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Computer Usage With Cold Hands; An Experiment With Pointing Devices

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Computers are used in the outdoors and in connection with cold store work. Cold hand and fingers limit data input, as studied here. Six input devices; trackballs, pens, and a mouse were tested by 19 participants in a Fitts' target acquisition task with 2 target sizes under 2 experimental conditions; warm and cold right hand. Measures were acquisition times, number of errors, participant's preferences, and observed handling of the devices. Effects of device, target size, and cold were significant. Learning and attempts to improve handgrip were confirmed. Large enough targets, a thick pen, and a mouse make computer work practicable in the cold. Direct visual feedback, as with pen on template with target images, shortened acquisition times by half a second.

cold hand computer use input device movement analysis acquisition time cold climate

1. INTRODUCTION

A considerable amount of work is done in cold environments, either in cold store rooms or outdoors in winter weather and some of this work includes data entry. The spread of Information Technology involves several professional

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groups in computer use under such conditions. Available devices are ordinary desktop computers, portables, and specially built hand-held computers (Blomkvist & Gard, 1998). Desktop computers in cubicles or in office rooms do well when workers can postpone data input and leave the cold area at intervals; a strategy recommended by Swedish trade unions. When data input must be performed immediately, portable and hand-held computers are used. Heat loss is great from fingers, so cold fingers and hands limit work in cold areas (Holmér, 1995; Kunesch, Schmidt, Nordin, Wallin, & Hagbarth, 1987; Virokannas, 1996). The best way to counteract cold, thermoregulatory exercises (Gavhed, Nielsen, & Holmér, 1991), does not combine itself with data entry.

Local cooling of the forearm and hand is determining for manual dexterity, and the dexterity is affected immediately (Giesbrecht & Bristow, 1992). Giesbrecht, Wu, White, Johnstone, and Bristow (1995) demonstrated that the decrements were almost entirely due to the local effects of arm tissue cooling, and that they were greater in fine motor tasks than in gross motor tasks. Cold muscles are activated more indiscriminately than warm (Kunesch et al., 1987). Dexterity decrements include tactile sensitivity, handgrip strength, and simple movements as well as more complex manipulations (Johnson & Leider, 1977; Leblanc, 1956; Meese, Kok, Lewis, & Wyon, 1984; Provins & Morton, 1960). Cold wrists restrain actors from twisting the hands (Leblanc, 1956). Details of results from experiments vary with the choice of motoric tests (Hellström, 1965; Heus, Daanen, & Havenith, 1995).

The critical lower level for sensitivity decrements is around 8 °C and for dexterity between 12 and 16 °C according to Fox (1967). A review by Heus et al. (1995) confirms that when local skin temperature is above 15 °C there is hardly any loss of performance. They recommend local skin measurements and subjective cold ratings for control of working conditions.

Movement patterns can be modified, making it possible to reach the same results with a cold as with a warm hand but at a reduced workpace (Gentile, 1987; Hammarskjöld, 1992). Influential nonphysiological factors are pre-experimental performance and natural aptitude and stress (Enander, 1986; Fox, 1967). General effects of raised arousal level due to cold exposure could be predicted to influence performance and interaction between arousal, task difficulty, and individual factors such as experience have been discussed (Provins, Glencross, & Cooper, 1973). Thus, present knowledge points to negative effects of cold hands on work with input devices, but not unambiguously to performance loss as the possibility that participants can find ways to counteract impaired dexterity, and an ambition to do so, must not be overlooked.

The aim in the present study was to explore the effects of moderately cold hands—a realistic condition of work in cold environments—on data input with various computer input devices and thus to contribute to demand specifications for such devices. Measures include participants' own judgements, performance measures, and observations of adaptive manual strategies. The study further includes the effect of direct visual feedback from device movements toward targets depicted on a template versus the indirect feedback presented when participants watch the target and the cursor on the screen.

Computer input devices on the market differ in their demands on handgrip and movement patterns. Trackballs may require small finger movements but not grip strength. Thin pens require a grip with the thumb and two fingers, and thick pens may allow for a grip with the thumb and three or four fingers. A mouse demands little grip strength and sensitivity. Differential effects of cold on the management of these devices would lead to advocating one type of device rather than another and reveal differing techniques for managing the devices in the warmth and the cold. Two dimensions of trackballs and pens were used in the present experiment in order to vary the amount of small muscle activities.

