Is Moving Improving?
Some Effects of Locomotion in Wall-Display Interaction

Mikkel R. Jakobsen & Kasper Hornbæk
Department of Computer Science, University of Copenhagen
Njalsgade 128, DK-2300 Copenhagen, Denmark
{mikkelrj, kash}@di.ku.dk

ABSTRACT
Physical movement plays an important role in interaction with wall-displays. Earlier work on its effect on performance has been inconclusive, however, because movement has not been experimentally controlled. In a first experiment, we controlled participants' ability to physically move in front of a 3-meter wide 24-megapixel wall-display. Participants performed a classification task involving navigation using a zoom-and-pan interface. Results suggest that the ability to move does not increase performance, and that a majority of participants used virtual navigation (i.e., zooming and panning) and little or no physical navigation (i.e., moving their bodies). To isolate the effects of physical and virtual navigation, a second experiment compared conditions where participants could navigate using either only physical movement or only virtual navigation. The second experiment showed that physical movement does benefit performance. The results from the experiments suggest that moving may not be improving performance, depending on the use of virtual navigation.

Author Keywords
Large display; wall-display; physical navigation; virtual navigation; user study

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces

INTRODUCTION
Physical movement plays an important role in interaction with high-resolution wall-displays. A key benefit of wall-displays is that they allow more information to be shown at the same time, thereby reducing the need for virtual navigation (e.g., zooming and panning). Users can physically navigate the display through *locomotion*. Previous research has concluded that locomotion increases performance in search and navigation tasks [2,5], and in classification tasks [17].

CHI 2015, April 18 - 23 2015, Seoul, Republic of Korea
Copyright 2015 ACM 978-1-4503-3145-6/15/04…$15.00
http://dx.doi.org/10.1145/2702123.2702312

The effects of locomotion in wall-display interaction and the reasons why locomotion may benefit interaction (e.g., through use of spatial memory [23] or other "embodied resources" [3]) are not well understood. In particular, we see two key concerns for current research. One concern is that most conclusions about physical navigation around wall-displays come from studies that do not experimentally control locomotion. In these studies, locomotion has resulted from an increase in display size, but increasing the display size may bring other benefits. For example, Liu et al. [17] found that a wall-display enabled users to reach targets at a distance without moving. Ball et al. [5], likely the most widely cited study on the idea that physical navigation increases performance, studied only correlations among performance and physical navigation, precluding any causal conclusions about the effects of locomotion. The extent to which locomotion contributes to performance thus remains unclear.

A second concern is that some empirical studies have used information spaces that fit on the display (e.g., [17]), where navigation can be done exclusively by locomotion, whereas others have used information spaces that do not fit on the display (e.g., [2]), requiring users to combine virtual and physical navigation. Work on navigating large information spaces suggests that these conditions lead to different behavior [13] and might also require users to use different strategies for navigation. Thus, comparing results is hard and muddles the picture of the benefits of moving.

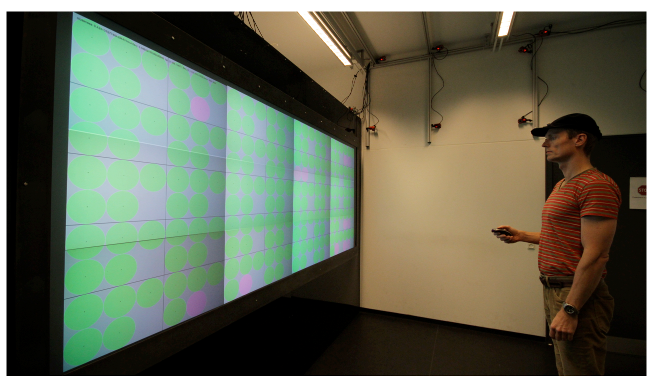


Figure 1: Participants in the experiments used a gyroscopic mouse for interacting with the wall-display, wearing a cap with markers used to track movement.

This paper investigates the effects of locomotion in wall-display interaction through two experiments. One experiment controls users' ability to move in front of a wall-display in order to examine the relative use of physical navigation and virtual navigation in a pan-and-zoom interface (see Figure 1). The experiment also varies the scale of information space used, thus manipulating the need for virtual navigation. A second experiment compares the relative performance of using either physical or virtual navigation. The results from these experiments show that users do not choose to use locomotion instead of virtual navigation in wall-display interaction, as previous research suggests, and that the performance effects of locomotion are small.

RELATED WORK

Physical movement of the body at a coarse scale (locomotion) is important in many user interfaces, including movement-based gaming [20] and virtual environments [24]. The present paper focuses on locomotion in interaction with large displays, extensively discussed in earlier work (e.g., [5,17]).

For large displays, locomotion may be beneficial because it can replace virtual navigation (e.g., with a mouse) with physical movement [2,5], because users may benefit from moving when working together on a shared task [14], and because users may step back to gain an overview and closer in order to view details or for direct interaction with touch displays. Next we discuss the technologies for supporting locomotion, the empirical studies of its effect, and some concerns about earlier work.

Input Technologies that Allow Users to Move

Some input options for large displays do not allow users to move in front of large displays, for instance, if they are using mouse or keyboard while seated at a desk. Although this use situation has been improved by using chair rotation [8] or having mouse and keyboard on a rolling stand [26], physical movement is nevertheless limited to head turning.

At least three approaches avoid tethering the user to a particular location and thus support locomotion. First, input devices such as a gyroscopic mouse [5], handheld devices [6,21,22], and tangibles [15] have been used as input.

Second, mid-air gestures with free hand movements have been explored. Nancel et al. [22] compared alternative mid-air pan-and-zoom techniques; they found two-handed linear gestures, using 1D or 2D movements on an input device instead of free-hand movements, to perform the best. Other mid-air techniques likewise allow users to move freely [18].

