Walkers use visual information about distance between target footholds to initialize the upcoming step

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1 Introduction

Across simple, predictable terrain, the intrinsic dynamics of the legs will produce highly efficient walking behavior with minimal active control [1]. However, over complex terrain, visual information about the path of locomotion can help tune parameters of these dynamics to account for obstacles and exploit safe footholds, while approximating the energetic efficiency of walking over flat terrain. Matthis, Barton, and Fajen [2] previously demonstrated a "critical control phase" in the gait cycle in which visual information is maximally useful for accurately stepping to a desired target foothold. Even very brief visual information about a target's position presented during this critical control phase significantly improved stepping accuracy over conditions in which visual information was presented either before or after the critical control phase.

We also found that stepping accuracy depended on whether consecutive targets were visible at the same time. When visibility manipulations were applied to consecutive targets in a sequence, performance in several conditions which contained the critical control phase was still significantly worse than when no targets were manipulated (full-vision). However, when these same visibility manipulations were applied to only a single target in the series, performance became indistinguishable from full-vision. This suggests that in addition to the importance of the critical control phase in traversing complex terrain, walkers also exploit visual information about a target's position, relative to other target footholds.

2 Present Study

In the present study we expand on the critical control phase hypothesis and suggest that the change in the stepping errors observed in our previous work was due to the change in the availability of visual information about the location of an upcoming target *relative to the previous target's location*. This hypothesis derives from the biomechanics of bipedal walking. The ballistic trajectory of the center of mass (COM) is largely determined by the position of the stance foot relative to the COM and the momentum of the COM at toe-off [3]. For actuated walking, the momentum of the COM is maintained primarily by a push-off force that occurs immediately prior to toe-off [4]. These parameters are co-dependent, such that the consequences of the push-off force will depend on the position of the stance foot. Therefore, visual information about where the stance foot will be placed relative to a walker's next step may be critical for preparing the necessary push-off force.

To investigate the role of visual information about relative target location in the critical control phase hypothesis, we employed a paradigm similar to our previous work in which subjects traversed a field of projected target footholds, stepping as accurately as possible under a series of visibility manipulations. We also manipulated the number of targets in a series to which the visual manipulations were applied in order to vary the availability of relative target position information. Subjects' movements were recorded using a VICON motion capture system. If walkers rely on visual information about target locations relative to a previous foothold, then those conditions in which relative information is absent should yield larger stepping errors.

3 Experimental Design

Four visibility conditions and three target conditions were used in the experiment to test the effect of relative target information on stepping accuracy. Visibility conditions were defined in terms of steps from target$_N$ (e.g. 1.5/1.0 indicates target$_N$ appears when a subject is one and a half steps away, and disappears when a subject is one step away). A small amount of lag (≈80 ms) produced by processing time and network communication caused the visibility manipulations to be shifted slightly from the programmed values. The mean calculated visibility manipulations, obtained by comparing motion capture data to the time-logs of the experiment, are presented below.

Visibility Manipulations
Condition 1: This was the full-vision condition in which all targets were visible at all times.
Conditon 2: 1.48/0.88 — In this condition, target$_N$ appeared on average half-way through the step to target$_{N-1}$ and disappeared shortly after the beginning of the step to target$_N$.
Condition 3: 1.93/0.52 — In this condition, target$_N$ appeared on average at the beginning of the step to target$_{N-1}$ and disappeared in the first half of the swing phase of the step to

$target_N$.
Condition 4: 1.92/0.89 — In this condition $target_N$ appeared on average at the beginning of the step to $target_{N-1}$ and disappeared shortly after the beginning of the step to $target_N$.

Target Manipulations
Visibility manipulations were applied either to *one* target, or *two* or *four* consecutive targets in the series. In the *one-target* condition, relative information about target location was visible for all visibility manipulations. For the *four-target* condition, relative information about target location was only available in *Condition 3*. In the *two-target* condition, relative information was present in *Condition 3* and limited in *Condition 4*.

4 Results

The results of this study are presented in Figure 1. We found a clear relationship between the presence of visual information of relative target position and stepping accuracy. In conditions where visual information about relative target position is intact, stepping error is indistinguishable from the "full-vision" condition. In conditions where it is absent, stepping error is significantly larger. Most interestingly, in *Condition 4* where visual information about relative target position was limited (but not entirely absent), we see a general trend towards "full-vision" for the *two-target* and *four-target* conditions, when compared to *Condition 2*.

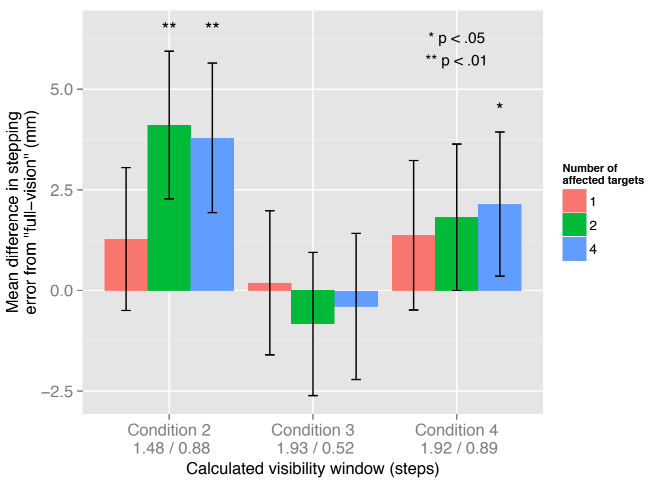

Figure 1: Results from the current experiment showing difference in stepping error between "full-vision" and restricted vision conditions. Error bars are 95% confidence intervals. When only a single target is affected by the visibility manipulation (red), visual information about relative target position is preserved in all visibility conditions. When four targets are affected (blue), relative information is only preserved in condition 3, leading to a larger stepping error in the other two conditions. When two targets are affected (green), relative information is intact in condition 3 and limited in condition 4; condition 2 remains significantly different from "full-vision".

5 Discussion

Our findings supported the hypothesis that visual information about target foothold location relative to a previous foothold is important for successfully traversing a complex ground plane. We also found evidence that stepping accuracy is affected by the availability of information about relative target position. By applying visibility manipulations which constrained the presentation of target footholds to a varying number of consecutive targets, we were able to control the presentation of relative information of target location, and demonstrate its importance in steady-state walking.

The *critical control phase* hypothesis provides an explanation of how visual information about complex terrain is temporally coupled to the biomechanics of bipedal walking. Visual information about the upcoming terrain is most useful when it can be exploited to tune control parameters that define the ballistic trajectory of a step, before the step is actually initiated. In this study, we expanded on this hypothesis by investigating what visual information is and how it might be used. When traversing complex terrain with limited safe footholds, successfully completing a step requires preparing a push-off force with respect to both the location of the stance foot, and the position of a desirable stepping target. Further, in order to execute this push-off force during the double-support phase, it must be prepared *before* the stance foot actually lands. Therefore, stepping accurately to a series of target footholds will be most successful when a walker is provided visual information about position of a $stepping\text{-}target_N$ relative to the position of the previous $stepping\text{-}target_{N-1}$.

References

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