The Effects of Constrained Movement on Physical and Mental Workload

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ABSTRACT

This paper reports the results of two experiments comparing *Constrained Movement* (CM) and *Free Movement* (FM) on a directed search task in a spatial multiscale environment (Jazz). The two experiments differ only in the amount of environmental information available. Results show a 30% increase in navigational performance while reducing physical activity by as much as 67%, with no change in error. Detailed analysis provides strong evidence that subjects were making fewer incorrect decisions, experienced less spatial disorientation, were making decisions faster, and were making more decisions while moving. The results indicate that CM can, in fact, be a very powerful means of decreasing navigational cost while increasing performance.

Author Keywords

Constrained Movement, Directed Navigation, Guided Navigation, Wayfinding, ZUI, Jazz, Lodestone, Leyline.

ACM Classification Keywords

H.5.2 User Interfaces.

INTRODUCTION

Navigation—the task of determining where things are and getting to them—is ubiquitous in human-computer interaction [12, 15]. One of the innumerable means of improving navigational performance that have been proposed is limiting what movement options are available, and a variety of *Constrained Movement* (CM) techniques have been developed [4, 5, 7, 8, 9, 11, 13, 16, 17, 19]. However, very little empirical evidence has been presented that establishes the effects or effectiveness of these techniques on navigational performance. This paper describes a study examining the effectiveness of CM in reducing the physical and mental workloads of navigation.

CM is here defined as movement that results from the application of constraints (whether heuristic or formal) to reduce movement options. In other words, CM *eliminates* paths rather than creating new ones. Like limited access highways in the physical world, CM is presumed to support the navigational subtask of *wayfinding*—deciding which movement options to take—by simplifying navigational decisions and reducing the number necessary to reaching a destination. CM typically also supports the subtask of *steering*—controlling movement—by reducing and simplifying the actions needed to select and follow paths.

The study compares a CM technique to a *Free Movement* (FM) technique—movement with no constraints imposed—on a directed search task in a spatial multiscale environment (Jazz). The underlying hypotheses are that the CM technique will reduce the physical and mental workloads of steering and the mental workload of wayfinding. Mental workload is operationalized as primary task and subtask performance (errors and time on task) [3] and physical workload as mouse activity.

The study comprises two experiments that differ only in the amount of environmental information available. Results from the first experiment overwhelmingly confirm the hypotheses, yielding a 30% increase in task performance while reducing physical activity by as much as 67%, with no change in task error. Detailed analysis provides strong evidence that subjects were making fewer incorrect decisions, experienced less spatial disorientation, were making decisions faster, and were making more decisions while moving. The results indicate that CM can, in fact, be a very powerful means of decreasing navigational overhead while increasing navigational performance.

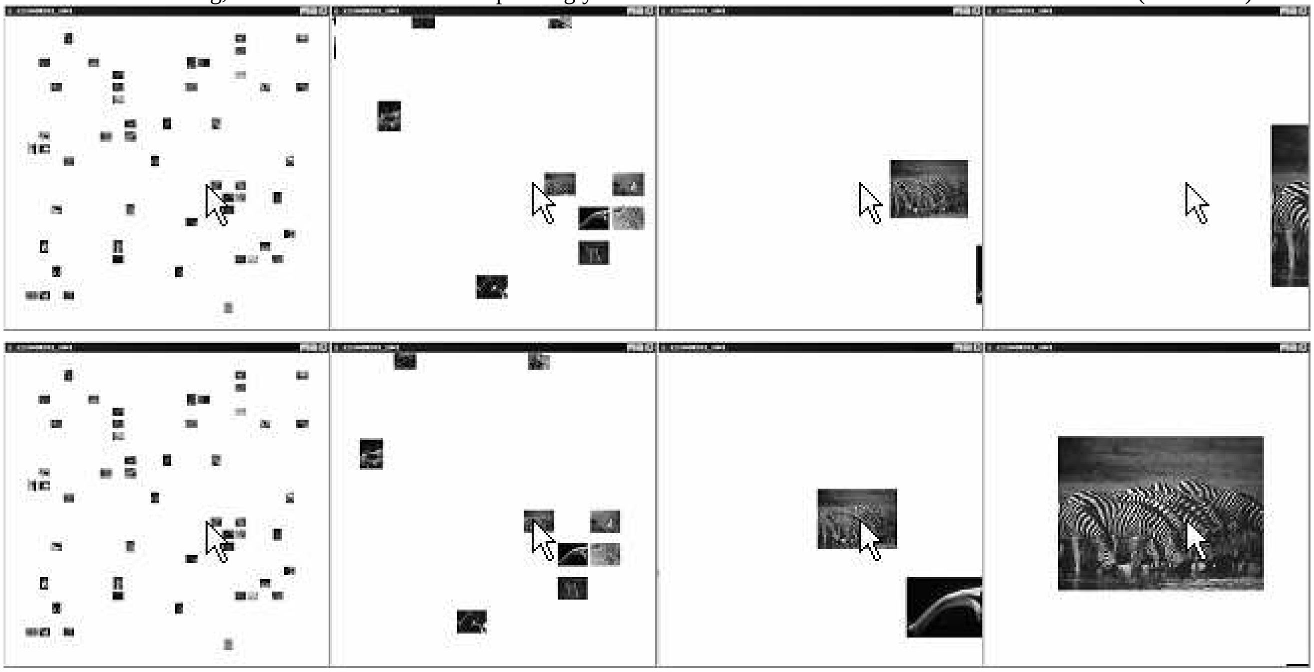
RELATED WORK

Prior efforts have addressed different aspects of and approaches to CM. Some focus on the concept itself. Jul [12] outlines a generic CM algorithm with hooks for functions that predict the user's desired destination and route (and negotiate predictions) based on user input and system state. Galyean [7] provides a conceptual analogy of a river to describe a CM technique for moving users along a scripted path automatically, while allowing them to control speed and movement within the boundaries of that path.