Third, research has explored using whole-body movements to navigate, where the locomotion is tracked and used as input [12,16,25]. For instance, Lehmann et al. implemented zooming based on zones of distance to the display and a lens based on gaze [16]. Research has used proxemics to exploit users' movement relative to other users or to devices in order to support interaction [9].

Empirical Studies of Locomotion

Independently of the above approaches, it remains an empirical question if locomotion benefits interaction. Ball and North [4] proposed that "physical navigation promotes higher order thinking, such as investigating data points that hold the most promise for solving a task, virtual navigation promotes more simplistic algorithmic strategies that are less efficient" (p. 16). The key benefits of locomotion seem to concern navigation performance, spatial memory, benefits contingent on display size, and input mode.

Locomotion may benefit *navigation*, in particular because users may rely less on virtual navigation. Ball and North studied peripheral vision and physical navigation [4]. They found that physical navigation had a positive effect on performance while peripheral vision did not. Ball and North [2] compared visualization and navigation tasks between displays consisting of 1, 3, and 9 tiled monitors. They concluded that larger displays that allow physical navigation perform better than smaller displays that use pan and zoom navigation. Ball et al. [5] compared performance in search and navigation tasks across different widths of a wall-display. Participants used a wireless gyromouse for zooming (with scroll wheel) and panning (by dragging the mouse). Results showed an increase in performance and physical navigation as display width increased. Increased virtual zooming was more strongly correlated with increased task time than was physical movement. Moreover, in tasks where virtual navigation was not required participants chose physical navigation over virtual navigation.

Spatial memory may also benefit from locomotion as opposed to virtual navigation. In virtual navigation with a tablet in front of a wall-display, Rädle et al. [23] found egocentric movement to improve navigation performance and spatial memory recall after a 15-minute distraction task.

The positive effects of locomotion also relate to *display size*. Liu et al. [17] compared physical navigation in front of a wall-display with virtual navigation using pan-and-zoom on a desktop display for a classification task. Participants could only navigate through movement in the wall-display condition (which fits all data) and through zoom-and-pan in the desktop condition. The input methods differed between the conditions: Participants used a mouse for manipulating data and for panning and zooming on the desktop display, but used a trackpad for controlling the cursor on the wall-display. Liu et al. found that a wall-display increased performance for more difficult classification tasks and for smaller labels that users could not read without navigation. Liu et al. pointed out that the wall-display enabled users to reach targets at a distance without moving while on the desktop they must pan and/or zoom. Andrews and North [1] found physical navigation on a large desktop-display to impact spatial organization for a sensemaking task, using a 17" display zoom-and-pan workspace as baseline for comparison. Shupp et al. [26] compared different display sizes with different curvatures. A curved wall-display performed faster than a flat. They observed that participants tended to do more rotational movements and less walking in the curved condition and more walking in the flat wall-display condition. Overall, these results show that the specific configuration of the large display may have different effects on performance.

The *input mode* used also shape locomotion. As mentioned, for wall-displays, such modes include free-hand gestures [27], input devices [6,21,22], tangible user interfaces [15], and whole-body movements for interacting with wall-displays [12,16,25]. Most work on using touch input for interacting with wall-displays has investigated indirect input through hand-held devices used in mid-air. Apart from studies of collaboration [14] and public displays [11], direct touch on wall-displays has been largely overlooked. This is curious, because touch-based interaction is familiar to most users and allows freedom of movement, except that the display has to be within reach of the user. The relation between physical movement and different input modes, including touch, remains unclear.

Two Concerns with Earlier Work

While the above empirical studies show benefits of locomotion, we raise two concerns about these findings: one about the experimental control of locomotion and one about the information spaces used in the studies.

Earlier studies of locomotion have treated it as a dependent variable, typically derived from tracking of users' movement (e.g., [4,5,17]). In these studies, physical movement is associated with an increase in display size, but increasing the display size may bring other benefits. Had locomotion been manipulated as an independent variable, then causal conclusions about its effect would have been possible. At the moment, though, mainly evidence about positive correlations between locomotion and performance [5] or spatial memory [23] exists.

The second concern is about the information spaces used in the studies mentioned above. The key take away from previous research is that reduced virtual navigation improves performance. However, even wall-sized displays may not always fit a large information space and users may want to view information at multiple scales. Most experiments have used information spaces that fit the largest display condition, which means that tasks have not required virtual navigation [2,17,28]. In studies of navigation techniques, a choice is whether to use tasks where data fit on the largest display condition or tasks where data do not fit [13], thus requiring virtual navigation also with a wall-display. Also, even if data fit on the wall-display, one can still support virtual navigation so that tasks can be completed without physical navigation.

Summary

Earlier work has shown various benefits of locomotion for interacting with large displays. It has not, however, experimentally controlled locomotion, nor has it explored the influence of information spaces of varying sizes that may or may not require virtual navigation. The experiments presented next aim to address those concerns.

EXPERIMENT 1: CONTROLLING PHYSICAL MOVEMENT

The first experiment investigated how physical movement affects performance by varying participants' ability to move. The ability to move was controlled by dimming the display if the participant's head moved outside of an allowed region.

Participants

Sixteen volunteers (5 female), 19–40 years old (M = 25.3, SD = 5.5), participated in the experiment. Their average height was 175cm (SD = 8cm). Participants were screened to have normal or corrected to normal vision. Participants were recruited by word of mouth and were provided the equivalent of €25 in compensation.

Apparatus

Participants used a 2.8m×1.2m display with 24 megapixels (see Figure 1). The bottom of the active display area is 89cm above the floor. The display consists of 4×3 tiles projected from the back by 1920×1080 projectors, manually aligned so as to minimize seams between tiles. The display is run by a single computer running Microsoft Windows 7. The room in which the display is set is 3.5m wide and the distance from the display to the back wall is 2.95m. Office ceiling light fixtures illuminate the room.

We used a NaturalPoint OptiTrack motion capture system (www.naturalpoint.com/optitrack/) for tracking the location and orientation of the participant's head via reflective markers attached to a baseball cap. Tracking had an average error around .5mm for each marker.

