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Insights from Dividing 3D Goal-Directed Movements into Meaningful Phases

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A new method for analyzing 3D goal-directed movements provides more insights than existing approaches by dividing them into meaningful phases. An experiment applying a simple 3D task, resembling a standardized 2D multidirectional pointing task, yielded insights that can help researchers better identify input devices' and interaction techniques' strengths and weaknesses.

Most computer interactions occur via a direct manipulation interface, also called a WIMP (window, icon, menu, pointing device) interface. The most obvious way to improve human-computer interaction is to create specialized input devices and interaction techniques to use in combination with WIMP interfaces. A more challenging approach is to develop new interfaces with interaction styles more closely related to real-world interactions—also called post-WIMP interfaces. For example, mixed-reality environments, which combine tangible and virtual interaction, offer great opportunities for creating more intuitive forms of interaction. These interaction styles are more intuitive because they let people apply their existing skills by interacting with everyday objects.[1] However, this in itself doesn't guarantee improved performance; we need systematic ways to establish new interaction techniques' performance.

Several methods exist for evaluating 3D input devices and interaction techniques, most of which are fairly subjective—for instance, cognitive walkthroughs, heuristic evaluations, or preference questionnaires.[2] A more objective way to investigate performance is to observe the movements people carry out while interacting. One way to do this is by collecting and analyzing movement trajectories. We will show that dividing 3D goal-directed movement trajectories into distinct phases and characterizing these phases will provide better insight into how interaction movements are actually performed.

3D Interaction Movements

In studies focusing on 2D interactions, researchers observe characteristics of interaction movements during the execution of basic tasks such as pointing, selecting, or steering. These standardized tasks are also included in an ISO standard (ISO 9241-9, Ergonomic Requirements for Office Work with Visual Display Terminals). Most common tasks employed in 3D-interaction research deal with navigation and manipulation. Too many of these tasks, however, are tailored to the devices and techniques under development and certainly aren't standardized yet,[3-5] so comparing devices remains difficult. Another problem we experienced is that existing 3D tasks don't necessarily induce goal-directed movements, so interpreting them can be difficult.

To get people to make rapid aimed movements, we designed a 3D multidirectional pointing task that resembles the ISO 9241-9 pointing task.[6] This task also resembles Robert Teather and his colleagues' recently proposed positioning task.[7]

Both the 3D pointing task and the method used to analyze the resulting movements require careful consideration. Until now, studies comparing the performance of 3D input devices or interaction techniques have focused mostly on overall characteristics such as movement time, through-

put, and error rate.[3–5,7] Such overall measures can reveal differences in performance between input devices and interaction techniques but don't provide much insight into the factors responsible for these differences. To draw more meaningful conclusions from interaction movements, we must look at these movements in more detail.
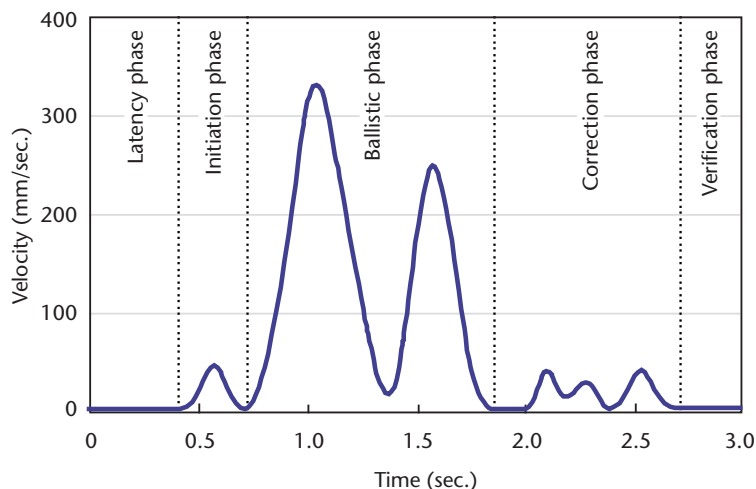
Movement Phases

As far back as 1899, Robert Woodworth published a model of aimed movements that divides them into two components.[8] According to this model, rapid aimed movements consist of an initial impulse or ballistic phase and a perceptually guided final control or correction phase. The ballistic phase is programmed to reach the target, and the unintended errors are corrected during the correction phase using sensory feedback. This division is a first step to providing more detailed insight into interaction movements.

We conducted a preliminary study to determine whether Woodworth's model can adequately describe movements produced in 3D environments and, if so, whether this division can provide insight into how 3D goal-directed movements are performed under different conditions.[6] This study demonstrated the potential of analyzing movements in more detail; for example, it showed different learning effects during the two phases for real-world environment and virtual environment interaction. However, we'll show that we can draw more information from this data than we did in our previous study.