Women quit cold work earlier then men (A. Anderson, personal communication, January 13, 1997). Women do—despite managing tasks in the cold about as well as men (Meese et al., 1984; Riley & Cochran, 1984)—show more physiological (LeBlanc, Côté, Dulac, & Dulong-Turcot, 1978) and negative subjective (Meese et al., 1984) reactions. For this reason data from men and women are compared in the present study. Comparison by Karlqvist (1997) of posture and muscular load during editing with a mouse and a trackball revealed less shoulder elevation and neck/shoulder muscle activity but more wrist extension when trackball was used than when mouse was used, and revealed gender differences. Men and women could have different preferred working postures due to the muscular differences (Lindman, Eriksson, & Thornell, 1991), but postures are also individualistic (Fernström & Ericson, 1996).

1.1. The Task

The experimental task[1] was to move a cursor back and forth between two targets according to Fitts' acquisition task (Fitts, 1954; Fitts & Peterson, 1964) quantifying information transfer capacity in terms of a ratio between

[1] Designed by A.-C. Blomkvist & L. Östcrbcrg in HyperCard.

movement amplitude *(A)* and target width *(W).* Fitts' task has been used to describe various devices (Card, Moran, & Newell, 1983) and probes (Hoffman, 1995; Hoffman & Sheikh, 1991), and to discuss measures of target width (Gillan, Holden, Adam, Rudisill, & Magee, 1992; MacKenzie, 1992; MacKenzie & Buxton, 1994; Walker, Mayer, & Smelcer, 1993), as well as to show the effects of delay times on errors (MacKenzie & Ware, 1993), and hand used (Kabbash, MacKenzie, & Buxton, 1993). MacKenzie (1992) stated that cross comparisons between device studies are difficult (using Fitts' task), but MacKenzie, Sellen, and Buxton (1991) showed within a study similar to the present one that information transfer was faster with pen than with mouse, which in turn was faster than trackball.

The test situation, devices, and screen layout are shown in Figures 1, 2, 3, and 4. Participants worked standing up so that their working posture would mimic the posture of workers hurrying in to a desk lop without adjusting the seat, or an outdoor situation where the computers are held on the arm (Blomkvist & Gard, 1998). Thus, the possibilities to support the elbow and the forearm were reduced. The screen layout demanded moves from upper left to lower right corner in order to minimise ballistic movement opportunities.

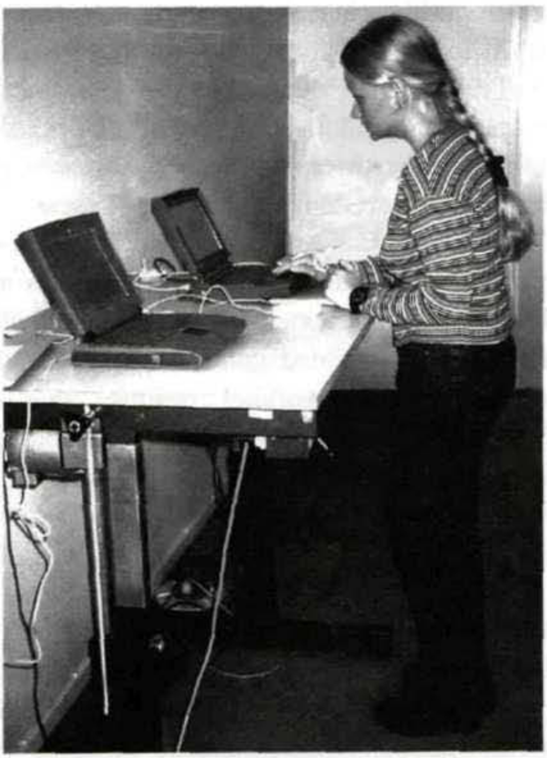

Figure 1. Experimental test situation with elbow-high table. The participant is using the small trackball. A corner of a tablet is seen to the left and the temperature probe is fastened on the right-hand middle finger.