Participants used a Gyration Air Mouse Elite wireless gyromouse. The mouse pointer was enlarged and mouse acceleration in Windows 7 settings was set to maximum. We decided on a gyromouse for several reasons: it is designed for single-handed use; typical operations like pointing, zooming, and panning work similar to a normal mouse; and it has been used in previous work [5], thus allowing comparison. We decided against using a trackpad [17], which would require use of both hands. Free-hand mid-air techniques and touch are interesting alternatives that however would be less familiar to participants and would make the results harder to relate to earlier work.

Main Experimental Conditions: Allowing Movement

In the *Move* condition, participants could move freely. In the *NoMove* condition, the display was dimmed to black if the participant's head moved outside of an allowed region. The region was located 1.5m from the center of the display.

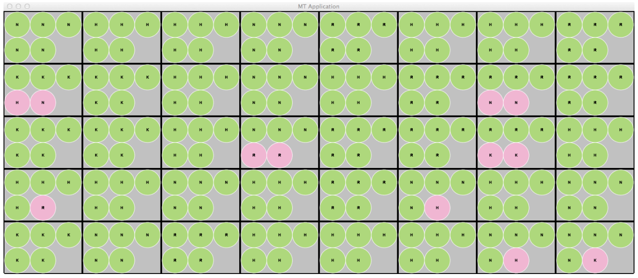


Figure 2: Display layout at the beginning of a task. Participants must move pink discs to their correct containers.

This distance was chosen to be far enough to ensure uniform luminosity in the back-projected image while retaining a wide field of view angle. The region covered a circular area with 40cm diameter, which was empirically defined to allow participants to comfortably turn their head and shift between standing poses. The display was gradually dimmed over 5cm so as to avoid abrupt changes. Also, when the display was dimmed a visual indicator appeared to guide the participant back to the allowed region. Although this control likely is artificial for participants, we found it preferable to alternatives such as fixing participants' head (which would be intrusive), physically constraining movement by fencing in the participant (which would allow leaning and therefore not as strict control), or having participants sit (which would impact comparison, e.g., with respect to fatigue). The display was dimmed at least once in 10% of the tasks (1.14 seconds per task on average for those tasks).

Task and Information Space

Participants performed the classification task described by Liu et al. [17]. We chose this task because it involves a combination of search, navigation, and manipulation of data. For each task the display shows a scene consisting of 40 containers arranged in an 8×5 matrix. Each container fits six labeled items represented as discs. Items are labeled according to class. The task requires participants to move items between containers so that each container holds items of the same class. Correctly and incorrectly classified items are green and pink, respectively; colors were chosen to be safe to color blindness. Figure 2 shows an example task.

Tasks begin with a layout of containers holding five items each. Twelve incorrectly classified items are evenly distributed across classes, but randomly distributed among containers: Four containers hold two incorrect items and four other containers hold one incorrect item. We generated a random layout for each task that satisfied a similar constraint as in Liu et al. [17].

Task difficulty: Number of classes

Items are labeled according to class. The number of classes was varied in order to vary the level of difficulty: *Easy* (two classes labeled “C” and “D”) and *Hard* (four classes labeled “H”, “K”, “N”, and “R”). The difficulty affects how much of the information space needs to be searched for the correct container. The average distance between an incorrectly classified item and the closest suitable container is between 1.2 and 1.4 for Easy tasks and between 2.4 and 2.6 for Hard tasks (distance calculated as the Euclidian distance between containers, where the distance between two adjacent containers is 1). Thus, more difficult tasks are expected to require more navigation.

Scale of the information space (Label size)

The scale of the information space also influences the need for navigation. We varied the scale of the information space by using different font sizes and thus control the level of navigation needed to read labels, similar to the approach of Liu et al. [17]. Legibility may be limited not only by distance to the display, but also by other factors such as viewing angle and not least display resolution: For very small font sizes, reducing the distance does not make text readable and virtual navigation is required. We therefore determined font sizes empirically so as to control the need for virtual navigation in both movement conditions. We used font sizes varying from 4pt to 32pt (letter size varying from 1mm to 9mm in height). Larger-scale information spaces contain higher levels of detail, with labels in a smaller font size. The levels are as follows:

- *Large-scale (4pt)* is not readable, regardless of the viewing distance, unless zoomed to at least 1.5× magnification. Virtual navigation is therefore always required, in both Move and NoMove conditions—participants cannot complete the task by physical navigation alone.
- *Medium-scale (8pt)* is readable from around 1m distance or closer to the display. The task can therefore be completed through physical navigation alone in the Move condition, but requires virtual navigation in the NoMove condition.
- *Small-scale (32pt)* can be read without navigation in both Move and NoMove conditions when the participant is standing in the starting position (the allowed region in the NoMove condition). This level therefore acts as a control condition. Letters at this scale have the same size at 1× magnification as letters of Large-scale at 8× magnification.

Interface

Participants pan and zoom the display content (the groups of items) using the mouse. To pan the user clicks and drags the mouse opposite the panning direction. The user scrolls the mouse wheel forward to zoom in and backward to zoom out. Each notch on the mouse wheel changes magnification by 25% and it is possible to zoom from highest to lowest level in one scrolling motion of the mouse wheel. The mouse cursor is used as the center of zooming. Zooming is constrained between the lowest level of 8× magnification and the highest level at which all containers fit the display. Each task starts with all contents shown (1× magnification).

Participants manipulated discs as described by Liu et al. [17], except that they click on a disc to highlight it; a second click moves the disc to another container (or leaves it in its original position if the clicked container is full).

Design

A within-subjects design was used in which the ability to move (Move, NoMove), scale (Small, Medium, Large), and task difficulty (Easy, Hard) were varied. Participants completed 12 tasks for each movement condition, the order of which was systematically varied across participants. Participants performed two tasks for each combination of label size × task difficulty, the order of which was systematically varied using a Latin square in order to reduce learning effects. In all, this resulted in 16 (participants) × 2 (movement conditions) × 3 (label sizes) × 2 (levels of difficulty) × 2 (repetitions) = 384 task trials.