The division into two components already provides more insight into goal-directed movements than an overall movement analysis. Many velocity profiles of rapid aimed movements, however, revealed more phases besides the ballistic and correction phases. This is supported by Neff Walker and his colleagues,[9] who claimed that two other phases exist—an initiation phase and a verification phase. From this assumption and our study of many velocity profiles, we concluded that we could robustly distinguish five phases: latency, initiation, ballistic, correction, and verification (see Figure 1).[10] The latency phase starts when the task is set and ends when the actual movement starts. The initiation phase consists of small movements made before the ballistic phase. The verification phase starts when the movement ends and stops when the task is finished (for instance, when someone selects a target by pressing a button).

Movement Parsing

To robustly divide movements into these five phases,

we developed new parsing rules. First, we filter the noisy position data as a function of time, because taking derivatives of noisy signals, which we'll need for the analysis, easily gives rise to spurious details. We use a Gaussian time filter with a standard deviation of 25 ms, which is comparable to the 7-Hz low-pass filter proposed in earlier studies.[11]

Next, we identify the interval in which actual movement occurs, leading to a latency phase at the start and a verification phase at the end, where no significant movement occurs (operationally, we select the interval in which the first and last 3 mm of the path are traversed, respectively). We then divide the interval between the latency and verification phases into distinct movement intervals. These intervals are separated by pauses in which the pointer doesn't move or moves only minimally (the speed remains below 0.05 times the movement's peak speed). We determine whether each identified movement interval makes a considerable contribution to approaching the target. If the path length crossed during a movement interval is more than 25 percent of the total path length, we consider it part of the ballistic phase.

We divide the identified movement intervals into submovements using criteria from David Meyer and his colleagues.[11] One reason to do this is to provide a more detailed description of the movement performance. We also use this division to determine whether the last movement interval of the ballistic phase contains some corrective submovements at the end.

We adjusted Meyer's criteria to apply them to velocity profiles based on path length:

- A type-1 submovement starts when the speed increases from zero to a value that's above 0.05 times the movement's peak speed (start of movement interval).
- A type-2 submovement occurs at a zero-crossing of acceleration from negative to positive (in
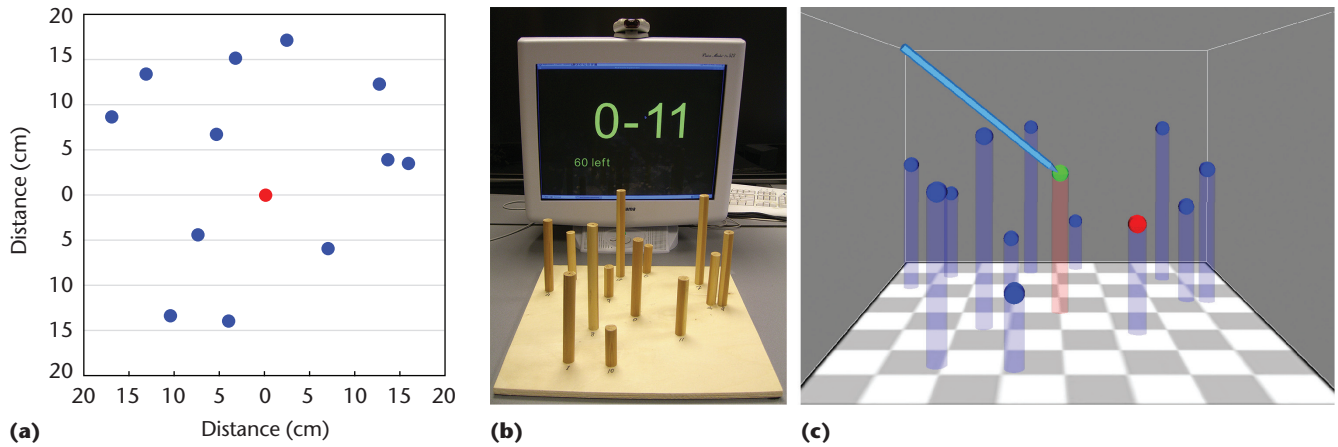
Figure 2. A 3D multidirectional pointing task: (a) target layout (top view), (b) the real-world environment, and (c) the virtual environment. The target layout shows the positions where we placed the wooden cylinders and the 3D graphics cylinders in the real-world environment and the virtual environment, respectively. In the virtual environment, the target areas are also visualized on top of the cylinders.

combination with a positive jerk that exceeds 0.01 times the maximally observed jerk).