Other efforts focus on specifics of individual techniques, including constraint specification, path computation, path specification and path selection. Individual techniques can be classified according to the factors considered in constraints: *Proximally Constrained Movement* (PCM) techniques uses only factors that are near the current location or within the current view. *Distally Constrained Movement* (DCM) techniques may incorporate factors that are distant from the current location or may even be non-spatial. For instance, constraining a line being drawn to the horizontal or vertical is a PCM technique, while graying of inoperable menu items is a DCM technique. Proximal techniques primarily support steering, whereas distal techniques typically support both steering and wayfinding.

Free Movement (FM)

When the user presses the mouse to zoom, the system scales the view around the surface point that is under the mouse. If the mouse is moved while zooming, the surface is moved correspondingly so that the center of the zoom remains under the mouse (not shown).



Constrained Movement (CM)

Zoom-In: When the user presses the mouse to zoom in, the system selects the object closest to the mouse (planar distance) as the intended destination and zooms toward a view in which that object is centered and occupies 95% of the screen in one dimension. If the mouse is moved, while zooming, to be closer to another object, movement is redirected to move toward that object (not shown).

Zoom-Out: When the user presses the mouse to zoom out, the system moves toward the *Top of the World* view—the most magnified view that contains all objects in the environment (left-most view)—regardless of mouse location.

Figure 1 Continuous zoom-in with no mouse movement using FM and CM. Note that in FM, points surrounding the mouse location move *away from the mouse*, whereas in CM, the object closest to the mouse moves *toward the center of the window*.

Two efforts address constraint specification. Hanson et al. [8, 9] present a variety of ways of defining *Guide Manifolds*—surfaces or trajectories to which the viewing camera is constrained. These may be based on characteristics of objects or might incorporated distal factors such as gravity or magnetism. Tan et al. [18] propose *Orbiting*, a proximal technique whereby the viewing camera is restricted always to face a given object.

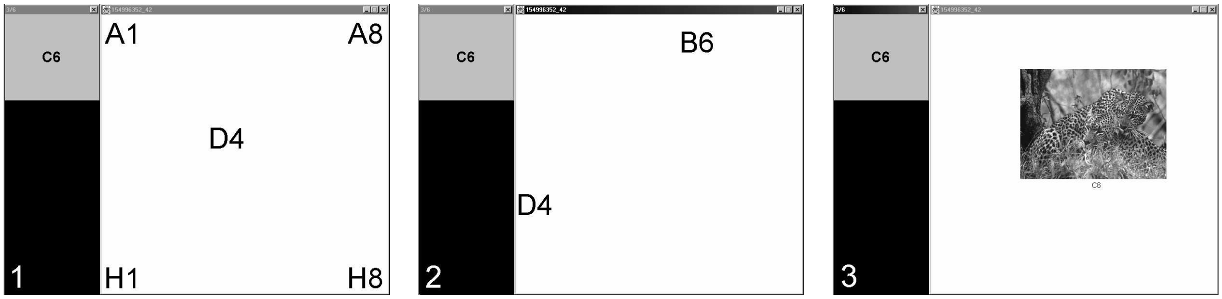
The majority of efforts focus on path computation and specification. Xiao and Hubbold [19] calculate a path as a sum of the forward motion requested by the user and forces from conceptual *Force Fields* around objects that repel movement. Salomon et al. [17] present a similar *Local Walk* technique that directs movement around or along any obstacles encountered. Igarashi et al. [11] use *Path Drawing* to allow the user to specify the desired path by drawing an approximation on a 2D screen. This specification is then projected into a 3D environment to compute a path for walking movement. These three techniques all rely on proximal factors.

Other path computation techniques provide for distal factors. Salomon et al. [17] precompute a "road map" of all paths in a virtual environment (assuming a walking or driving metaphor of movement), and then, in a *Global Walk* technique, select the shortest route that leads to the user's chosen destination. Mackinlay et al. [16] allow the user to indicate a *Point of Interest* on an object (potentially in a disjoint view), and then calculate a visually satisfying path to move the viewpoint to view that point. Jul [12, 13] describes a *Lodestones and Leylines* technique for zoom-based interaction that predicts the user's intended destination, and then computes a path to that location.

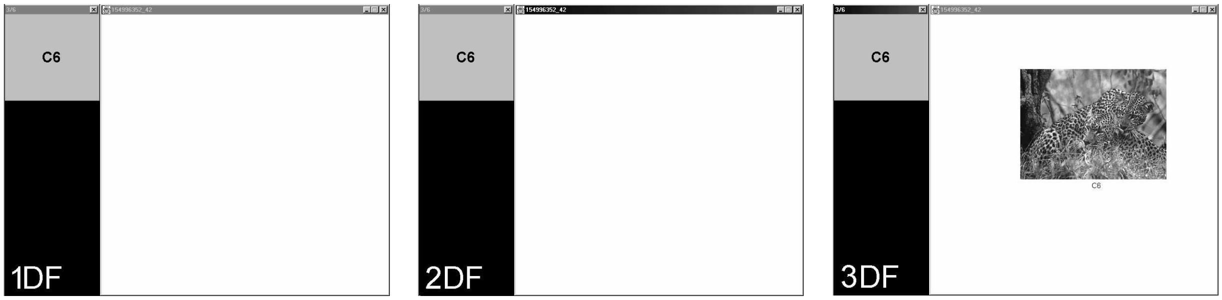
Finally, other CM efforts focus on selecting a subset of the existing paths to be made available to the user. Da Silva et al. [5], for instance, hide or reveal links in an educational hypertext system to correspond to the student's presumed level of understanding. The practice of graying inoperable menu items also falls into this category. Such techniques typically rely on non-spatial factors.

