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Stepping to recover balance in complex environments: Is online visual control of the foot motion necessary or sufficient?

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ABSTRACT

Rapid step reactions evoked by balance perturbation must accommodate constraints on limb motion imposed by obstacles and other environmental features. Recent results suggest that the required visuospatial information (VSI) is acquired and stored "proactively", prior to perturbation onset (PO); however, the extent to which "online" (post-PO) visual feedback can contribute is not known. To study this, we used large unpredictable platform perturbations to evoke rapid step reactions, while subjects wore liquid crystal goggles that occluded vision: (1) prior to PO (forcing use of *online-VSI*), (2) after PO (forcing use of *stored-VSI*), or (3) not at all (*normal-VSI*). Subjects stood behind a barrier in which the location of a narrow slot, through which the foot had to be moved during forward step reactions, was varied unpredictably between trials. Within subjects who were able to do the task (6 of 8 young adults tested), responses in *stored-VSI* and *normal-VSI* trials were very similar. However, in *online-VSI* trials, the foot-off time for the step through the slot was delayed (by ~50 ms, on average). Presumably, this delay allowed more time to acquire and process online-VSI regarding the required foot trajectory, yet subjects were still more likely to select the "wrong" foot (contralateral to the slot location) and to contact the barrier while moving the foot through the slot, in *online-VSI* trials. These results suggest a critical role for stored-VSI during the earliest phase of the step, in selecting the step limb and planning the initial trajectory. Online acquisition and processing of the required VSI may be too slow to allow effective control of this early phase, particularly in situations where the demands for accurate foot motion are high.

The control of balance while interacting with the environment requires visuospatial information (VSI) about the constraints on limb and body movement imposed by the environment. Studies have shown that feedforward visual sampling of obstacles and constrained step paths predominates during voluntary stepping and gait [6,13,17], but that rapid visually driven feedback can also modulate ongoing volitional steps to accommodate sudden environmental changes [15,16,18]. What is far less clear is how VSI is acquired when stepping to recover balance in response to a sudden perturbation [8].

There is reason to suspect that quite different visual control mechanisms may be involved, given that there exist some fundamental distinctions between volitional and perturbation-evoked stepping. For example, step direction is known in advance for voluntary stepping movements, so visual sampling can be directed, in a predictive manner, to the intended path of gait progression and/or forthcoming landing site [5,14]. Conversely, a stepping reaction evoked by a sudden unpredictable or unexpected balance perturbation cannot be planned in advance, as the step length and direction is dictated by the need to arrest the perturbation-induced falling motion [10]. The capacity for online visual control may also be limited, as the rapid timeframe of the stepping reaction (driven by the pressing need to recover balance) may severely limit, if not altogether preclude, the capacity to redirect gaze to scan the surroundings and use the acquired VSI to modulate the rapidly emerging step.

Recent studies of perturbation-evoked stepping and reaching movements [3,11,19,21] suggest that the CNS circumvents these limitations by maintaining an egocentric visuospatial map of the immediate surroundings. If and when a sudden loss of balance

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occurs, the “stored” VSI can be combined with multi-sensory feedback about the perturbation-induced body motion so as to rapidly initiate a limb movement that is directed and scaled to counter the destabilization while accommodating surrounding environmental constraints. While the use of “stored” VSI to guide these limb reactions appears to be a preferred strategy [11,19,21], the extent to which VSI acquired after perturbation onset (“online” VSI) is necessary, or sufficient in itself, to guide stabilizing limb movements in complex environments has not been directly tested.

The present study addressed this issue by manipulating access to VSI during step reactions evoked by large unpredictable multi-directional platform perturbations, while imposing challenging and unpredictable constraints on step trajectory. Three visual conditions were tested: (1) *online-VSI* (vision occluded prior to perturbation onset, PO); (2) *stored-VSI* (vision occluded after PO); or (3) *normal-VSI* (no occlusion). In view of the very rapid timeframe of these perturbation-evoked step reactions, we hypothesized that the forced reliance on *online-VSI* would compromise acquisition of the VSI needed to initiate an effective step, and would thereby lead to an increased frequency of errors in limb selection and step trajectory, in comparison to *normal-* and *stored-VSI* trials. While a delay in step initiation could presumably help to mitigate this problem, we did not expect to see large delays because this could compromise the effectiveness of the step in restoring equilibrium and preventing a fall from occurring.