- A type-3 submovement occurs at a zero-crossing of a jerk from positive to negative (in combination with a negative value of its derivative that exceeds 0.01 times the maximally observed value).

The minimal requirements for a submovement are that it should traverse a distance of at least 3 mm and last for at least 75 ms and that the maximum velocity should exceed 0.05 times the maximally observed speed. We combine submovements that don't meet these requirements with neighboring submovements. These criteria let us avoid detecting many small, insignificant submovements.

Important considerations when carrying out goal-directed movements are the distance that's crossed, the time it takes, and the accuracy at the end of the movement. Different input devices or interaction techniques might lead to different speed-accuracy trade-offs, which we expect will be revealed in a different behavior of one or more movement phases. This was confirmed in a study investigating 2D goal-directed movements carried out with a mouse and a stylus with a tablet.[10] This study demonstrated that the five phases' duration and other measures applied to the ballistic and correction phases can indeed provide more information about the movement strategies people use when interacting through different input devices.

Our article's main contribution is to demonstrate that we can extrapolate these findings to 3D by applying the same analysis to the data collected in a previous experiment.[6] As we mentioned earlier, we will show that applying measures such as duration, speed, and path efficiency to the ballistic and correction phases can indeed provide a more detailed description of 3D goal-directed movements.

Experiment 1: The Effect of Environment

Our first experiment aimed to determine how a virtual environment affects interaction movements differently from a real-world environment.

Method

This section describes the experimental setup, including the 3D pointing task, equipment, and procedure.

Participants. Six skilled computer users experienced with 3D virtual environments volunteered for the study. All participants were male, and all but one were right-handed.

Task. The participants had to first select the home area and then select one of 12 target areas, which were positioned on top of cylinders surrounding the home cylinder (see Figure 2). The home cylinder was 14 cm tall; the target cylinders had four different heights: 6 cm, 10 cm, 14 cm, and 18 cm. The target cylinders' distances to the home cylinder varied, but they could be clustered in three groups: short (9.4 cm to 11.7 cm), medium (14.8 cm to 16.8 cm), or long (17.9 cm to 19.4 cm).

For the real-world environment, we made wooden models of the home and target cylinders. The space above each cylinder was the designated target area, which had a diameter and height of 17 cm. We placed the physical model 30 cm in front of the participants. Participants selected the home and target areas by pressing the button of a tracked stylus when the stylus tip intersected the area (just above the cylinders). A monitor behind the setup indicated which target the participants had to select. Data collection stopped at the first button press after the trial started.

For the virtual environment, we recreated the physical model using 3D graphics. We represented the targets as spheres and placed each target's midpoint on top of its cylinder. The stereoscopically perceived interaction space was such that the virtual cylinders were at the same location as the real-world cylinders. This means that the visual space was 30 cm behind the interaction space. So, the participants sat 60 cm in front of the CRT. They made selections in the virtual environment with the same tracked stylus as in the real world. As in the real-world environment, for the selection to be successful, the stylus tip had to intersect the target area when the participant pressed the stylus button. Participants received visual feedback indicating which target to select. Data collection continued until the participant correctly selected the target.

Apparatus. The hardware for the virtual environment included a 20-inch viewable stereo-capable Iiyama A202D DT monitor and a PC with a high-end GPU. The monitor resolution was 1,400 × 1,050 pixels at 120 Hz with NuVision 60 GX stereoscopic LCD glasses. For tracking head movements, we used an ultrasound Logitech 3D head tracker at 60 Hz. We used the Polhemus Fastrak to sample a 6-DOF (degrees of freedom) stylus at 120 Hz. The overall end-to-end system latency was 45 ms.

Design. We used a within-subjects design, with the environment (real-world or virtual) and target distance (short, medium, or long) as independent variables. The sessions in the real-world environment and virtual environment each contained 60 trials—five repetitions of the 12 targets. We presented the trials randomly, with the restriction that the order during the real-world session was the same as during the virtual-environment session.

The experiment involved these dependent variables:

- *duration*—the time interval from the beginning to the end of the trial or phase,
- *path length*—the length of the traveled (pointer) path in mm,
- *speed*—the average pointer speed in mm/sec.,
- *path (length) efficiency*—the ratio between the traveled (pointer) path and the shortest path,
- *submovements*—the number of submovements,[11]
- *correction distance*—the distance to the target at the correction phase's start,
- *pause time*—the number and mean duration of the pauses in the correction phase, and
- *target misses*—the frequency of trials in which the stylus button is clicked outside the target area.

We applied duration, path length, speed, path efficiency, and number of submovements to the total trial as well as to the ballistic and correction phases (as indicated in Figure 1).

Procedure. The participants received brief instructions about the task, after which they started the experiment.