Procedure

Participants were first given an introduction to the experiment. The interface and the task were explained to them. Participants first used the display while moving freely: they performed three training tasks in the Move condition, first using a Medium-scale information space in which they were encouraged to move in front of the display, moving closer to read the labels, etc. This was followed by three tasks in the NoMove condition. After the introduction, participants completed two blocks of 12 tasks, one block for each of the movement conditions. Participants were told before each of the two blocks whether they could move. To begin a task, participants had to stand in the starting position 1.5m from the center of the display and click a button on the screen, whereby the groups of items were presented. After completing all tasks in a movement condition, participants were administered a questionnaire with four questions from NASA TLX [10] asking about mental demand, physical demand, effort, and frustration. After completing all tasks, participants were asked about performing tasks in each of the conditions. We probed for reasons if they had not moved much. We explicitly asked whether it was clear if they could move or not; none of the participants were confused about the conditions. The experiment lasted around 75 minutes for each participant.

Hypotheses

Tasks can be solved using virtual navigation in both Move and NoMove conditions. However, previous research raises several expectations about how participants would use, prefer, and benefit from locomotion compared to virtual navigation:

H_1: The wall-display affords physical navigation: participants will move, if allowed to, when solving the tasks. This hypothesis is based on previous research that has found wall-displays to afford physical navigation [5,17].

H_2: Participants choose locomotion over virtual navigation in the Move condition. Ball et al. [5] found that when virtual navigation is not required and users have a choice to either virtually navigate or physically navigate, they prefer to physically navigate. Also, Liu et al. [17] found that participants moved even for tasks that could be completed without any navigation.

H_3: Participants perform better in the Move condition where they can physically navigate. An increase in physical navigation (and a decrease in virtual navigation) has been correlated with an increase in performance [5].

Results

We performed a 2 (movement) × 3 (scale) × 2 (difficulty level) repeated measures analysis of variance on the task completion times and virtual navigation actions ($N = 384$).

Performance

Surprisingly, we found no main effect for movement, $F(1, 15) = 1.69$, ns. H_3, which states that physical movement results in better performance in the Move condition (M = 101s, SD = 63s) compared to the NoMove condition (M = 105s, SD = 63s), is not supported. The benefit of movement might depend on level of difficulty and the scale of information space (label size), as can be seen in Figure 3, which shows mean task completion times for the different conditions. We found main effects for both label size, $F(2, 30) = 83.9$, $p < .001$, and for difficulty, $F(1, 15) = 87.3$, $p < .001$. However, no interaction was found between neither movement and scale, nor movement and difficulty.

Locomotion

We analyzed participants' locomotion to find a possible explanation for the lack of difference in performance between the two movement conditions. We computed the length of participants' movement paths (from tracking their head) filtered using the Douglas-Peucker algorithm [7] with

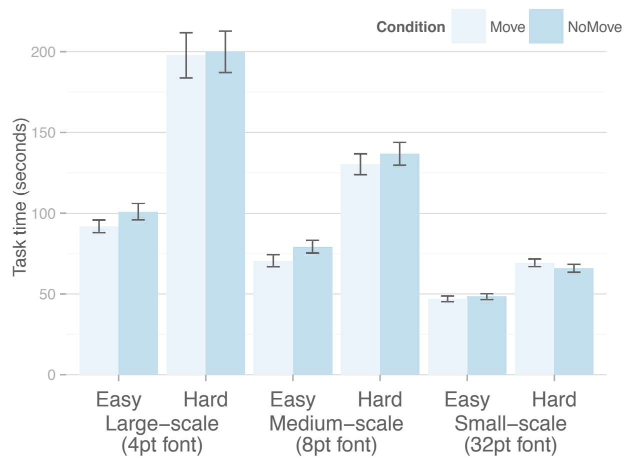


Figure 3: Mean task completion times for Move and NoMove condition across different levels of difficulty (Easy, Hard) and scale of information space (Large-scale, Medium-scale, Small-scale). Error bars show standard error of the mean.

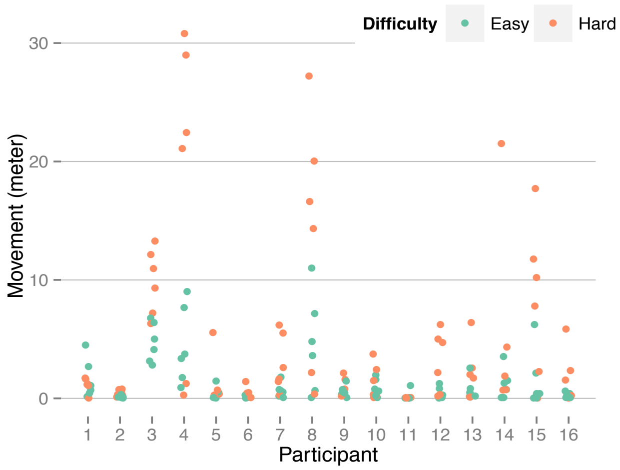


Figure 4: Locomotion in meters per task (all tasks, each represented as a point) for each participant.

a 10cm tolerance. The tolerance level was set so as to give an overall low measure of locomotion (M = 0.3m) in the NoMove condition—ideally this measure should be zero since participants were restricted from locomotion.

In the Move condition, participants moved 2.9m on average (SD = 5.4m) per task, so the display did afford physical navigation, giving support for H_1. However, there was great variation in locomotion across participants, see Figure 4. Five participants moved much (3.0m – 10.9m), whereas the others moved little or not at all (.1m – 1.8m). It seems participants either chose to use locomotion (and did so extensively for many of the tasks, e.g., participants 3, 4, 8, 15), or to not move at all (e.g., participants 2, 6, 11). Figure 4 shows examples of locomotion in a two Large-scale tasks for one of the participants that moved the most.