We tested eight healthy young adults (4/4 male/female; 23–30 years; height 1.52–1.82 m; weight 45–102 kg), all of whom had participated in previous balance-perturbation studies. All had a minimum corrected Snellen visual acuity of 20/40. Each subject provided written informed consent to comply with ethics approval granted by the institutional review board.

Perturbations were applied using a large (2 m × 2 m), semi-enclosed motion platform that was computer-controlled to produce sudden, unpredictable horizontal movements [12]. At the start of each trial, the subject stood at the center of the platform, on two force plates embedded in the platform surface, 10 cm behind a transverse barrier (Fig. 1). For safety, the barrier was designed to give way if struck by the foot (see Fig. 1), and a harness was worn to prevent falling.

A narrow slot in the barrier permitted forward motion of the foot during forward step reactions, and the location of this slot (either left or right of mid-line; Fig. 1B) was varied unpredictably from trial to trial (using a motorized device [21]) so as to prevent preplanning of the step trajectory (i.e. the slot location was unknown to the subject at the start of each trial). To further deter any attempts to preplan the step trajectory, we also randomly varied: (1) the starting foot position (either “narrow” or “wide” stance; Fig. 1C and D); and (2) the characteristics of the platform motion (forward, backward, left or right; acceleration 0.6–3.0 m/s^2; velocity 0.2–0.9 m/s; onset 2–5 s after barrier deployment). Subjects were instructed to avoid hitting the barrier with the foot when stepping forward, and to avoid moving their feet prior to PO. Instructions to try to direct forward steps through the slot in the barrier were given if the subject made no attempt to do so.

Access to VSI was manipulated using custom-designed goggles in which a liquid crystal (LC) element was held flush against the rim of the orbit of each eye by a flexible mask. This design provided complete occlusion of both central and peripheral vision when the LC elements were activated (opaque) and near-complete field-of-view (185° horizontally, 50° down, 30° up) when deactivated (transparent). The goggles were computer-controlled to change configuration simultaneously (±5 ms) with the onset of the platform acceleration (>0.1 m/s^2), so as to achieve the three visual