In the real-world environment, the participants first learned the targets' layouts because the targets were only indicated with a number. At each trial's start, we presented the assigned target number on the monitor. After the participant successfully selected a target (after first selecting the home area), a new target number appeared on the monitor.

Our first experiment aimed to determine how a virtual environment affects interaction movements differently from a real-world environment.

For the virtual environment, we indicated the assigned target by color. When each trial started, both the home sphere and the assigned target sphere were red, whereas the other targets were blue. When participants entered the home area, the corresponding sphere turned green. After the participant selected the home area (by pressing the stylus button), the home sphere and target sphere turned yellow and the background also changed from gray to black. These changes indicated that the participant could carry out the interaction movement and that data recording had started. When the participant entered the target area, the corresponding sphere changed from yellow to green, indicating that he could select the target to end the trial.

Results

We performed repeated-measures analysis of variance (ANOVA) with two independent variables (environment and target distance). Table 1 shows the results and the observed power of the test. Our description and discussion of the results focus on the different trends we observed in the identified movement phases because they show the added value of our detailed movement analysis.

Environment. The analysis of the total trial duration shows that the environment has a large effect

Table 1. The results of repeated-measures analysis of the data in Experiment 1. (Total = total trial, Bal = ballistic phase, and Cor = correction phase.)

Movement characteristics		Environment			Target distance			Interaction		
		F-value df(1,5)	p-value	Observed power	F-value df(2,10)	p-value	Observed power	F-value df(2,10)	p-value	Observed power
Duration	Total	40.08	<0.01	1.00	40.26	<0.01	1.00	32.82	<0.01	1.00
	Bal	30.54	<0.01	0.99	35.92	<0.01	1.00	3.66	=0.06	0.54
	Cor	29.96	<0.01	0.99	3.75	=0.06	0.55	3.38	=0.08	0.50
Speed	Total	74.86	<0.01	1.00	78.94	<0.01	1.00	40.78	<0.01	1.00
	Bal	49.32	<0.01	1.00	286.50	<0.01	1.00	13.07	<0.01	0.98
	Cor	1.87	=0.23	0.20	6.61	<0.05	0.80	0.10	=0.91	0.06
Path length	Total	0.08	=0.79	0.06	974.55	<0.01	1.00	0.43	=0.66	0.10
	Bal	5.06	=0.07	0.44	1,066.36	<0.01	1.00	5.66	=0.06	0.50
	Cor	3.35	=0.13	0.32	9.43	<0.01	0.92	2.02	=0.18	0.32
Path efficiency	Total	0.09	=0.78	0.06	46.24	<0.01	1.00	0.46	=0.64	0.11
	Bal	5.25	=0.07	0.46	11.36	<0.01	0.96	1.78	=0.22	0.29
	Cor	1.88	=0.23	0.20	0.14	=0.88	0.07	1.76	=0.22	0.28
Number of submovements	Total	37.58	<0.01	1.00	8.53	<0.05	0.71	7.17	<0.05	0.83
	Bal	37.80	<0.01	1.00	12.53	<0.01	0.98	2.61	=0.12	0.40
	Cor	15.85	<0.05	0.89	2.92	=0.10	0.44	0.74	=0.50	0.14
Number of pauses	Cor	2.47	=0.18	0.25	0.85	=0.46	0.16	1.24	=0.33	0.21
Pause duration	Cor	11.95	<0.05	0.79	0.09	=0.92	0.06	1.23	=0.33	0.21
Correction distance	Cor	2.76	=0.16	0.27	20.54	<0.01	1.00	0.19	=0.83	0.07
Target misses	Cor	0.01	=0.96	0.05	1.32	=0.31	0.22	1.65	=0.24	0.26
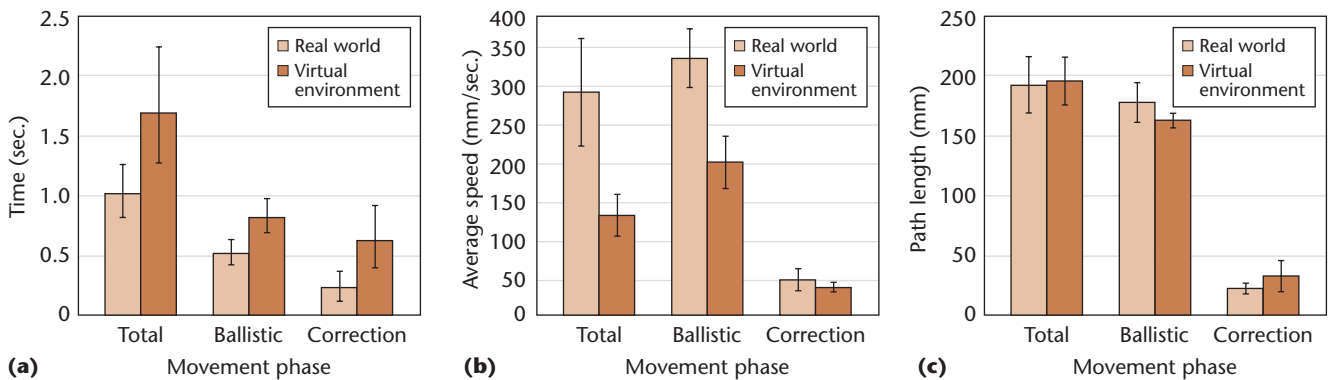
Figure 3. The (a) duration, (b) speed, and (c) path length as a function of environment (real-world or virtual). All results have a 95 percent confidence interval. This figure shows the environment's different effects on the ballistic and correction phases' duration, speed, and path length.

