Modelling and Simulating Action Dynamics in Underconstrained Tasks in Virtual Reality

Patric C. Nordbeck, Maurice Lamb, Paula Silva

Department of Psychology, Center for Cognition, Action, & Perception, University of Cincinnati.

Bernstein (1967) defined dexterity as the ability to consistently achieve a desired level of task performance across a wide variety of contextual conditions. This ability implicates adaptability of action patterns to both the requirements of the intended behaviour and to the ever-changing demands of the context in which activities unfold. For example, a simple arm extension is sufficient to successfully pick up a cup that is within reach, but trunk and arm movements have to be coordinated if the cup is further away. Relatedly, very different patterns of movement would have to be assembled to pick up a cup of hot coffee from the hands of a well-trained waiter than to recover it from the hands of a young child. Thus, to achieve desired functional goals, humans (and animals) must organize and reorganize action patterns in response to contextual constraints defining the available opportunities for action.

Action selection is shaped by both hard and soft constraints (Fajen, 2007). Hard constraints are factors that define limits on how an action can be performed. For instance, if a driver wishes to stop her car before hitting the garage wall, she must initiate braking *early enough* to stop with (at least) a minimal space between the car and the wall. The latest time at which braking must start illustrates a hard constraint, defined by the dynamic relationship between velocity, distance to the wall, and maximal deceleration rate. A hard constraint defines an affordance boundary, here the boundary of brake-ability. If this boundary is crossed, task failure results. Within the boundary imposed by this constraint, however, there are multiple ways to successfully accomplish the task: One might start pressing the brake early and decelerate smoothly, or wait until the last minute and press the brake maximally coming to an abrupt stop, or any combination of the two. Factors that shape these decisions are considered soft constraints and may include mood, goals, habits, ability, distractions, need for safety, and so on.

Organism-environment relations that define affordance boundaries, and hence, constitute hard constraints on selection of action patterns have been identified for a variety of tasks, such as climbing, reaching, and grasping (Carello et al., 1989; Cesari & Newell, 1999; Richardson et al., 2007; Warren, 1984). Individuals show sensitivity to affordance boundaries and organize their action patterns accordingly (Carello et al., 1989). The role of soft constraints on action selection is much less studied despite its potential for explaining different levels of performance in underconstrained tasks, that is, tasks allowing for more than one solution for successful completion. Nordbeck et al. (2019) have recently proposed a novel experimental paradigm to focus on this issue. In this experiment,

participants transported balls between a starting location and a large wooden box located 9m away. Participants' action patterns were assessed under variations in the temporal interval of ball presentation. A variety of action patterns were expected and observed (moving all the way up to the box and dropping the ball, throwing the ball from afar, and some combination of the two). A single task dynamic with two parameters (formalized by the Cusp Catastrophe model; Thom, 1975), however, was able to capture the wide range of participant responses to contextual change (i.e. presentation interval) by accounting for the effect of soft constraints (e.g. motivation). The aim of the present study was to assess whether this model is generalizable to a different underconstrained task designed in virtual reality (VR). The overarching goal is to determine whether the Cusp Catastrophe model can provide an appropriate formal basis for the study of soft constraints affecting context sensitivity of action solutions in underconstrained tasks.

Method

Thirty undergraduate students participated for partial course credit. A virtual environment was created (see Figure 1) where pucks (marked '1' in Figure 1) were released from a dispenser (marked '2') and slid out onto the starting area ('3'). The bridge ('4') connected the starting area to a goal container ('5'). They were informed that their task was to get the pucks into the container by pushing them with a handheld controller up to any distance, or striking them from afar, and letting them slide the rest of the way over the bridge. Participants were also told to avoid letting the pucks stack up in the starting area. Then they were equipped with a HTC Vive VR equipment and lined up with their right leg in front of the bridge. After a verbal countdown the task was started by presenting pucks to participants. After the first block was completed, participants were given the option to have a short break, the presentation rate was reversed and participants again performed the transportation task. Controller position data was continuously recorded throughout the experiment.

The distance at which participants stopped pushing, or struck, each puck was extracted and averaged across each presentation rate for each block. The resulting time-series of release points were then the basis for calculation of two main variables. The first variable took the average of each time-series, indexing the average distance participants used (*Md*). The second variable was calculated by finding the largest difference between two consecutive distances. Then the absolute difference between the average distance before versus after this point made up the second variable (ΔMd). The two variables were then used to classify the time-series into one of four general solution types that vary in sensitivity to contextual conditions (see Figure 2). Exemplar time-series of the different solutions are plotted in Figure 3 along with comparison solutions (participant and simulated) from Nordbeck et al. (2019).

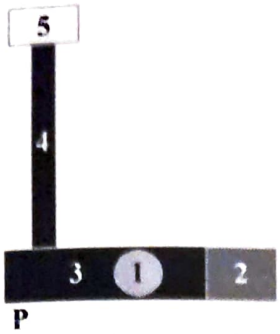

Figure 1. General experimental setup.