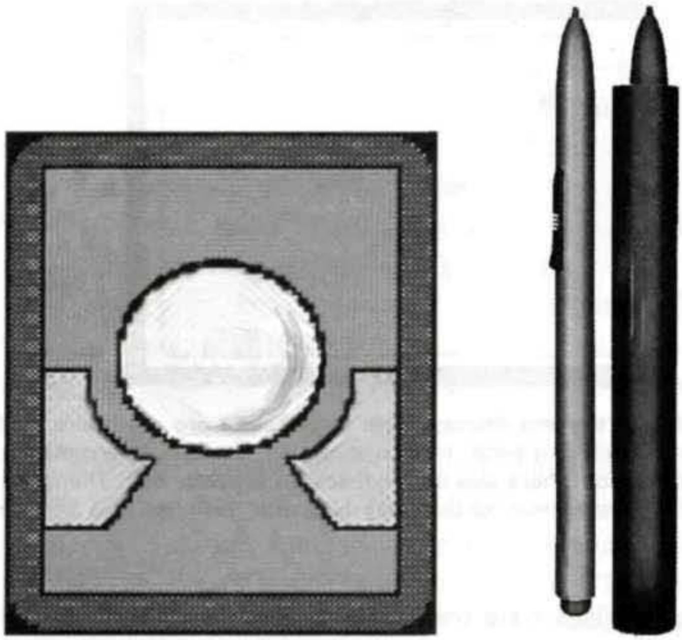

Figure 2. The large trackball, the thin and thick pens. The keys are just to the left and the right of the trackball, and participants could use either key for selection. The keys of the pens were not used.

Figure 3. The small trackball and the mouse—seen in the display. The keys for selection are just above the trackball, to the left and the right, and participants could use either of them. There was one key on the mouse.

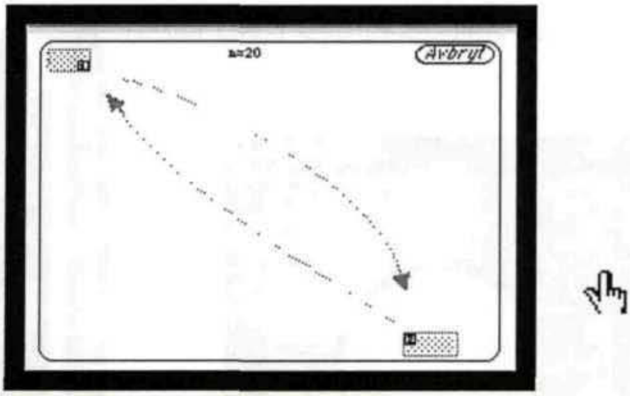

Figure 4. Outline of the test display. Both target sizes are seen here. In Fitts' task the marker is moved back and forth. In this study the test was interrupted by a blink and a beep after 20 hits, but there was no feedback on separate hits. The marker was a hand and participants were instructed that only hits with the forefinger tip counted.

The tested devices were one large and one small trackball (diameters 5.5 and 2.9 cm), two thin pens (diameters 0.9 cm), one thick pen (diameter 1.5 cm), and a mouse. The pens were used with Wacom tablets. One tablet was placed on the table (pen-on-table) and another was overlaid with a template and carried on the arm (pen-on-arm) as if it were a portable computer. Hereafter, the devices are called large trackball, small trackball, thin pen-on-table, thin pen-on-arm, thick pen-on-arm, and mouse.

There were two target sizes, one large target similar to a checkbox or closing box (0.35 • 0.35 cm), and one small target similar to a start or close button of a graphical interface (3.00 * 0.70 cm). The distance between the targets' closest corners was 16 cm. After a total of 20 hits there was a bleep, the subtest was closed and an **instruction** to return to the start screen was shown. There was no feedback on hits or errors during the subtest.

2. METHOD

2.1. Procedure

The experiment was carried out in April 1996 and each participant spent 2 hrs in the laboratory. First the participants answered questions on background data; computer experience, dispositions for cold hands and feeling cold, age, height, and weight. Then they had a temperature probe attached to the back of the right middle finger for control of skin temperature and were asked to open and close a window with one device at a time to make sure that the probe did not restrict the movements.

To accomplish cooling, the participants' right hand and wrist were immersed in snow mixed with water, until the finger skin temperature reached 11 °C. Giesbrecht et al. (1995) assumed that skin temperature quickly approaches water temperature after immersion. Enander (1982) mentioned wide variations of time between participants. Thus, finger skin temperature was chosen as criterion—not immersion time. Warming up again was done under running, lukewarm water. The first cooling to 11 °C and the warming up again to precooling temperature took approximately 10 min each.

Table height was set to elbow height for each participant (see Figure 1) and eye-computer screen distance to 60 cm. The distance to the centre of the pointing device was 25 cm from the table edge at every start of a test. When the template on the Wacom pad was used and held on the arm, participants were allowed to choose their own working and viewing distances.

Participants were paid and were further told that the one making least errors and the one making the quickest moves would be paid extra after the data were analysed.