on performance (see the high F-values in Table 1): the time to complete a trial is considerably shorter in the real environment than in the virtual environment. We can observe this effect in both the ballistic and correction phases (see Figure 3a).

However, the environment didn't have the same effect on the speed of the ballistic and correction phases (see Figure 3b). Analysis showed a significant environmental effect only on the ballistic speed, not on the correction speed (see Table 1).

As Figure 3c shows, the environmental effect on path length of the ballistic and correction phases even seems reversed, resulting in an overall path length that's equally large for the real-world and virtual environments. Although the analysis revealed that the environment had no significant effect on the path length of the ballistic and correction phases, we believe these tests' observed power was only slightly too low to indicate a significant effect (see Table 1). Path efficiency showed the same reversed effect of environment.

Distance. Table 1 shows that target distance has a much larger effect on the movement characteris-

tics (that is, speed, path efficiency, and so on) of the ballistic phase than on those of the correction phase. This is especially shown in the magnitudes of the F-values—for example, the F-values for distance's effect on the ballistic and correction speeds are 286.50 and 6.61, respectively. Table 1 and Figure 4 also show that target distance significantly affects correction distance. This means the larger the target distance, the larger the remaining distance to the target at the beginning of the correction phase. This might be the main reason that target distance significantly affects some of the correction phase's movement characteristics, such as speed and path length—especially because target distance has no significant effect on the number and duration of pauses (see Figure 5).

Interaction effect. The largest interaction effects between environment and target distance are in the overall movement's duration and speed. Although the interaction effect is equally large on the ballistic and correction phases' duration, it's not equally large on those phase's speeds. The environment and target distance have an interaction effect on the ballistic phase's speed but not on the correction phase's speed (see Figure 4).

Discussion
This experiment showed that the ballistic and correction phases were longer in the virtual environment than in the real-world environment. However, the different measures applied to the phases indicated different reasons for this finding. The ballistic phase was longer primarily because the average speed was significantly lower than in the real-world environment. The correction phase was longer because the pauses made during it were longer. These results show that applying multiple measures to different movement phases can provide a more thorough description of how people carry out goal-directed movements.

In addition, the correction phase's path efficiency was relatively lower in the virtual environment, and the participants made many errors (11 percent) when trying to select the targets. From these results, we conclude that people will likely profit a lot from input devices or interaction techniques (such as automation) that facilitate the correction movements preceding the selection.

However, actively guiding the ballistic phase's path wouldn't be beneficial because its path efficiency is already relatively high. Enabling the participants to move faster during the ballistic phase would of course improve overall performance, provided that path efficiency can be maintained.
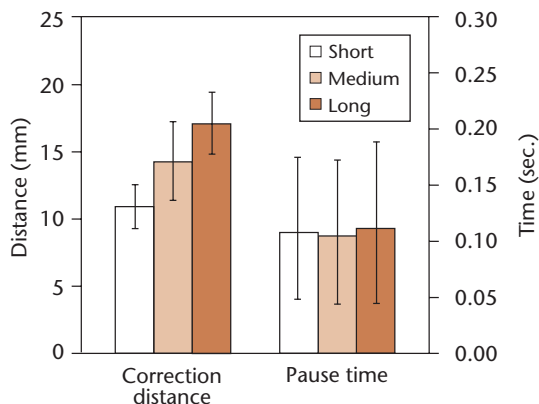
Figure 4. Correction distance and pause time as a function of target distance for the correction phase, with a 95 percent confidence interval. This graph shows that correction distance, distance to target at the beginning of the correction phase, increases with target distance.
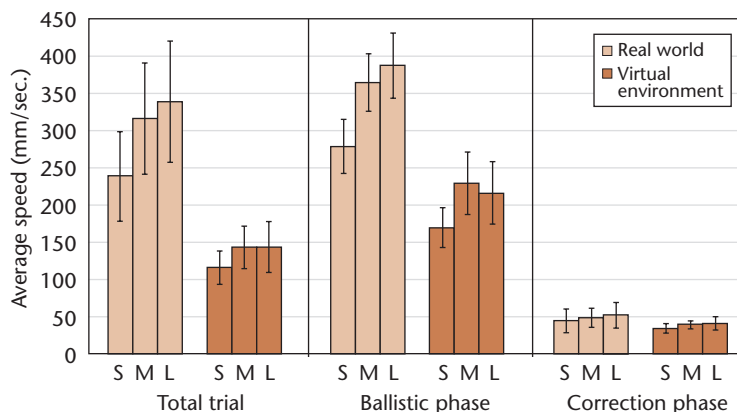
Figure 5. Speed as a function of environment and target distance (short, medium, or long), with a 95 percent confidence interval. This graph shows that environment and target distance have an interaction effect on the ballistic phase's speed but not on the correction phase's speed.