Results and Discussion

The VR reaching task produced varied action patterns that could be classified into four general classes of solutions, similarly to Nordbeck et al. (2019) with the exception of not finding the most extreme ends in this particular setup. The time-series mimicked those of the previous task as well as the model simulations. Results support the utility of the Cusp Catastrophe model in research designed to study the role of soft constraints on affordance actualization. Importantly, it opens up the possibility to explore the versatility of VR in the identification of factors modifying individuals' sensitivity to soft constraints, and how this sensitivity might explain different levels of performance in underconstrained tasks.

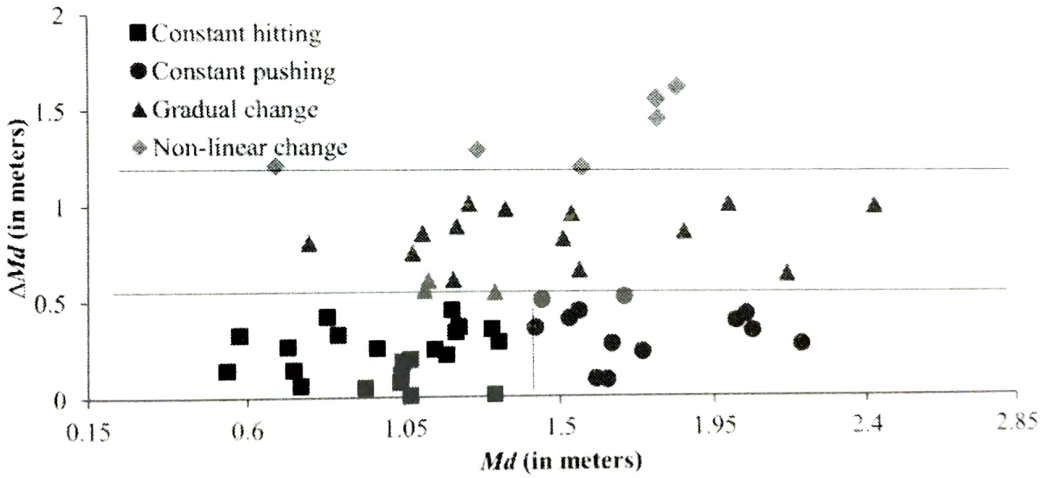

Figure 2. Participant data behaviourally classified as a function of mean distance moved (*Md*) and difference in mean pre-post max change in distance (*ΔMd*). Note. In Nordbeck at al. (2019), behaviours characterized by low *Md* & low *ΔMd* map on to constant throwing and those characterized by high *Md* & low *ΔMd* map on to constant walking.

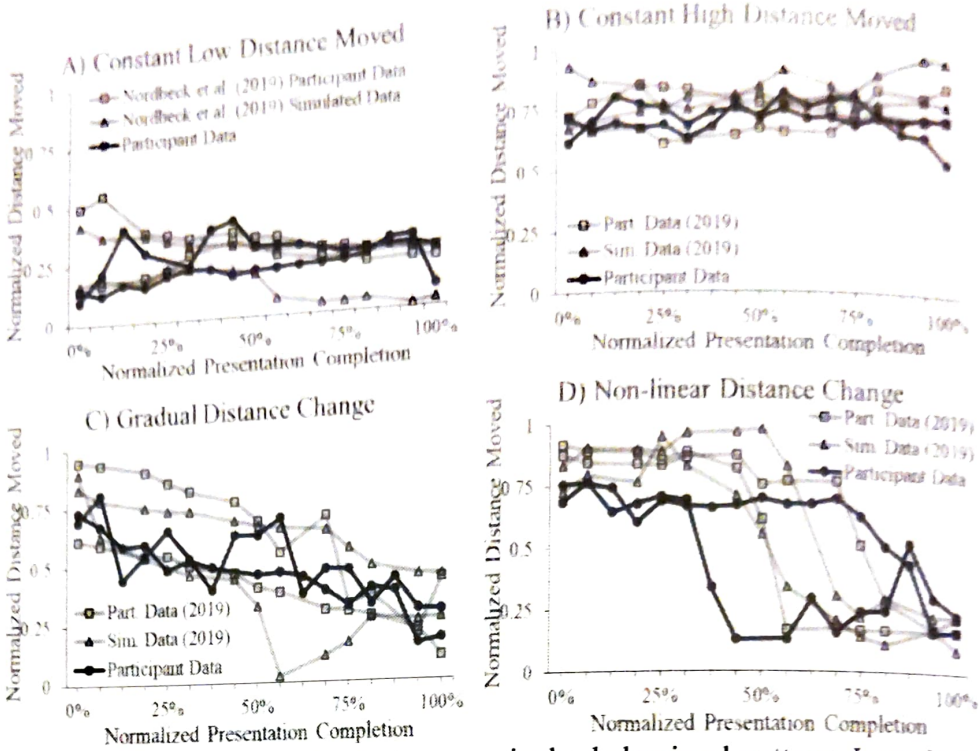

Figure 3. Each figure illustrates a particular behavioral pattern: Low *Md* & Low *ΔMd* (A), High *Md* & Low *ΔMd* (B), gradual (C), and non-linear (D), and contains two examples of each data type: participant and simulated data from Nordbeck et al. (2019), and participant data from the present research.

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