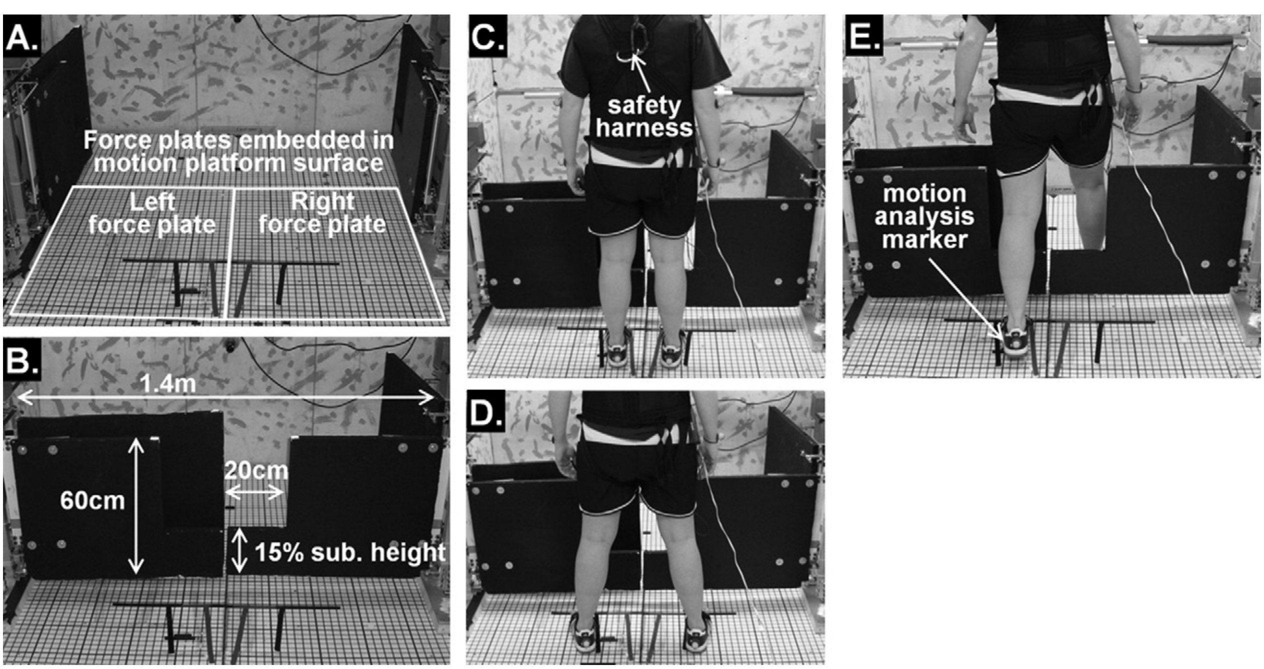

Fig. 1. Environmental-constraint conditions. Photographs show the motor-driven “obstacle-mover” system mounted on the motion platform. At the start of each trial, these devices were used to move black styrofoam panels into place, so as to form a barrier (1.4 m wide, 0.6 m high) in front of the subject (10 cm from toes). Note that each panel is cantilevered and supported only by Velcro® attachments to the obstacle-mover shaft (located at the lateral edge of the panel), and hence will easily give way if struck with the foot. (A) Shows all styrofoam panels retracted at the start of the trial. (B) Shows one of the two tested configurations, with the slot in the barrier located to the right of the midline. In the other tested configuration (not shown), the slot is located to the left of the midline. The slot was 20 cm wide, and the bottom edge of the slot was located ~25 cm (15% of subject height) above the motion-platform surface. (C) and (D) Illustrate the “narrow-stance” and “wide-stance” starting positions (great toes 15 cm or 40 cm apart, respectively). (E) Shows the final position of a subject after stepping forward through the slot (using the foot ipsilateral to the slot location) in response to a sudden backward platform translation.

conditions noted earlier, i.e. forcing reliance on either *stored* (pre-PO) or *online* (post-PO) VSI or else allowing *normal* vision.

The sequence of events, within each trial, was: (1) subject told "trial about to begin"; (2) barrier moved into place (3 s); (3) random time delay (2–5 s); (4) PO. In *online-VSI* trials, the LC goggles occluded vision prior to barrier deployment and restored vision at PO. In *stored-VSI* trials, vision was allowed until PO and then occluded for the remainder of the trial (3 s).

The focus of the study was on trials in which forward stepping reactions were evoked by large backward platform translation (3 m/s^2, 0.9 m/s, 0.26 m, 0.6 s). Trials were blocked by *visual condition*, each block comprising (in random order) eight of these "focus" trials (2 *stance widths* × 2 *slot locations* × 2 trials) plus four trials involving different perturbations (included solely to increase unpredictability, as detailed above). At the start of each new trial block, subjects were informed of the *visual condition* for the forthcoming trials and were allowed to become accustomed to the new task conditions (four trials, not analyzed). This experimental design was chosen to avoid confounding effects that can arise if there is uncertainty about the forthcoming visual conditions [7]. Two trial blocks were tested for each *visual condition*, and the order of the blocks was balanced both within and across subjects. The protocol yielded, for analysis, 48 "focus" (forward-step) trials for each subject (2 blocks × 2 trials per block × 3 *visual conditions* × 2 *stance widths* × 2 *slot locations*).

For each "focus" (forward-step) trial, video (60 Hz) recordings from four overhead cameras were used to determine whether the step was executed with the foot ipsilateral or contralateral to the slot location, and whether the foot was moved successfully through the slot without contacting the barrier. In addition, we examined whether the initiation of the step was delayed, by analyzing foot-off time (determined in relation to PO, i.e. platform acceleration >0.1 m/s^2). A step was defined to occur when the force-plate data (200 Hz) indicated unloading of the leg (<1% of body weight) and video analysis confirmed measurable horizontal displacement (>1 cm) of a marker on the heel.

Repeated measures analysis of variance (ANOVA), with Tukey *post hoc* comparisons ($\alpha = 0.05$), was performed to assess effects of *visual condition*. *Stance-width* and *slot-location* were also included as factors, to control for possible confounding effects. All data were rank-transformed prior to analysis (equivalent to performing a non-parametric test [1]). For the coded events (e.g. foot-contact with barrier), we analyzed the percentage of trials in which the event occurred as calculated for each task condition, within each subject.

Six of eight subjects were able to step through the slot during balance recovery, either avoiding the barrier entirely or contacting the barrier while stepping through the slot. These six subjects stepped through the slot (with or without barrier contact) in ~80% of trials, independent of *visual condition* ($p = 0.52$). The two remaining subjects were unable to step through the slot, in any trials, but did not differ from the other subjects in any obvious ways (height, weight, age, gender). In trials where the subject did not step through the slot, either the foot hit straight into the barrier and knocked it loose (81% of trials) or the subject was able to recover balance by taking multiple small steps that avoided contact with the barrier (19% of trials). All trials where subjects did not step through the slot were excluded from further analysis.