Because target distance deteriorates the ballistic phase's performance, we expect that the interaction effects between environment and target distance will be less prominent when the execution of the ballistic movement is somewhat facilitated.

Experiment 2: The Effect of Practice
As we mentioned before, the participants in experiment 1 were already familiar with 3D virtual environments. We thought it would be relevant to see how novices performed before and after some practice.

Method
This section describes the experimental setup, including the experimental task, materials, and procedure.

Table 2. The results of repeated-measures analysis of the data in Experiment 2. (Total = total trial, Bal = ballistic phase, and Cor = correction phase.)

Movement characteristics		Practice level			Target distance			Interaction		
		F-value df(1,5)	p-value	Observed power	F-value df(2,10)	p-value	Observed power	F-value df(2,10)	p-value	Observed power
Duration	Total	34.47	<0.01	1.00	33.17	<0.01	1.00	0.18	=0.84	0.07
	Bal	20.39	<0.01	0.96	35.57	<0.01	1.00	0.21	=0.82	0.07
	Cor	6.88	<0.05	0.56	28.72	<0.01	1.00	0.54	=0.60	0.12
Speed	Total	41.71	<0.01	1.00	25.53	<0.01	1.00	0.53	=0.60	0.12
	Bal	17.38	<0.01	0.91	77.51	<0.01	1.00	1.44	=0.28	0.24
	Cor	2.49	=0.18	0.25	42.03	<0.01	1.00	0.83	=0.46	0.16
Path length	Total	38.07	<0.01	1.00	191.92	<0.01	1.00	0.66	=0.54	0.13
	Bal	18.56	<0.01	0.93	124.72	<0.01	1.00	0.28	=0.77	0.08
	Cor	2.53	=0.17	0.25	16.13	<0.01	1.00	0.41	=0.67	0.10
Path efficiency	Total	35.64	<0.01	1.00	38.78	<0.01	1.00	0.26	=0.78	0.08
	Bal	25.59	<0.01	0.98	24.78	<0.01	1.00	0.26	=0.78	0.08
	Cor	0.34	=0.59	0.08	1.88	=0.20	0.30	0.90	=0.44	0.16
Number of submovements	Total	57.09	<0.01	1.00	5.76	<0.05	0.74	1.77	=0.22	0.29
	Bal	24.78	<0.01	0.97	8.46	<0.01	0.89	0.93	=0.43	0.17
	Cor	123.89	<0.01	1.00	3.12	=0.09	0.47	0.61	=0.56	0.13
Number of pauses	Cor	3.42	=0.12	0.32	34.35	<0.01	1.00	0.19	=0.71	0.07
Pause duration	Cor	11.37	<0.05	0.77	10.28	<0.01	0.94	0.15	=0.86	0.07
Correction distance	Cor	4.18	=0.10	0.39	15.46	<0.01	0.99	0.12	=0.89	0.06
Target misses	Cor	2.22	=0.20	0.23	1.88	=0.20	0.30	1.34	=0.30	0.17
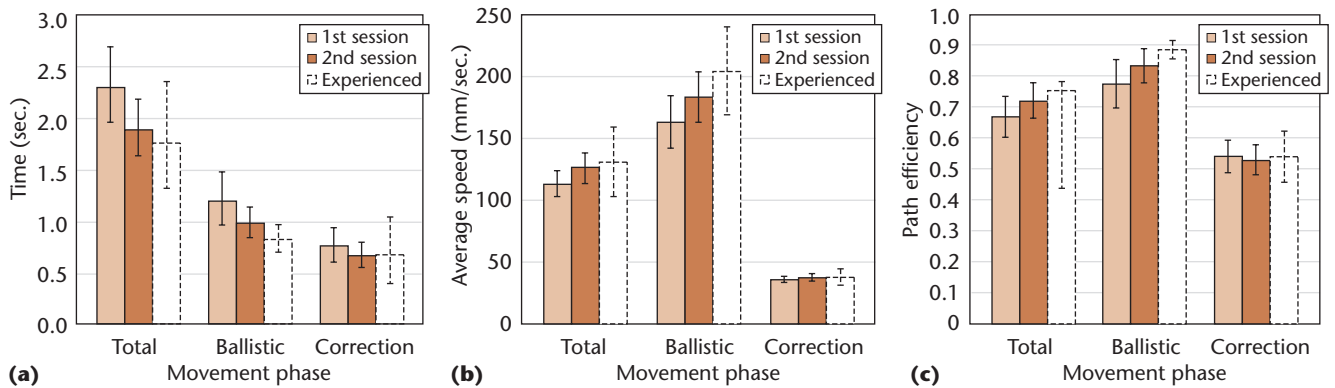
Figure 6. The (a) duration, (b) speed, and (c) path efficiency as a function of practice level (first session, second session, or experienced). All results have a 95 percent confidence interval. This figure shows the different effects that practice has on the ballistic and correction phases' duration, speed, and path efficiency.