2.2. Participants

Nine male and 10 female students participated. Their mean age was 25 and 22 years, respectively. Medium height and weight were 179 cm and 78 kg for the men; 167 cm and 61 kg for the women. All participants wanted to use their right hand for the devices, also one woman who was left-handed.

2.3. Experimental Design

The experimental design included repeated measures with 4 sessions x 6 device tests x 2 target-size subtests. In each subtest there were 19 sequential moves, acquisitions, between the two targets. The large target subtest was directly followed by the small target subtest. The participants first tried the devices for a short while. Then there was a practice session, Session 1. Acquisition times and errors from Session 1 are included in the presentation of the results. In Session 3 the participant's right hand was cooled before each test with each device, and if skin temperature rose to 14 °C under the large target subtest the hand was cooled again before the small target subtest. Prior to Session 4 the hand was warmed up once in warm water.

Half of the participants first used the large trackball, the small trackball, and the thin pen-on-table, in this order, and thereafter the thin pen-on-arm, the thick pen-on-arm, and the mouse. For the other half of the participants the order was thin and thick pen-on-arm, the mouse, then the trackballs and the pen-on-table.

2.4. Observations

Unobtrusive observations of working postures were made during Sessions 2, 3, and 4. Neck and back flexion, use of table support for hand and forearm and prevalence of static strain, as well as which finger or fingers were used for manipulation of each of the six devices were annotated and photographed. After the experiment, participants were asked about their own observations of the effects of cold.

2.5. Subjective Ratings

After each small target subtest in Sessions 2, 3, and 4, participants rated acquisition time, ease-to-hit the target, ease-to-use the keys of the trackballs and the mouse, appropriateness of the device, and the number of errors made. They also rated the right hand temperature in comparison to the left. **All** subjective ratings were made on scales from -10 to +10. Participants' ratings took much longer time than the subtests. It was recognised in a small pilot that ratings after the large target subtests—that is, between the large target subtests and the small target subtests—would more than double the length of Session 3, for which reason ratings were made of the small target subtests only. After the experiment, participants were asked to rank order the devices according to appropriateness for work, rank 1 to 6, for both warm and cold conditions and for the two target sizes together.

2.6. Statistics

MANOVAs to test differences between means were used on temperature measurements, the performance measures, and participants' ratings. The number of errors was calculated from acquisition times: When a participant missed a target without noticing, the time measurement did not stop until the same target was really hit. Thus, a measured acquisition time three times as long as the average time counted as one error; five times as long counted as two errors, and so forth. Acquisition times were not corrected for errors. Blocking and grouping was done according to rated computer experience, order of device use, and sex, one at a time. Comparisons among the participants' ratings and between ratings and measurements were made by Spearman's rho. For paired comparisons between corresponding measures *t* tests and Pearson *r* were used. The general level of significance was taken as 5%, highly significant as 1%, and $p < 7\%$ is called a tendency.

3. RESULTS

3.1. Background Data and Temperatures

Female participants reported significantly more often than the men that their hands easily felt cold. The men tended to have more computer experience.

TABLE 1. Hand Skin Temperatures; Mean Values *(M)* Over the Six Devices and Standard Deviations *(SD).* For Session 3 the Average of All Three SD Measurements Is Shown for Conciseness

	Session 1		Session 2				Session 3, Cold				Session 4	
	Start		Start		End		Start	Middle	End		Start	
Participants	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*M*	*M*	*SD*	*M*	*SD*
Men	28.0	3.5	30.3	3.3	30.0	2.7	11.6	13.2	14.1	1.2	28.6	2.9
Women	29.2	2.6	29.6	3.7	28.8	3.7	11.4	12.8	13.6	1.1	28.8	2.5

Room temperature varied from 20.1 to 23.4 °C. Room and skin temperatures did not correlate. Hand skin temperatures are shown in Table 1. Women's hand temperature was lower than the men's in Session 2, but not significantly so. Their subjective ratings were lower too, but apart from that there were no gender-related temperature differences nor differences in temperature ratings, although more women than men reported being sensitive to cold when asked at the start of the experiment. The participants' mean ratings of the right hand temperature relative to the left hand during Session 3 was -5.7 (on a scale reaching -10), which significantly differed from the ratings in Session 2 with a mean of 0.2, but also showed that participants could imagine being even colder.

Cooling was efficient, but the temperature rise was highly significant within each device test, though not during the separate subtests. The significance of that rise can partly be explained as an effect of low variance between participants after cooling. Further, the longer time it took to finish a subtest the warmer the hands got meanwhile. On average, cold hand skin temperature was about 12.5 °C during subtests with the large target and about 13.5 °C during subtests with the small target. We judged the skin temperatures to be within the range of interest with reference to our intention to mimic work in the field.