Participants moved more for Hard tasks (M = 4.4m, SD = 6.0m) than Easy tasks (M = 1.4m, SD = 2.2m) and moved more for Large-scale (M = 4.4m, SD = 6.5m) and Medium-scale spaces (M = 3.4m, SD = 6.0m) than Small-scale spaces (M = 0.9m, SD = 1.8m) that require no navigation.

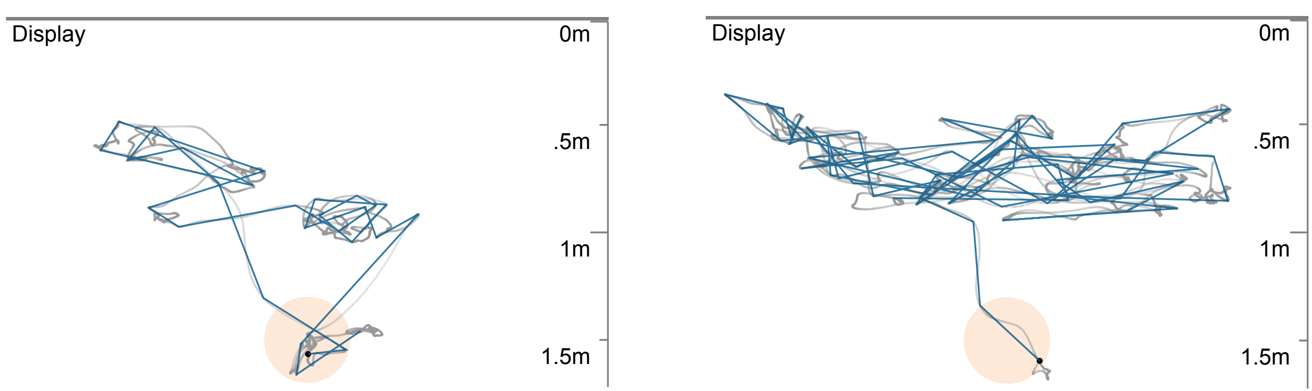
	Zoom		Pan	
	Move	NoMove	Move	NoMove
Average	14	15	22	28
Difficulty				
Easy	9	10	12	18
Hard	19	20	32	38
Scale				
Large	28	30	41	50
Medium	14	14	20	28
Small	0	1	4	5

Table 1: Average number of virtual navigation actions performed in each task for the Move and NoMove conditions.

Virtual navigation

The two movement conditions required participants to use the mouse for navigating to varying extent, as can be seem from Table 1, which summarizes zoom and pan actions performed across the different conditions (consecutive scrolling events using the mouse wheel in the same direction, with less than 1s in between events, count as one zoom action). We found a main effect of scale on the number of zoom actions, $F(2, 30) = 48.6$, $p < .001$, and pan actions, $F(2, 30) = 9.44$, $p < .001$. The number of navigation actions performed increase as the information space increase in scale (smaller label sizes). We also found a main effect of difficulty on number of zoom actions, $F(1, 15) = 36.3$, $p < .001$, and pan actions $F(1, 15) = 10.0$, $p < .001$. Harder tasks required more navigation actions. Small-scale tasks required no actions, yet participants panned the view 4-5 times on average in both conditions—these are likely accidental panning actions where participants actually wanted to pick or drop an item.

We expected that the ability to move would offset the need for virtual navigation (H_2), but this was only partly the case: No main effect was found for movement condition on the number of zoom actions performed, $F(1, 15) = 3.72$, p = .07, or on pan actions, $F(1, 15) = 3.76$, $p = .07$. Participants tended to do more panning actions, and panning across a larger distance, in the NoMove condition (M = 27.6, 42012 pixels panned in motor space) than in the Move condition (M = 21.9, 50089 pixels).



(a) Participant 4, Task 8 (Large-scale, Easy), 9 meters

(b) Participant 4, Task 11 (Large-scale, Hard), 29 meters

Figure 5: Movement path of two tasks. Blue paths show data filtered using the Douglas-Peucker algorithm with a 10cm tolerance, which measure 9m and 29m, respectively; gray paths show the logged data points. The orange circle indicates the starting position.

	Move			NoMove		
	Large	Med	Small	Large	Med	Small
1×	11%	25%	98%	10%	17%	100%
2×	17%	50%	2%	16%	55%	0%
3×	39%	23%	0%	33%	22%	0%
4×	25%	1%	0%	24%	6%	0%
5×	6%	0%	0%	12%	0%	0%

Table 2: Time spent at different magnification levels for the Move and NoMove conditions and for different scales of information space (label size). Time spent at the 6 – 8× magnification levels accounted for less than 2% for Move and 4% for NoMove.

Participants spent time at different magnification levels, determined mainly by the scale of the information space (see Table 2). For Small-scale, no zooming was required, whereas more time was spent at higher magnification levels for Medium-scale and still higher levels for Large-scale. However, this did not vary between Move and NoMove conditions. When allowed to move, participants could have move closer in order to reduce the amount of magnification required through zooming, but they did not—not even for the Medium-scale information space for which virtual navigation could be completely replaced by locomotion. The affordance of physical navigation did therefore not appear to offset the need for virtual navigation.

Subjective satisfaction

The average of the TLX questions suggests differences between the movement conditions, $F(1, 15) = 5.15$, $p < .05$. Individual analysis of variance suggests significance only for the question about physical demand: the Move condition was rated as less physically demanding (M = 2.81, SD = 1.47) than the NoMove condition (M = 3.75, SD = 1.34). In comments after the experiment, seven participants said that it was quite tiring to have to hold the same posture (e.g., "tiring to stand still") and not move just a little bit. However, eight participants emphasized that even when they were allowed to move, they did not (e.g., it was "easier to stay in the same place").

Summary

Participants did not solve tasks faster when they could navigate using locomotion (H_3). Our data could not confirm the positive relation between increased physical movement and task performance found in earlier work [5,17].