Participants. The six volunteer participants comprised three males and three females, all right-handed.

Task and apparatus. We used the same virtual multidirectional pointing task and apparatus as in experiment 1.

Design. This experiment also used a within-subjects design, with practice level (first session or second session) and target distance (short, medium, or long) as the independent variables. We used the same dependent variables as in experiment 1.

Procedure. The procedure was also similar to that of experiment 1. However, in this experiment, participants performed both sessions (60 trials) in the virtual environment to investigate the effect of practice.

Results

Once again, we carried out repeated-measures ANOVA with two independent variables (practice and target distance). Table 2 shows the results and the observed power. The description and discussion of the results again focus only on the trends observed in the identified movement phases.

(a)

(b)
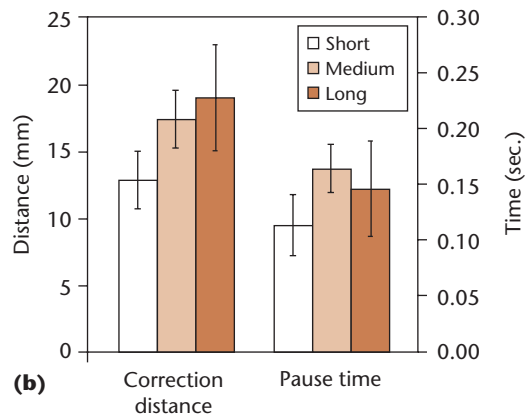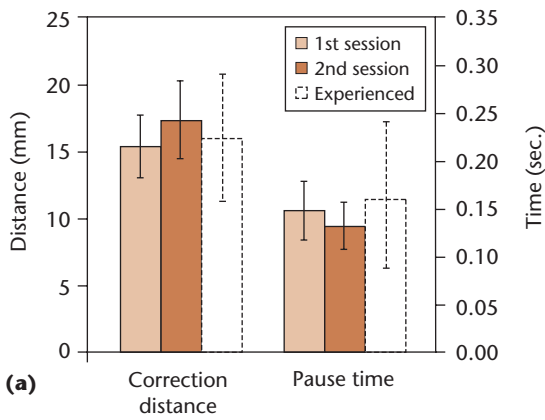
Figure 7. Correction distance and pause time as a function of (a) practice level and (b) target distance (short, medium, or long) for the correction phase. All results have a 95 percent confidence interval. This figure shows that pause duration decreases with practice and that correction distance and pause duration increase with increasing target distance.

Practice. The analysis of total trial duration showed that practice has a large effect on performance (see high F-values in Table 2): the time to complete a trial is considerably longer during the first session than during the second session (see Figure 6a). Figure 6a also shows that this effect is evident in both the ballistic and correction phases. However, practice had a larger effect in the ballistic phase than in the correction phase (F-value = 20.39 versus F-value = 6.88). Table 2 further shows that for speed, path length, and path efficiency, only the ballistic phase shows an effect of practice. Figures 6b and 6c show that only the ballistic phase's performance improves with practice. For the correction phase, practice had no significant effect on speed (see Figure 6b), path length, path efficiency (see Figure 6c), correction distance, or the number of pauses. In the correction phase, however, practice affected pause duration (pauses were longer during the first session; see Figure 7a).