3.2. Acquisition Times and Errors

Average acquisition times and the calculated number of errors made by men and women are shown in Table 2. It can be seen that cold and target size affect acquisition times. The differences between men and women on the time measures were so small that gender will be left out for the rest of the acquisition time analysis. The women made almost twice as many errors as the men.

The sequences of acquisition times during small target subtests summarised over the devices in each session are seen in Figure 5. Results from an overall MANOVA showed that sessions differed significantly. Sessions 1 and 3 both took significantly longer than 2 and 4, but Sessions 1 and 3 did not differ between each other and nor did 2 and 4 (according to Scheffe's test of multiple comparisons). In the cold Session 3, the participants worked 12% slower on the large targets subtests and 15% slower on the small targets subtests than in Sessions 2 and 4.

As can be inferred from Figure 5, learning during Sessions 1 and 3 was significant (Pearson correlation coefficients between acquisition times and hit order number were -.47 and -.54), but insignificant during Sessions 2 and 4. Significance was the same for the large target subtests (the corresponding coefficients were -.55 and -.80 for Sessions 1 and 3, and near zero for Sessions 2 and 4). A MANOVA was also run with an assumed "learning factor," so that Sessions 1 and 3 were classified as learning sessions and Sessions 2 and 4 as nonlearning ones, and in that way a highly significant interaction effect between learning and nonlearning sessions could be achieved. The impression of learning in Session 3 could be

TABLE 2. Averages of Test Results of the Six Devices. Mean Acquisition Times Are in Seconds. Total Number of Errors per Participant and Condition Is Shown. Session 2 and 4 are Averaged for Comparison to the Cold Session 3. Session 1 is Included in "All"

	Mean Acquisition Times					Number of Errors per Participant				
		Sessions 2 and 4 Warm	Session 3 Cold	Sessions 2 and 4 Warm	Session 3 Cold		Sessions 2 and 4 Warm	Session 3 Cold	Sessions 2 and 4 Warm	Session 3 Cold
Participants	All	Large Target	Large Target	Small Target	Small Target	All	Large Target	Large Target	Small Target	Small Target
Men	.51	1.18	1.33	1.59	1.88	4.7	1.4	1.6	1.4	2.3
Women	.55	1.20	1.33	1.69	1.89	3.7	2.2	2.5	3.2	3.9

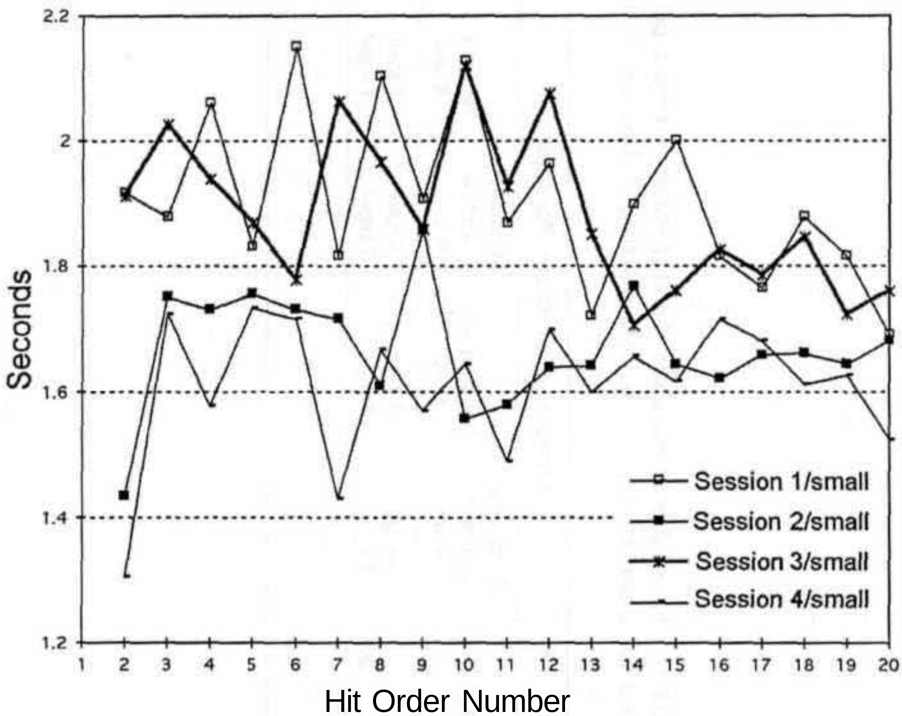

Figure 5. Learning curves; averages of successive acquisition times for all six devices with a small target. Seconds on *y* axis. Learning took place in Sessions 1 and 3. Participants worked fast and even in Sessions 2 and 4.

influenced by the warm-up during subtests mentioned under background data, but the temperature rose less than 1 °C during each subtest, so the conclusion here is that learning took place not only in Session 1 but also again in Session 3.