The display afforded physical navigation (H_1), but did it promote physical navigation (H_2)? Not really. It seems participants to a large extent preferred virtual navigation over locomotion. Only five participants used locomotion extensively to navigate. We do, however, note that the participants generally used and express satisfaction with moving, such as leaning closer to better be able to read text. Also, participants used a large amount of virtual navigation, even those that also used locomotion. This runs counter to earlier findings of significant decreases in virtual navigation when users can physically navigate.

EXPERIMENT 2: PHYSICAL VS. VIRTUAL NAVIGATION

One key difference between Experiment 1 and earlier work is that we included information spaces that did not fit the display and required virtual navigation also in the Move condition (e.g., Liu et al. [17] fitted data on the wall-display, whereas Ball et al. [5] required semantic zooming in all conditions). Because participants thus used physical and virtual navigation in combination, we do not know how participants would perform if navigating only by locomotion or navigating only by zooming and panning using a mouse. Perhaps participants in the first study performed in a way that resulted in less than optimal performance, for instance by using virtual navigation when locomotion would have been faster. To investigate this, we conducted a second experiment in which we manipulate whether participants could use *either* physical navigation *or* virtual navigation, but not both, for solving the tasks.

Participants

Ten volunteers (4 female), 18–32 years old, participated in the experiment. Their average height was 174cm (SD = 7cm). Participants were screened to have normal or corrected-to-normal vision. Participants were recruited by word of mouth and compensated the equivalent of 25€.

Design

The experimental design was similar to that used in Experiment 1. The conditions used, *Physical* and *Virtual*, were similar to the Move and NoMove conditions, respectively, except that participants in the Physical condition could not zoom and pan using the mouse, but only navigate through locomotion; in the *Virtual* condition, participants could zoom and pan with the mouse, but were kept from physically moving by dimming the display if they moved outside of an allowed region. Another difference is that tasks that used a small-scale information space (4pt font) were excluded, because they can only be completed with the use of virtual navigation.

A within-subjects design was used in which the type of navigation (Physical, Virtual), scale (Medium, Large), and task difficulty (Easy, Hard) were varied. For each navigation type, participants completed eight tasks—two for each combination of label size × task difficulty. In all, this resulted in 10 (participants) × 2 (navigation types) × 2 (scales) × 2 (levels of difficulty) × 2 (repetitions) = 160 task trials.

The hypothesis was that participants would perform better in the Physical condition than in the Virtual condition.

Interface

The interface used was the same as in Experiment 1, except that the mouse-functionality for zooming and panning the view was disabled in the Physical condition; participants could still select and move items, necessary for completing the task.

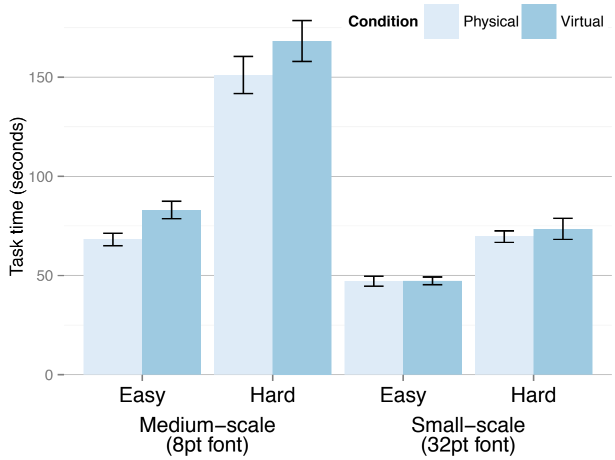


Figure 6: Mean task completion times for the Physical and Virtual navigation conditions across levels of difficulty (Easy, Hard) and scale of information space (Medium-scale, Small-scale). Error bars show standard error of the mean.

Procedure

The procedure was as in the first experiment. The experiment lasted around 45 minutes per participant.

Results

We performed a 2 (navigation type) × 2 (scale) × 2 (difficulty level) repeated measures analysis of variance on the task completion times ($N = 160$).

Performance

We found a main effect of navigation type, $F(1, 9) = 7.29$, $p < .05$, $\eta^2 = .04$. The hypothesis was supported: Participants completed tasks faster using Physical navigation (M = 84s, SD = 46s) than using Virtual navigation (M = 93s, SD = 53s), although the effect size is low. Mean completion times for different levels of difficulty and scale of information space can be seen from Figure 6. We found main effects of scale, $F(1, 9) = 145.2$, $p < .001$, $\eta^2 = .64$, and difficulty, $F(1, 9) = 100.2$, $p < .001$, $\eta^2 = .60$. There was a marginal interaction between the navigation type and scale of information space, $F(1, 9) = 4.85$, $p = .055$, $\eta^2 = .02$. As expected, participants performed tasks equally fast using physical and virtual for small-scale information spaces where there was no need for navigation. In contrast, for medium-scale spaces participants were slower using virtual navigation (M = 126s, SD = 56s) than using physical navigation (M = 110s, SD = 52s).

	Exp. 2, Physical			Exp. 1, Move		
Small-scale	Easy	Hard	*M*	Easy	Hard	M
M	0.7m	1.7m	1.1m	0.5m	1.3m	1.0m
SD	(0.6)	(1.7)	(1.3)	(0.8)	(2.3)	(1.5)
Medium-scale						
M	6.7m	23.8m	15.2m	1.5m	5.2m	3.3m
SD	(3.1)	(8.8)	(10.8)	(1.9)	(7.9)	(6.1)

Table 3: Locomotion in the Physical condition and the Move condition (experiment 1) for comparison.

Locomotion vs. Virtual Navigation

Participants in the Physical condition moved 8.23m (SD = 10.41m) on average per task. This is noticeably more than in the Move condition of the first experiment (M = 2.9m, SD = 5.4m), likely because participants used both physical and virtual navigation in the Move condition. The amount of movement across task conditions is shown in Table 3, compared to the Move condition in Experiment 1. Participants moved more for Medium-scale than Small-scale, and they moved more for Hard than Easy tasks.