A common strategy involved taking a small (1–10 cm) initial step before stepping through the slot with the other foot. This occurred in ~80% of wide-stance trials, regardless of the visual condition; however, there was a pronounced influence due to *visual condition* in the narrow-stance trials (interaction between *stance-width* and *visual-condition*, $p = 0.038$). *Post hoc* comparisons ($\alpha = 0.05$), within the narrow-stance trials, showed that subjects were much more likely to adopt this two-step strategy when dependent on *online-VSI*, in comparison to the other two visual conditions (Fig. 2A).

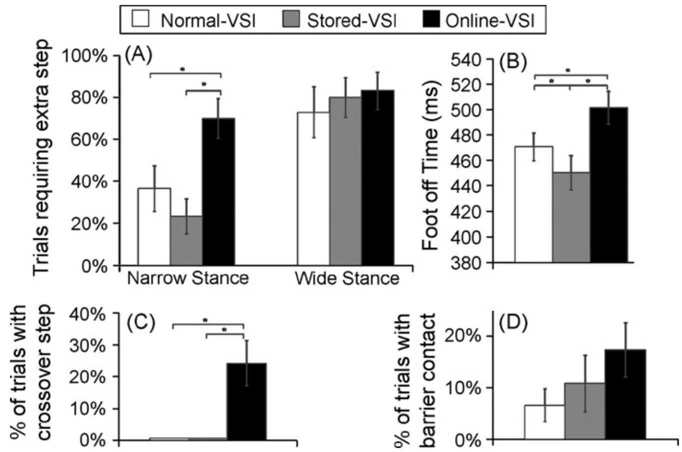

Fig. 2. Summary of the main findings: (A) percentage of trials where the subject took a small (1–10 cm) initial step before stepping through the slot with the other foot; (B) foot-off time for the step through the slot; (C) percentage of trials where the subject stepped through the slot with the foot contralateral to the slot location; (D) percentage of trials in which contact with the barrier occurred while stepping through the slot. In each bar graph, the mean and standard deviation is shown for each of the three visual conditions that were tested. In (B), (C) and (D), the data are pooled across the two stance-width conditions, as there was no significant interaction between visual condition and stance-width. In (A), there was such an interaction; hence we have shown the data separately for the two stance widths. [*Indicates a significant difference between means ($p < 0.05$).]

Regardless of whether the step through the slot was the first or second step taken, the timing of the "step-through" step was delayed in the *online-VSI* trials. ANOVA revealed a significant main effect due to *visual condition* ($p = 0.045$), and *post hoc* comparisons confirmed that foot-off timing was delayed (by ~50 ms, on average) in the *online-VSI* trials (Fig. 2B).

Presumably, the delay in initiating the "step-through" step afforded increased time for visual processing. Nonetheless, subjects were much more likely to step with the "wrong" foot in *online-VSI* trials. In nearly 25% of these trials (Fig. 2C), the "step-through" step was executed with the foot that was contralateral to the slot location, thereby necessitating a complex crossover trajectory that resulted in a precarious landing posture, i.e. legs crossed. This *never* occurred in the other visual conditions (main effect $p < 0.001$). Contact with the barrier, during the "step-through" step, was also influenced by visual condition (main effect $p = 0.029$), occurring nearly twice as frequently in *online-VSI* trials, compared to *stored-* and *normal-VSI* trials (Fig. 2D).

The present findings showed no evidence of differences between the *normal-* and *stored-VSI* conditions. This suggests that the subjects relied primarily on stored-VSI to guide the forward step reactions in the normal-vision condition, despite the fact that access to online visual feedback was available. This result is consistent with the findings from previous studies of natural gaze behavior. Such studies have shown that subjects commonly guide forward stepping reactions without redirecting gaze toward the foot, floor or step landing site at any time during the execution of the reaction, even when challenging obstacles and/or step targets increase the demand for accurate foot motion [11,19,21]. The present findings re-affirm the conclusion that online-VSI is not necessary to guide the foot movement.

