzed and this might not be the case (cf. Liu, Mayer-Kress, & Newell, 1999). For instance, if in most of the trials a first relation is observed but, provided some other aspect (e.g., the range of the KR magnitude, previous movement, beginning/end of the experiment), some trials do not conform to this first relation, the autocorrelation technique will suppress such information into a single value – that would be more representative of the first relation.

To encompass these divergent pathways of change, we draw on the proposition that the relation between change and information observed in each task emerges from the confluence of organismic, environmental and task constraints (Newell, 1986). Thus, when different task constraints are considered, new relations in the pattern of change might be observed. Specifically, the finding of a proportional relation between KR and change might be limited to parameter ranges of these variables in which the inherent variability of the system does not surpass the required change in outcome to meet the task goal. In tasks where the range is necessarily exceeded, new relations between KR and outcome change might be apparent (leading to a discontinuity in the relation over a sequence of practice trials as found previously - Blackwell & Newell, 1996; Wolpert et al., 1992). For instance, in throwing a ball to a close target, the individual modifies the parameters in close agreement with the outcome (if the ball was more to the left, change to the right), now if the distance of the target is large, small deviations at beginning cause large deviation in the end, requiring a different type of search (probably dependent on other parameters). Thus, the first goal of the present study is to analyze the relation between KR and behavioral change when task constraints are considered. That is, we investigate when proportional *and* discontinuous relations emerge in the change of discrete movement outcome.

The idea of a low dimensional perceptual-motor workspace can be derived from the concept of special purpose devices (Bingham, 1988; Fowler & Turvey, 1978) and the open and non-linear characteristics of the biological system (Kugler et al., 1980; Kugler, Kelso, & Turvey, 1982) that result in attractor states that can support the task at hand. In this view, the observed order in the output (in terms of movement outcome, for instance) occurs a posteriori; the observed pattern cannot be attributed to an a priori structure within the system. A consequence of this derivation is that the system can show a common pattern of organization between similar tasks but slight changes in the task (or other) constraints might also change the stability of previously observed patterns (Kelso, 1984). Evidence of such constrained behavior has been provided in several motor behavior tasks (e.g., Kelso,