Note that CM, which *reduces* the number of paths available to the user, should not be confused with *Augmented Movement*, which *adds* paths to the environment. For instance, Igarashi and Hinckley [10] and Tan et al. [18] create new paths by introducing, respectively, zooming and flying metaphors of movement. Some history and bookmarking mechanisms also fall into this category. CM should, like-

Grid Markers Experiment



Desert Fog Experiment



View 1: Top of the World view in a small layout (8 x 8 grid).

View 2: View zoomed toward **C6**. Note appearance of a secondary grid marker (**B6**) in Grid Markers.

View 3: Target destination (**C6**), identified by a label below the photograph.

Figure 2 Experimental stimuli. The large window is the multiscale interaction space. The small window presents the experimental stimuli (a destination location, here, **C6**).

wise, not be confused with techniques that provide information to guide movement but do not affect actual movement. Chittaro and Burigat [4], for example, provide 3D arrows that point to the user's selected destination, but that do not alter what movement is possible.

Despite the number and variety of CM techniques proposed, little empirical evidence is available regarding their effectiveness and no full experiments have been reported previously. Three of the efforts cited briefly describe studies comparing CM to FM. Jul [13] conducted a pilot study showing that Lodestones and Leylines increased performance significantly on a simple search task. Xiao and Hubbold [19] found that Force Fields decreased errors (object collisions) reliably, but show no significant difference in performance on a path-following task. Hanson et al. [9] conducted a pilot study showing that Guide Manifolds increased awareness of inconspicuous objects.

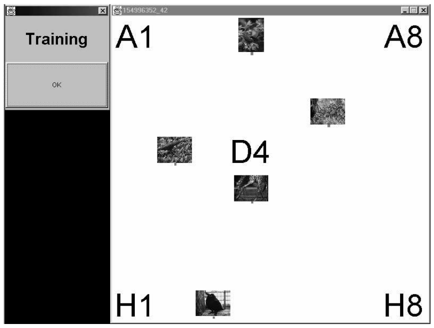
Igarashi et al. [11] compare Path Drawing to other types of movement control, but results confound effects of steering and movement techniques so are inconclusive with respect to CM. Tan et al. [18] describe an extensive study of a variety of Augmented Movement techniques, but do suggest that Orbiting improves performance on an object relocation task. Thus, there has been neither systematic study of the effects of different CM techniques nor a thorough examination of any one of them.

EXPERIMENTAL DESIGN

The two experiments compared a DCM technique to a conventional FM technique. Each experiment employed a 1 x 2 factorial within-subject design with repeated measures. The first factor, movement technique, was manipulated within subject. The second factor, order of presentation of the two techniques, was varied between subjects to counter-balance possible order effects. The two experiments differed only in the amount of environmental information available.

The *Grid Markers* experiment was designed to emulate a situation in which the user's destination is not in the view, but the user has approximate knowledge of its location relative to the current location. This is a normal occurrence in much interaction, for example, getting to a file from the desktop in one's personal file system, or finding a particular page in a website. In this experiment, sufficient environmental information to allow subjects to orient themselves was always available.

In the *Desert Fog* experiment, no environmental information was provided, except for labels identifying individual objects. This experiment was not intended to simulate a realistic task, but tested the supposition that CM can alter the demands of wayfinding so dramatically that an impossible task is made possible. ("Desert fog" is a condition in which no information is available upon which wayfinding decisions can be based [14]. It is inherent to certain types of environments and is a recognized problem that realistic designs must address.)



Photographs shown are at **A4**, **C6**, **D2**, **E4** and **H3**. Subjects saw this view during training but never in testing.

Figure 3 Example layout of photographs (8 x 8 grid).

The two experiments were interleaved so that a subject performed both experiments using one technique before repeating them with the other. Subjects received extensive training and practice before tests were administered.

Subjects

25 subjects (9 female, 15 male) participated in the study, all university students or staff in a variety of disciplines. All had extensive experience with mouse-based computers, but none reported prior familiarity with zooming user interfaces. Each subject participated in a single 1.5 – 2 hour session and received a $25 gift certificate.

Interaction Environment

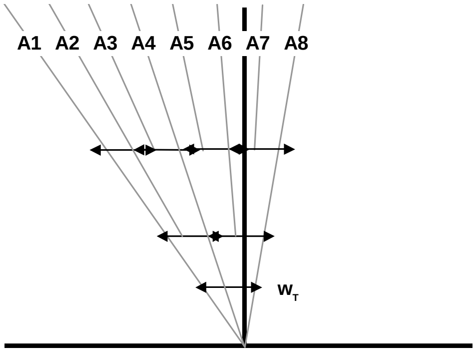
The interaction environment used for the study was Jazz [2]. Like its predecessor, Pad++ [1], Jazz employs an interaction metaphor of a conceptually infinite two-dimensional surface that can be viewed at a conceptually infinite range of magnifications. Objects have position and extent on the surface. Their visibility can be configured to depend on the scale of the view, e.g., fading away when the amount of detail is too small to be useful.