Figures 6 and 7a also include the results of the experienced 3D virtual-environment users in experiment 1. We'll compare these results with those of the novices a little later.

Distance. This experiment's results show that target distance has a much larger effect on the movement characteristics of the ballistic phase than on those of the correction phase (see Table 2). This is especially shown in the magnitudes of the F-values; the F-values of the ballistic phase characteristics are systematically higher than those of the correction phase characteristics. In addition, target distance significantly affects ballistic path efficiency but doesn't affect correction path efficiency. Table 2 and Figure 7b also show that the target distance significantly affects the correction distance. This might be an important reason for the target distance's significant effect on the correction phase's movement characteristics, such as duration, speed, and path length.

Interaction effect. Practice level and target dis-

tance had no interaction effect on the dependent variables.

Discussion

Experiment 2 demonstrated that practice has a considerably different effect on the characteristics of the ballistic and correction phases. Although both phases were shorter after practice, the different measures applied to them indicated different reasons for this finding (as in experiment 1). As we mentioned before, the level of practice significantly affected the speed, path length, and path efficiency of the ballistic phase but not of the correction phase. So, the ballistic phase's shorter duration is most likely due to higher path efficiency and higher average speed, whereas the correction phase's shorter duration is more likely due to the shorter pauses.

This experiment's findings again support the suggestion that people would benefit more from assistance during the correction phase than during the ballistic phase. Practice mainly reduces the time people are standing still and the number of submovements during the correction phase. However, the other measures showed that the correction phase's speed and path efficiency didn't really increase with practice. In addition, after a single practice session, the novice users didn't differ much from the experienced users of experiment 1 for this movement phase.

The ballistic phase's performance, however, improved on most measured movement characteristics between the first and the second session. When comparing the novice users' results with the experienced users' results, it seems likely that the ballistic phase's performance can still be improved (maybe even beyond the experienced users' level), which is less likely for the correction phase.

Scott Frees and Drew Kessler acknowledged the importance of assisting precise movements.[12] According to them, the potential of virtual environments hasn't yet been realized because of the limited precision with which users can interact with virtual environments.

Besides demonstrating the added value of dividing movements into meaningful phases, we propose several improvements for the experiments we've discussed in this article.

For experiment 1, the mean number of errors (11 percent) is relatively high for both the real-world and virtual environments. Although the mean number of errors is similar across conditions, we believe that there are different reasons. For the real-world environment, we didn't verify the participants' performance. This means, they could continue with the next trial even if they clicked outside the target area. Once participants realized this, they could decide to aim for higher speed and lower accuracy. However, in the virtual environment, participants had to continue until they correctly selected the target. So, we assume

> *This experiment's findings again support the suggestion that people would benefit more from assistance during the correction phase than during the ballistic phase.*

that they tried harder to select the target correctly. Nonetheless, they still often missed the target because the task was more difficult.

Therefore, we propose that a revised experiment should use the same task completion criterion in both cases. Having to continue until the task is performed correctly would also more closely resemble real-life interaction with computers.

Because of the incomplete experimental design, systematically examining the effects of the targets' height and spatial position is impossible. In the virtual environment, we could have systematically changed the height and position.

In the real-world environment, systematically varying the wooden cylinders' height and width would have posed a problem, especially when it must be done in a balanced way. For instance, having high targets in the front will constrain the participants' movements when they reach for targets in the back. In addition, if we had included more directions and more target distances, the number of target positions would have increased and the participants would have experienced increasing difficulty correctly associating a target number on the screen with a physical target location. Therefore, we figured that an incomplete design would be the best option.

However, for investigating interactions in a virtual environment, the independent variables target size, target distance, and target height should be systematically varied, as ISO 9241-9 advises. One way to accomplish this in a 3D environment is to position the targets uniformly across the surfaces of spheres with different diameters, centered on a home target. This would have been the best option for experiment 2, but then we wouldn't have been able to compare both experiments' outcomes.

We've applied our movement analysis method only to rapid aimed selection movements. However, it would be relevant to look at more difficult tasks such as steering and docking. Unlike a pointing task, a steering task requires continuous control over the position. Docking tasks, on the other hand, require that an object be correctly repositioned and have the right orientation.

To investigate the performance on such tasks in a more structured way, a first step would be to design simple tasks with characteristics similar to the ISO 9241-9 standardized task. The second step would be to investigate how to adapt our analysis method to cope with such tasks. For example, steering requires more continuous pointer precision than selection does. So, steering movements will most likely be subject to ongoing corrections, and a prominent ballistic movement might be absent in such case. Adopting our method to cope with orientations should be fairly straightforward because descriptions of orientation changes (such as in terms of quaternion) are well documented.

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