Participants could only use virtual navigation in the Virtual condition. Table 4 summarizes the number of zoom and pan actions performed across the different task conditions. Participants did as much virtual navigation as in Experiment 1 (cf. Table 1). For Medium-scale, participants zoomed 14 times on average, similar to the NoMove condition in Experiment 1, and they panned 23 times on average, compared to 20 times in the NoMove condition.

Subjective Satisfaction

We found no difference for the reported workload values, $F(1, 9) = .53$, ns. Participants were also split in their preference for the navigation types: six preferred physical navigation, three preferred virtual, one preferred a combination. One factor that shapes these preferences is the ability to keep an overview; three participants said this was a benefit of physical (e.g., "easier to keep the big picture") and a drawback of virtual navigation (e.g., "the overview is lost"). Another factor was movement, which four participants said required excessive effort.

Summary

We have found a clear difference in performance between physical navigation and virtual navigation using a mouse to zoom and pan by experimentally controlling participants' ability to use *only* physical *or* virtual navigation. The results provide evidence supporting earlier work [5,17] that has shown that physical navigation can have a positive, if small, impact on performance.

DISCUSSION & CONCLUSION

The purpose of this paper has been to investigate the use of locomotion for interaction with large displays and its effect on task performance. The key findings of the two experiments can be summarized as follows:

(a) Locomotion does not seem to improve performance when users can choose to virtually navigate (or when the scale of the information space requires them to).

	Zoom			Pan		
	Easy	Hard	*M*	Easy	Hard	*M*
Medium	9	19	14	11	35	23
Small	1	0	1	3	5	4
M	5	10	7	7	20	13

Table 4: Mean number of virtual navigation actions for each task in the Virtual condition.

(b) Physical navigation is not preferred over virtual navigation, neither in behavior nor in stated preferences.

(c) Locomotion seems to improve performance when users could not use virtual navigation, that is, when the information space fit the display.

Differences to Earlier Work

Our findings contrast those of earlier work, in particular the studies by Ball et al. [5] and by Liu et al. [17]. Ball et al. [5] concluded that "larger displays lead to more physical navigation, which reduces the need for virtual navigation, which offers improved user performance" (p.199). We cannot comment on the first step of this inference, as we did not manipulate display size. However, the last two steps are not consistent with our findings. Although participants in Experiment 1 used physical navigation, there was no significant difference in the amount of zooming and panning they did compared to that in the condition that prevented them from navigating physically. Perhaps for that reason, physical navigation did not lead to improved performance.

Liu et al. [17] compared physical and virtual navigation indirectly because their main focus was on comparing wall-size displays (which allowed only physical navigation) with desktop (which had only virtual navigation). They reported an interaction with task difficulty so that desktop is more efficient for easy tasks whereas the wall is more efficient for hard tasks. In some parts of their paper, Liu et al. attribute this difference to navigation (e.g., "Experiment 1 showed a strong performance advantage of physical navigation on a wall-size display when compared with pan-and-zoom navigation on a desktop interface for difficult classification tasks", p. 4155). Our Experiment 2 suggests an advantage of physical navigation for the same task, which is not contingent on a large difference in display size.

What might be behind the differences between our experiments and earlier work? Several factors vary between our paper and the work of Ball et al. and Liu et al., including:

- *Experimental Design*. A key difference to Ball et al. [5] and Liu et al. [17] is that we experimentally manipulated locomotion and isolated it from display size. The artificial control of telling people not to move might influence their behavior throughout the experiment (e.g., they may be unsure if they are allowed to move in the Move condition). However, we got not such indications when probing participants and find it unlikely to have had much effect.
- *Display Characteristics.* With regard to size, the display in the present study is comparable in width to that used by Ball et al. [5], but only around half the width of the display used by Liu et al. [17]. Participants did not move for large label sizes, as participants in the study by Liu et al. did. Because their display is almost twice as wide as the one used in this study, it requires a larger field of view. Perhaps our display width better accommodates a sweet spot in field of view, whereas wider displays require movement?
- *Room Characteristics.* Ball et al. commented that a key factor in encouraging physical navigation was that there was "large physical space for range of motion" (p. 199). The room the experiments were set in was smaller than that of Liu et al. and possibly also to that of Ball et al. (though it is not clear from their paper). However, in the sample plots of movement provided by Liu et al. ([17], p. 4153), participants seem to not back up more than 2.5m, less than the space available in front of the display in the present study.
- *Task.* Our experimental task differs from that of Ball et al. [5]. They emphasized that physical navigation was useful to users for scanning large amounts of information at multiple levels of scale. The task proposed by Liu et al., which we also used, asks participants to use information at one level of detail only. If the task were extended to include classification at several scales (e.g., hierarchies of containers), that might promote multi-scale navigation, with different physical navigation behavior to follow.
- *Size of information space.* Only in our Experiment 2 did we find a performance benefit of physical navigation. However, the benefit of physical navigation is tied to the information space being of a scale so that it fits the display, a precondition of most of earlier research that shows benefits of physical navigation. In fact, when given the means to virtually navigate participants did not use physical navigation to significant advantage (Experiment 1).

Open Questions

We have investigated a classification task, which requires participants to inspect and move objects. Thus, locomotion may have several other benefits that we have not discussed. For instance, Rädle et al. [23] looked at memory in large display navigation and found a benefit of egocentric movement.

Earlier work has manipulated display size (e.g., desktop vs. wall [17], columns of display [5]). Obvious future work is to include display size as a parameter. This would allow a better understanding of the difference to in particular the work of Liu et al. [17], where both display size and navigation type were manipulated.

Some forms of input affect movement patterns more than the use of a gyro-mouse, used in the present study. Touch on wall-displays are rarely studied (though see [14]), and affect physical movement by requiring users to move to the display to touch. Touch may, however, be combined with other techniques, such as mid-air gestures [19], which might completely change the interplay of physical and virtual navigation. We see a need to study this.