The FM technique used in the study is that which was supplied as the default in Pad++. This technique defines movement in terms of the geometry of the environment itself (Figure 1 Views 1–4F). It allows unconstrained zoom and pan as well as combined pan-zoom movement. The CM technique used is the Lodestones and Leylines technique proposed by Jul [13]. This technique defines movement in terms of the geometry of the layout of objects in the environment (Figure 1 Views 1–4C). Movement is only permitted that leads to an object or to a special "Top of the World" view (Figure 1 View 1). In the form used here, simple panning is not permitted.

A two-button mouse was used to control movement, with left and right buttons assigned to zoom-out and zoom-in, respectively. In FM, panning is achieved by pressing the alt key and dragging with either mouse button. An animated cursor provides feedback about movement status.

Stimuli

The experimental stimuli are shown in Figure 2. A randomly set of professional photographs is laid out on the surface. A photograph is invisible until the view magnification is such that it covers at least 190 pixels along one dimension. This ensures that it is necessary to make wayfinding decisions with no photographs in the view, and that there is time to make such decisions while moving. Photographs all reach the visibility threshold at the same scale and are spread out to prevent visual occlusion (Figure 3).



Top-level grid markers (**A1**, **A4**, **A8**) are always visible. Secondary markers (**A2**, **A6**, **A3**, **A5**, **A7**) appear with each 1.75 increase in magnification.

Figure 4 Space-scale diagram [6] of fractal grid coordinate markers for grid with 8 columns.

Photographs are positioned relative to a conceptual grid sized so that at most 10% of the cells will be occupied; a 23 x 23 grid in the Grid Markers experiment (50 photographs) and an 8 x 8 grid in Desert Fog (6 photographs). The placement of photographs in the grid is random and generated uniquely for each training or testing run.

The informational design imposes an alphanumeric coordinate system on this grid (Figure 3). Each photograph is labeled with its grid address (Figure 2 View 3). In the Desert Fog experiment, no other environmental information is available (Figure 2 View 1DF–3DF), however, subjects were informed (and reminded) that all runs start at the Top of the World. In the Grid Markers experiment, the addresses of selected reference locations are displayed on the surface. These *grid markers* follow a fractal grid design [6] with secondary markers appearing at regular intervals in scale (Figure 4). Grid markers are fixed in size and do not change with view magnification.

The experimental task is to move from one photograph to another. A random sequence of locations of photographs is selected without replacement, and presented, one at a time (Figure 2, small windows). Subjects press the space bar to indicate that they have arrived at the target destination. If they are at the correct location, the next location cue is presented. Subjects performed 15 and 5 trials (moving from one photograph to another) in the Grid Markers and Desert Fog experiments, respectively.

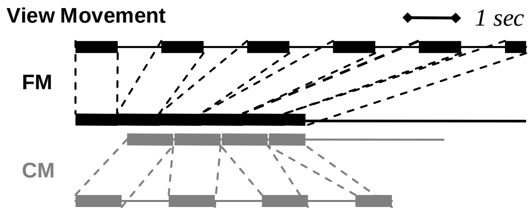
Data Collection

Behavioral data collected included the duration of each trial—from the presentation of the location cue until the subject presses the space bar with that location in the

		FM	CM	%	t(23)	p <
	Total Time on Task (sec/100SU)	9.4	6.6	-30	4.93	.0001
View Movement	**Total Move Time (sec/100SU)**	4.8	3.7	-22	3.12	.005
	Total Moves (moves/100SU)	5.5	3.8	-31	4.72	.0001
	Time per Move (sec/move)	.88	1.0	+15	2.83	.005
	Total Non-Move Time (sec/100SU)	4.6	2.9	-38	6.24	.0001
	Time per Non-Move (sec/non-move)	.85	.75	-11	2.38	.02

In this and the following tables, % column indicates change from FM to CM, and bold type denotes statistically significant values. Note that all values are obtained from actual data; discrepancies in derivable measurements are due to round-off.

Table 1 Overall results for task performance and view movement in Grid Markers experiment.



Top and bottom rows show average frequency and duration of view movements (thick bars) and non-movements (thin bars) used to move a net distance of 100 Surface Units (SU) in FM (dark lines) and CM (gray lines) conditions, respectively. Center rows show cumulative view movement and non-movement.

Figure 5 Illustration of overall results for task performance and view movement in Grid Markers experiment.

view—and the number of response errors (spacebar pressed when the target is not in the view). View and mouse locations were sampled and recorded approximately every 100 ms. (A sampling rather than an event-driven strategy was used to avoid introducing different computational costs of data collection caused by variations in event frequencies between the two techniques.)

The study was conducted on a laptop computer with a Pentium II 266 MHz processor and 96 MB memory, running Windows 98, Java 1.3.1 and Jazz 1.0. Although the zoom rate—the change in magnification with each zoom increment—is constant and identical for the two techniques, the computational cost of zooming is greater with the CM technique: The mouse position is sampled every 20 ms when zooming and changes trigger a system response. In CM, this causes an O(n) target selection algorithm to be executed. In FM, it causes a single translation of an affine transform.

PREDICTIONS

CM is based on two premises. First, that automating path selection and specification reduces the amount of physical activity necessary to select and follow a path. This yields two predictions the Grid Markers experiment:

1. There will be fewer mouse moves during view movement.
2. During view movement, each mouse move will be smaller in both time and space.