None of these previous studies, however, examined the extent to which online-VSI may suffice, in situations there is no opportunity to scan and map the environment prior to perturbation onset. The present results suggest that online-VSI can suffice, *provided* that there is sufficient time available to acquire and process the

VSI needed to direct the step. In the present task conditions, which imposed high demands for accurate trajectory control, there apparently was not sufficient time to plan an initial step that could meet these demands, in a large proportion of trials. The observed delay in initiating the "step-through" step in the *online-VSI* trials is consistent with efforts to "buy more time" for visual scanning and processing.

A strategy in which a small initial step preceded the step through the slot with the other foot may have helped such efforts to "buy more time". This, in turn, might explain why the "two-step strategy" occurred most commonly in *online-VSI* trials. To examine this possibility, we performed *ad hoc* analyses to compare one- and two-step responses, within subjects who exhibited both types of response. On average, in narrow-stance trials, the two-step strategy delayed step-through foot-off time by 18–36 ms, depending on the visual condition (for wide-stance trials, infrequency of one-step responses precluded analysis). Presumably, the extra initial step permits the delay in foot-off because it slows the forward falling motion of the body [9]. Although this was not the focus of our study, we can note that it is likely that the extra step also provides mechanical benefits, in helping to: (1) arrest the forward falling motion, and (2) preserve lateral stability during the step-through step (by shifting the center of mass toward the leg that will provide the single-leg support [20]). The latter benefit is particularly important in wide-stance trials, and may explain why the two-step strategy predominated in this task condition.

Despite the extra time afforded by delaying initiation of the step-through step in *online-VSI* trials, subjects were still less able to achieve an accurate and effective response. The higher frequency of barrier contact, in the *online-VSI* trials, indicates that there was less accurate control of the foot trajectory, while the tendency to step with the "wrong" foot indicates a problem during the very earliest stage of motor planning, i.e. selection of the step foot. The increased difficulty in controlling the more complex crossover trajectory necessitated by the selection of the "wrong" foot may have also contributed to the trajectory errors. Such problems suggest that the delay in initiation of the step-through step provided insufficient additional time for effective acquisition and processing of VSI, in a substantial proportion of trials. Presumably, the temporal constraints imposed by the need to arrest the perturbation-induced body motion (and prevent a fall from occurring) prohibited the introduction of any further delay in the initiation of the "step-through" step. One would expect these temporal constraints to be alleviated in responding to smaller perturbations; however, the present study cannot provide any direct evidence to support this [the small perturbations included to increase unpredictability were limited in number and too small to consistently require stepping through the slot (only seven such trials occurred)].

While the similarity of the *stored-* and *normal-VSI* responses may suggest that online control offers little or no benefit for directing the compensatory foot movement, the present study did not assess the potential contribution of online visual feedback during the later phases of the step trajectory. Constraints traversed relatively early in the step trajectory, such as the slot in the barrier, may be accommodated via an initial "ballistic" phase based on stored-VSI, whereas constraints encountered later in the trajectory (such as restrictions on the step landing site) may provide sufficient time to utilize online visual control [19]. Previous studies of compensatory stepping have, in fact, shown that young adults were better able to land the step foot on a target in trials where they redirected gaze toward the floor [19]. This is also consistent with results from studies of targeted volitional stepping [2,4].

Further work is needed to establish the degree to which the subjects analyzed here are representative of the general population, and to determine how impairments in vision and visual processing affect the ability to utilize stored and online visual information to guide the stepping reactions. The influence of other neuromusculoskeletal deficits also needs to be determined. Such impairments can occur as a result of aging or disease; however, the fact that two of our eight healthy young-adult subjects were unable to perform the step task suggests that even sub-clinical deficits may have a profound effect. Work in progress is aimed specifically at identifying factors that affect the capacity of the CNS to acquire, process, store and retrieve the VSI required to execute effective balance-recovery reactions. One such study involves using LC goggles to reduce the amount of time available to acquire VSI prior to PO or to increase the amount of time that the acquired VSI has to be stored before executing the balance reaction.

In summary, the present results suggest a critical role for stored-VSI during the earliest phase of the step, in selecting which limb to use and in planning the initial trajectory. Online acquisition and processing of the required VSI may be too slow to allow effective control of this early phase, particularly in complex or "cluttered" environments where the demands for accurate foot motion are high. As suggested by other studies, online-VSI is more likely to play a more important role during the later phases of the step, where more time is available, and hence may contribute to adjusting the final stage of the trajectory and the location of the landing.

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