ACKNOWLEDGEMENTS

This work has been supported in part by the Danish Council for Strategic Research under grant 10-092316. We thank Dan-Adrian Avram for his assistance with the experiments and the reviewers for helping us improve this paper.

REFERENCES

1. Andrews, C. and North, C. The Impact of Physical Navigation on Spatial Organization for Sensemaking. *IEEE TVCG 19*, 12 (2013), 2207–2216.
2. Ball, R. and North, C. Effects of tiled high-resolution display on basic visualization and navigation tasks. *CHI extended abstracts*, ACM (2005), 1196–1199.
3. Ball, R. and North, C. Visual Analytics: Realizing embodied interaction for visual analytics through large displays. *Comput. Graph. 31*, 3 (2007), 380–400.
4. Ball, R. and North, C. The effects of peripheral vision and physical navigation on large scale visualization. *Proc. GI*, Canadian Information Processing Society (2008), 9–16.
5. Ball, R., North, C., and Bowman, D.A. Move to improve: promoting physical navigation to increase user performance with large displays. *Proc. CHI*, ACM (2007), 191–200.
6. Baudisch, P., Sinclair, M., and Wilson, A. Soap: A Pointing Device That Works in Mid-air. *Proc. UIST*, ACM (2006), 43–46.
7. Douglas, D. and Peucker, T. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *Cartographica 10*, 2 (1973), 112–122.
8. Endert, A., Fiaux, P., Chung, H., Stewart, M., Andrews, C., and North, C. ChairMouse: leveraging natural chair rotation for cursor navigation on large, high-resolution displays. *CHI extended astracts*, ACM (2011), 571–580.
9. Greenberg, S., Marquardt, N., Ballendat, T., Diaz-Marino, R., and Wang, M. Proxemic interactions: the new ubicomp? *interactions 18*, 1 (2011), 42–50.
10. Hart, S.G. and Staveland, L.E. Development of NASA-TLX: Results of empirical and theoretical research. *Human Mental Workload*, Elsevier (1988), 139–183.
11. Jacucci, G., Morrison, A., Richard, G.T., et al. Worlds of information: designing for engagement at a public multi-touch display. *Proc. CHI*, (2010), 2267–2276.
12. Jakobsen, M.R., Haile, Y.S., Knudsen, S., and Hornbæk, K. Information Visualization and Proxemics: Design Opportunities and Empirical Findings. *IEEE TVCG 19, 12* (2013), 2386-2395.
13. Jakobsen, M.R. and Hornbæk, K. Interactive Visualizations on Large and Small Displays: The Interrelation of Display Size, Information Space, and Scale. *IEEE TVCG 19*, 12 (2013), 2336–2345.
14. Jakobsen, M.R. and Hornbæk, K. Up Close and Personal: Collaborative Work on a High-resolution Multitouch Wall Display. *ACM Trans. Comput.-Hum. Interact. 21*, 2 (2014), 11:1–11:34.
15. Jansen, Y., Dragicevic, P., and Fekete, J.-D. Tangible remote controllers for wall-size displays. *Proc. CHI*, ACM (2012), 2865–2874.
16. Lehmann, A., Schumann, H., Staadt, O., and Tominski, C. Physical navigation to support graph exploration on a large high-resolution display. *Proc. AVI*, Springer-Verlag (2011), 496–507.
17. Liu, C., Chapuis, O., Beaudouin-Lafon, M., Lecolinet, E., and Mackay, W.E. Effects of Display Size and Navigation Type on a Classification Task. *Proc. CHI*, ACM (2014), 4147–4156.
18. Markussen, A., Jakobsen, M.R., and Hornbæk, K. Vulture: A Mid-air Word-gesture Keyboard. *Proc. CHI*, ACM (2014), 1073–1082.
19. Marquardt, N., Jota, R., Greenberg, S., and Jorge, J.A. The continuous interaction space: interaction techniques unifying touch and gesture on and above a digital surface. *Proc. INTERACT*. Springer, 2011, 461–476.
20. Mueller, F. and Isbister, K. Movement-based Game Guidelines. *Proc. CHI*, ACM (2014), 2191–2200.
21. Nancel, M., Chapuis, O., Pietriga, E., Yang, X.-D., Irani, P.P., and Beaudouin-Lafon, M. High-precision Pointing on Large Wall Displays Using Small Handheld Devices. *Proc. CHI*, ACM (2013), 831–840.
22. Nancel, M., Wagner, J., Pietriga, E., Chapuis, O., and Mackay, W. Mid-air pan-and-zoom on wall-sized displays. *Proc. CHI*, ACM (2011), 177–186.
23. Rädle, R., Jetter, H.-C., Butscher, S., and Reiterer, H. The Effect of Egocentric Body Movements on Users' Navigation Performance and Spatial Memory in Zoomable User Interfaces. *Proc. ITS*, ACM (2013), 23–32.
24. Ruddle, R.A., Volkova, E., and Bülthoff, H.H. Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Trans. Comput.-Hum. Interact. 18*, 2 (2011), 10:1–10:20.
25. Shoemaker, G., Tsukitani, T., Kitamura, Y., and Booth, K.S. Body-centric interaction techniques for very large wall displays. *Proc. NordiCHI*, ACM (2010), 463–472.
26. Shupp, L., Andrews, C., Dickey-Kurdziolek, M., Yost, B., and North, C. Shaping the Display of the Future: The Effects of Display Size and Curvature on User Performance and Insights. *Human-Computer Interaction 24*, 1 (2009), 230–272.
27. Vogel, D. and Balakrishnan, R. Distant Freehand Pointing and Clicking on Very Large, High Resolution Displays. *Proc. UIST*, ACM (2005), 33–42.
28. Yost, B., Haciahmetoglu, Y., and North, C. Beyond visual acuity: the perceptual scalability of information visualizations for large displays. *Proc. CHI*, ACM (2007), 101–110.