CM is not expected to affect mouse movement while the view is stationary to any significant extent. However, as mouse movement during view movement is expected to represent the bulk of view movement, there should be a significant reduction in total mouse movement:

3. Overall mouse movement will be decreased.

Second, CM is based on the premise that limiting the number of available paths simplifies and reduces the number of navigational decisions necessary to reaching a particular destination. This should result in users taking shorter (more direct) routes, doing less backtracking, making fewer decisions and making them faster. Shorter routes and less backtracking yield two further predictions:

4. Time on task will be reduced.
5. Subjects will move the view fewer times to reach a target destination (and, as a corollary, make fewer stops between view moves).

Fewer decisions and faster decision-making yields two further predictions:

6. The duration of each view move will be longer.
7. The duration of each stop in view movement will be shorter.

The Lodestones and Leylines technique used in this study reduces the number of paths to a finite set and provides a fixed reference location (the Top of the World). Thus, it is theoretically possible for subjects to employ systematic exhaustive search to reach any destination, even in the absence of environmental information. This yields the following prediction for the Desert Fog experiment:

8. Subjects should reach more targets successfully.

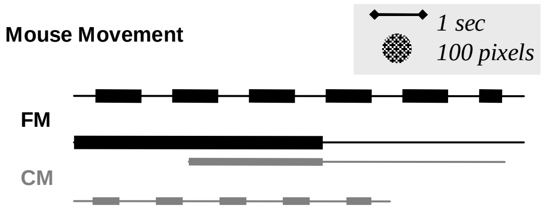
Note that Predictions 1 and 3–7 should hold, to some degree, for any CM technique. Prediction 2 depends on the interaction design. E.g., Point of Interest [16] may yield fewer but longer mouse moves. Prediction 8 is specific to techniques that exhibit the two properties mentioned.

RESULTS

Data from one subject were eliminated due to faulty equipment, leaving 12 subjects in each starting condition. Because each experiment has only two conditions and CM is predicted to be superior, paired one-tailed t-tests are used, except as noted otherwise.

		FM	CM	%	t(23)	p <
Total Time on Task (sec/100SU)		9.4	6.6	-30	4.93	.0001
Mouse Movement	**Total Move Time (sec/100SU)**	5.2	2.8	-47	7.08	.0001
	Total Moves (moves/100SU)	5.5	4.9	-11	1.23	.15
	Total Move Distance (pixels/100SU)	1492	487	-67	9.51	.0001
	Avg. Speed (pixels/sec)	290	178	-39	6.23	.0001
	Time per Move (sec/move)	.89	.78	-12	2.22	.02
	Distance per Move (pixels/move)	290	99	-66	7.62	.0001
	Total Non-Move Time (sec/100SU)	4.2	3.8	-15	1.17	.15
	Time per Non-Move (sec/not-move)	.77	.81	+6	.77	.25

Table 2 Overall results for mouse movement in Grid Markers experiment.



As in Figure 5, length of bars indicates duration of movement activity (in this case, mouse movement). Additionally, the visual area of a bar is proportional to the total distance the mouse was moved, and, consequently, line thickness indicates the average speed of movement.

Figure 6 Illustration of overall results for mouse movement in Grid Markers experiment.

Grid Markers Experiment

Five separate analyses are performed on the Grid Markers data: Error, Time on task and view movement (Table 1/Figure 5), Overall mouse movement (Table 2/Figure 6), Mouse movement during a single view move (Table 3/Figure 7), and Mouse movement during a single view non-move (Table 4/Figure 8).

Because of the randomness of layouts and target sequences, the minimum distance that must be traversed differs across runs. Certain measures are therefore normalized to *net planar distance traveled*, that is, the total planar distance between targets in a given target sequence. Planar distance is measured in *Surface Units* (SU), which, at the canonical magnification of 1, correspond to pixels.

Error

There was no significant difference in the number of erroneous space bar presses, $t(23) = .24$, $p < .6$.

Time on Task and View Movement

Table 1 shows the results for overall time on task and view movement. All but three subjects were faster when using CM, taking 9.4 sec to move a net distance of 100 SU in FM, but only 6.6 sec in CM, $t(23) = 4.93$, $p < .0001$. This 30% decrease was not distributed uniformly between time spent moving the view (*View Move Time*) and time spent looking at a stationary view (*View Non-Move Time*): View Move Time was reduced from 4.8 sec to 3.7 sec, $t(23) = 3.12$, $p < .005$, a 22% reduction, whereas View Non-Move Time was reduced from 4.6 sec to 2.9 sec, $t(23) = 6.24$, $p < .0001$, a 38% reduction.

The number of times the view was moved (and, correspondingly, not moved), *View Moves*, was reduced from 5.5 moves per 100 SU in FM to 3.7 moves in CM, $t(23) = 4.72$, $p < .0001$. Durations of individual view movements and non-movements also changed. The duration of an average view move (*Time per View Move*) increased from .88 sec in FM to 1.0 sec in CM, $t(23) = 2.83$, $p < . 005$. The duration of an average view non-move (*Time per View Non-Move*) decreased from .85 sec in FM to .75 sec in CM, $t(23) = 2.38$, $p < .02$.

In short, subjects were considerably faster and spent a larger proportion of their time actually moving the view when using the CM technique. They moved the view fewer times, but when they did, they moved it for longer periods. However, intervals between view moves were shorter. These results are illustrated in Figure 5.

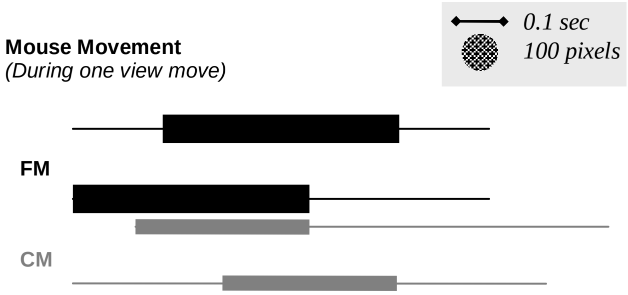
Overall Mouse Movement

Table 2 shows the results for overall mouse movement. To move the view a net distance of 100 SU, subjects moved the mouse (*Mouse Move Time*) for 5.2 sec in FM and for 2.8 sec in CM, $t(23) = 7.08$, $p < .0001$. The distance they moved the mouse (*Mouse Move Distance*) was 1492 pixels in FM and 487 pixels in CM, $t(23) = 9.51$, $p < .0001$. The average speed of mouse movement (*Mouse Move Speed*) was 290 pixels/sec in FM, 178 sec in CM, $t(23) = 6.23$, $p < .0001$. There was no significant difference in the amount of time they held the mouse still (*Mouse Non-Move Time*): 4.2 sec in FM and 3.8 sec in CM, $t(23) = 1.17$, $p < .15$.

The number of times subjects moved (and, correspondingly did not move) the mouse (*Mouse Moves*) per 100 SU of net view movement did not differ significantly: 5.5 moves in FM versus 4.9 moves in CM, $t(23) = 1.23$, $p < .15$. However, an average mouse movement lasted longer (*Time per Mouse Move*) in FM: .89 sec in FM versus .78 sec in CM, $t(23) = 2.22$, $p < .02$. In contrast, there was no significant difference in how long stops between mouse moves were (*Time per Mouse Non-Move*): .77 sec in FM versus .81 sec in CM, $t(23) = .77$, $p < .25$. The average mouse move was also greater in distance (*Distance per Mouse Move*): 290 pixels in FM versus 99 in CM, $t(23) = 7.62$, $p < .0001$.

		FM	CM	%	t(23)	p <
Time per View Move (sec)		.88	1.0	+15	2.83	.005
Mouse Movement	**Total Move Time (sec)**	.50	.37	-25	3.56	.001
	Moves per View Move (moves)	.48	.77	+60	5.75	.0001
	Total Move Distance (pixels)	146	58	-60	6.97	.0001
	Avg. Speed (pixels/sec)	297	163	-45	5.47	.0001
	Time per Move (sec/move)	1.1	.47	-58	6.00	.0001
	Distance per Move (pixels/move)	349	76	-78	5.26	.0001
	Total Non-Move Time (sec)	.38	.63	+67	6.31	.0001
	Time per Non-Move (sec/not-move)	.84	.94	+12	1.07	.15

Table 3 Results for mouse movement during a single view move in Grid Markers experiment.



(Time and distance scales differ from previous figures.)

Figure 7 Illustration of results for mouse movement during a single view move in Grid Markers experiment.

In summary, when examined overall, subjects moved the mouse for shorter periods of time, over shorter distances and more slowly in CM. They moved the mouse equally often, so individual moves were both shorter in time and smaller in space. Pauses in mouse movements were not significantly different. These results are illustrated in Figure 6.

Note that view movement and button presses are synonymous—the view moves if and only if a mouse button is pressed, so button press activity is not analyzed separately.

Mouse Movement during a Single View Move

Table 3 shows the results of analysis of mouse movement during a single view move. In the course of a single view move, Mouse Move Time accounted for .5 sec in FM and .37 sec in CM, t(23) = 3.56, p < .001. This 25% reduction was substantially smaller than the 47% reduction exhibited by the overall findings. Total Mouse Move Distance decreased from 146 pixels in FM to 58 in CM, t(23) = 6.97, p < .0001. Average Mouse Move Speed was 297 pixels/sec in FM and 163 pixels/sec in CM, t(23) = 5.47, p < .0001. Unlike in the overall findings, there was a significant difference in Mouse Non-Move Time: .38 sec in FM versus .63 sec in CM, t(23) = 6.31, p < .0001.

The number of Mouse Moves, also unlike the overall findings, differed significantly, increasing from .48 in FM to .77 in CM, t(23) = 5.75, p < . 0001. (A value of less than 1 is perhaps best interpreted as representing the probability that the mouse will be moved.) Each mouse move was shorter in duration, 1.1 sec in FM and .47 sec in CM, t(23) = 6.00, p < .0001. This 58% decrease was substantially larger than the 12% decrease observed in the overall findings. Distance per Mouse Move fell from 349 pixels in FM to 76 pixels in CM, t(23) = 5.26, p < .0001. As in the overall findings, there was no significant difference in the Time per Mouse Non-Move: .84 sec in FM versus .94 sec in CM, t(23) = 1.07, p < .15.

In short, during a given view move, subjects were more likely to move the mouse in CM but moved the mouse less in both time and distance if they did. When they did, they moved the mouse considerably more slowly, and each move was substantially shorter in duration and shorter in spatial magnitude. Subjects spent considerably more time not moving the mouse, although there was no difference in how long each pause in mouse movement lasted. Thus, although subjects were more likely to move the mouse, the proportion of time they spent, not moving it increased. These findings are illustrated in Figure 7.

Note that, although the number of Mouse Moves per View Move differed significantly, the total number of mouse moves coincident with view movement did not differ, due to the reduced number of view moves: 2.6 moves/100 SU in FM and 2.9 moves/100 SU in CM, t(23) = 1.21, p < .15.

Mouse Movement during a Single View Non-Move

Table 4 shows the results of analysis of mouse movement during a single view non-move. As no difference was expected, these results are analyzed using a paired two-tailed t-test. During an average view non-move, Mouse Move Time was .50 sec in FM and .36 sec in CM, t(23) = 4.41, p < .0005. Mouse Move Distance was 129 pixels in FM and 70 in CM, t(23) = 6.54, p < .0001. Average Move Speed decreased from 285 pixels/sec in FM to 201 pixels/sec in CM, t(23) = 5.3, p < .0001, (both somewhat faster than during view movement). As in the overall results and unlike the results for view movement, there was no significant difference in the total Mouse Non-Move Time: .39 sec in FM and .40 in CM, t(23) = .36, p < .7.

Again as in the overall results and unlike the results for view movement, there was no significant difference in the number of Moves per View Non-Move: .52 moves in FM

		FM	CM	%	t(23)	p <
Time per Non-View Move (sec)		.85	.75	-11	2.38	.02
Mouse movement	**Total Move Time (sec)**	.50	.36	-22	4.41	*.0005*
	Moves per View Non-Move (moves)	.52	.53	+2	.39	*.7*
	Total Move Distance (pixels)	129	70	-45	6.54	*0001*
	Avg. Speed (pixels/sec)	285	201	-30	5.3	*.0001*
	Time per Move (sec/move)	.93	.68	-27	5.62	*.0001*
	Distance per Move (pixels/move)	276	135	-51	5.31	*.0001*
	Total Non-Move Time (sec)	.39	.40	+2	0.36	*.7*
	Time per Non-Move (sec/non-move)	.74	.73	-2	.28	*.8*

Table 4 Results for mouse movement during a single view non-move in Grid Markers experiment. Italics indicate measures for which a two-tailed t-test was used.

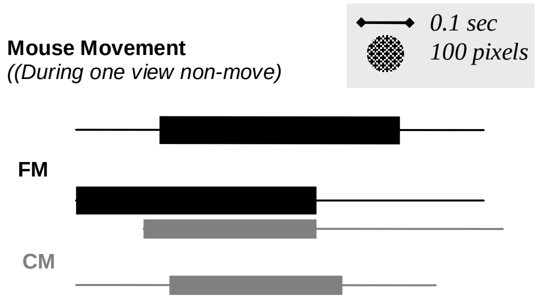


Figure 8 Illustration of results for mouse movement during a single view non-move in Grid Markers experiment.

and .53 in CM, t(23) = .39, p < .7. The Move Time for each move decreased from .93 sec in FM to .68 sec in CM, t(23) = 5.62, p < .0001. Move Distance decreased from 276 pixels in FM to 135 in CM, t(23) = 5.31, p < .0001. The decreases in time and distance, while substantial, are not as great as those observed during view movement. The difference in Time per Non-Move was not significant, as in both overall results and results during view movement; .74 sec in FM versus .73 sec in CM, t(23) = .28, p < .8.

In short, contrary to expectations, mouse movement during view non-movement was affected by CM. Although equally likely to move the mouse in the two conditions, subjects moved the mouse less in both time and space in CM. Individual mouse moves were shorter and smaller, and subjects moved the mouse more slowly. They spent about the same amount of time not moving the mouse and the durations of individual mouse non-moves did not differ. These results are illustrated in Figure 8.

Note that, although there was no significant difference in Mouse Moves per View Non-Move, the total number of mouse moves during view non-movement was reduced significantly, due to the reduced number of view moves: 2.9 moves/100 SU in FM versus 2.0 moves/100 SU in CM, t(23) = 3.47, p < .005. Similarly, although Time per Mouse Non-Move was largely unchanged, the total time spent moving neither the view nor the mouse was reduced significantly: 2.2 sec/100 SU in FM versus 1.5 sec/100 SU in CM, t(23) = 3.65, p < .005.

Desert Fog Experiment

The only data analyzed in the Desert Fog experiment were trial completions. When using CM, all subjects completed all five trials successfully. No subject was able to complete all trials using FM, giving up (discontinuing the run) after an average of .29 trials, t(23) = 31.57, p = 0 (Figure 9).

Qualitative Results

In a post-test questionnaire, subjects reported greater satisfaction with the CM technique. 16 of the 24 subjects stated that they preferred or strongly preferred CM, in general. When asked which model they would prefer if they “were doing something technique while [they] were performing this task—say talking on the phone,” 21 subjects favored CM. 19 subjects found CM easier or much easier to use, while 3 thought FM was easier, and 2 subjects thought they were about the same.

Many subjects cited the ability to return to the Top of the World and the need for less accurate mouse control as particularly attractive features of the CM technique. Many cited the ability to pan as a positive feature of FM and lack thereof a defect of CM.

DISCUSSION

The data largely support the predictions and show clearly that the physical workload of steering has been reduced. They suggest strongly that the mental workloads of steering and wayfinding have also been reduced, although alternate explanations are possible in some cases.

Prediction 1 (fewer mouse moves during view movement) is supported by the cumulative data showing that there were fewer total mouse moves during view movement, but is contradicted by the data showing a greater probability of mouse movement during any given view move. The latter is partially accounted for by “target following” behavior, a tendency to keep the mouse centered on the target (or presumed target location). While necessary in FM, target following has no effect in CM and may, in fact, backfire if the mouse is moved excessively. The increased likelihood of mouse movement may also reflect increased overlap in steering and wayfinding, to be discussed shortly.

Predictions 2 (smaller shorter mouse moves) and 3 (less mouse movement overall) are supported directly by the data (Table 3/Figure 7, Table 2/Figure 6). Thus, the data show, conclusively, that the physical workload of steering has been reduced (the contradiction mentioned above notwithstanding). As steering is a deliberate physical activity that must be guided by some mental processes, this reduction in physical workload is taken to be accompanied by a reduction in the mental workload of steering.

Predictions 4–6 are also supported by the data (Table 2/Figure 5): time on task was decreased (Prediction 4), and subjects moved the view fewer times (Prediction 5) but for longer periods (Prediction 6). As speed of view movement was the same for the two conditions (cf. *Data Collection* above), these results could only be achieved if subjects were taking shorter routes. Shorter routes but with fewer stops implies that subjects were making fewer incorrect decisions, had greater confidence in their decisions, and were either making fewer decisions or were making more decisions while moving.

Note that fewer incorrect decisions imply fewer decisions overall. In theory, because of the reduction of movement options, fewer correct decisions should be necessary to reach destinations; however, the present data are insufficient to determine whether subjects are, in fact, also making fewer correct decisions.

Prediction 7 (shorter stops between view movements) is also supported (Table 2/Figure 5). This result, however, could be attributed to any of three causes. First, the reduced physical and mental workloads of steering could result in less recovery time between view movements. Decreased rest time, however, would reasonably be expected also to manifest as decreased mouse non-movement. Such a decrease was not found.

Second, shorter stops between view movements could reflect transfer of mental resources from steering to wayfinding, i.e., that subjects were able to make more decisions while moving. This explanation is supported by the increased likelihood of mouse movement during any single view move: Some of the increased mouse activity may be deliberate steering actions resulting from wayfinding decisions made during movement.

However, if increased overlap between steering and wayfinding were the sole explanation for shorter stops, the reduction in view non-movement time should be no greater than the reduction in view movement time: Assuming that the mental processing required for wayfinding is at least as complex as that required for steering, if N seconds of mental processing are freed from steering then at most N seconds of mental processing can be redirected to wayfinding. However, the reduction in View Non-Move Time (1.7 sec/100 SU) is greater than the reduction in View Move Time (1.1 sec/100 SU).

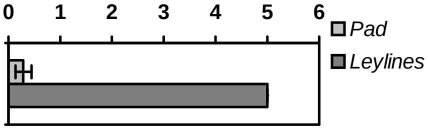


Figure 9 Mean number of trials (out of 5) completed in the Desert Fog experiment. t(23) = 31.57, p = 0.

Finally, shorter stops in view movement could be due to faster decision-making. This explanation is supported by the unanticipated decrease in mouse movement and the slower, more deliberate nature of mouse moves during view non-movement. These results suggest that were better spatially oriented with respect to the target and that they were therefore able to make decisions faster. Improved spatial orientation is also suggested by anecdotal and observational evidence: Subjects expressed feelings of being lost less frequently and exhibited less “marking” (pointing to inferred grid locations with the mouse) and “doodling” (e.g., moving the mouse in rapid circles) behavior while stopped in the CM condition. The Desert Fog experiment provides further evidence of improved spatial orientation: all subjects eventually lost spatial orientation in the FM condition, but were able to complete the task in the CM condition.

Thus, the data strongly suggest that subjects were making fewer incorrect decisions and were making decisions faster. Combined with qualitative and anecdotal evidence, they allow a guarded conclusion that CM reduced the mental workload of wayfinding. Although the data cannot show whether the required number of correct decisions have been reduced, they show that decisions have been made easier. Thus, of the three commonly cited components of mental workload—mental effort, the time load and psychological stress [3], mental effort has been reduced.

Finally, the data overwhelmingly support Prediction 8, in that all subjects reached all targets successfully in CM but not in FM. This supports the conclusion that the Lodestones and Leylines technique has altered the wayfinding task fundamentally.

FUTURE WORK

The present analysis has only considered behavioral data. Analysis of interactions between performance and other factors, such as sex, age and spatial ability, are underway. Additionally, other experiments are anticipated that examine the efficacy of CM with increased population density, interaction between CM and informational design, and the effect of CM on *spatial knowledge preservation*—the navigational subtask of preserving and retrieving spatial knowledge. Finally, of course, the generality of the present findings should be verified with other CM techniques.

CONCLUSIONS

The reported study examined the effects of constraining movement on the physical and mental workloads imposed by steering and wayfinding. It compared a distally constrained movement technique to free movement on a directed search task. The study comprised two experiments varying the amount of environmental information available. Results showed, conclusively, that the CM technique simplified the control of movement, reducing the physical and, presumably, the mental workload of steering. They also support a guarded conclusion that planning movement was simplified, reducing the mental workload of wayfinding.

The Lodestones and Leylines technique used for the study is one of the more sophisticated CM techniques proposed in the literature, in that it addresses destination selection as well as path selection and computation. Nonetheless,

Although Lodestones and Leylines is one of the more sophisticated CM techniques (in that it addresses destination selection as well as path selection and computation), the results of the study are expected to hold, in varying degrees, for other CM techniques. All CM techniques can be expected to reduce the physical and mental workloads of steering, although DCM techniques producing longer path segments may produce greater benefits. PCM techniques may simplify wayfinding decisions by eliminating options, but do not reduce the number of decisions, so can only be expected to produce small, if any, reductions in the mental workload of wayfinding.

Needless to say, the success of any CM technique depends on how closely it matches the needs of the task to be performed. The more irrelevant paths it eliminates, the greater the performance improvements. However, if any relevant or necessary paths are eliminated, all benefits are negated. It is thus critical not only to develop techniques for constraining movement, but also to understand how task needs can be employed in defining constraints. The present study shows that CM can yield substantial performance improvements and be a powerful means of reducing the cost of navigation.

ACKNOWLEDGEMENTS

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