The jagged curves in Figure 5 seem to hint at slow movements toward the lower target on the screen. The large and small trackballs and the thin pen-on-arm contributed to this impression, but the effect is insignificant. The first rapid moves seen in Sessions 2 and 4 were managed mainly with the thin and thick pen-on-arm.

The 19 acquisition times of the subtests were averaged when effects of devices and cold were analysed. MANOVA showed that the main effects of session (again), device, and target size were highly significant. Interactions between session and device as well as between device and target size were also highly significant, and the interaction between session and target size significant. These effects were present also when Session 1 was excluded. Thus, there is a differentiating effect of cold on device management and target size. In the large target subtests, cold had an effect on the use of the trackballs only. Grouping of participants according to experimental order (half of the participants used the trackballs first, etc.) revealed no order effects. Blocking according to rated computer experience showed that those who rated themselves as experienced were significantly better, but there were no interaction effects, which means that the difference by experience did not even out during the sessions, nor did cold affect the experienced participants less than the others.

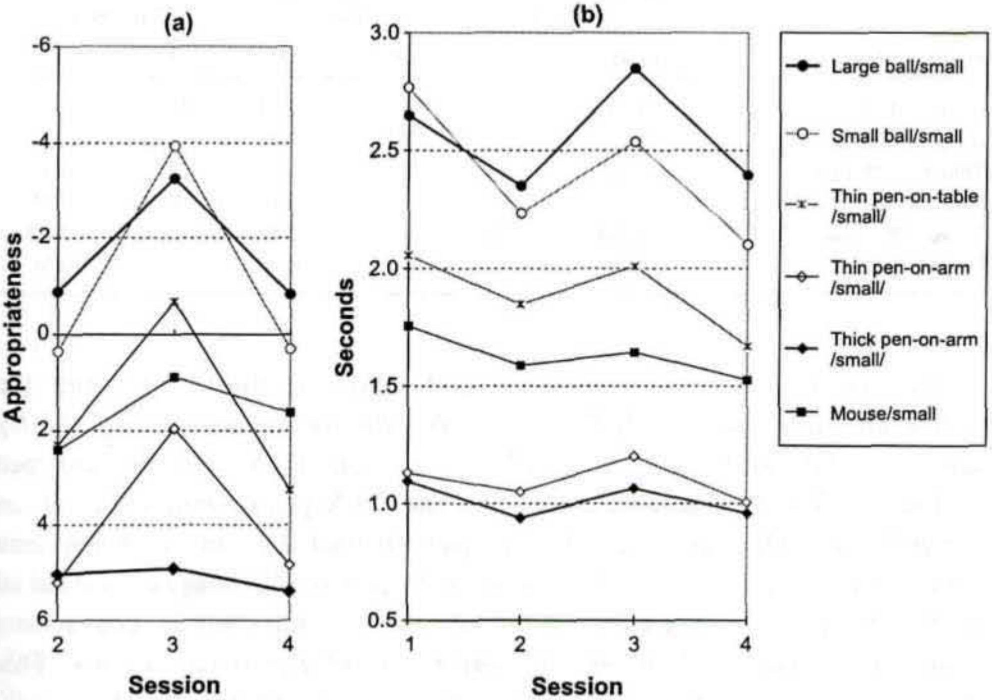

Figure 6. — a. Participants' appropriateness estimates. Note that the scale on the ordinate is reversed in order to match the acquisition times measured in seconds in Figure 6b. — b. Means of acquisition times for the separate devices and for the small target. The large trackball caused the longest acquisition times and the thin and thick pens-on-arm the shortest.

Acquisition times of the large and small trackballs were significantly longer than the times of the mouse and thin pen-on-table, which were longer than the times of thick and thin pen-on-arm (according to Scheffe's test of multiple comparisons). The trackballs took more than twice the time of the pens-on-arm. The order between the devices stayed the same in Sessions 2, 3, and 4 within both target sizes. Mean acquisition times of the small target subtests are shown in Figure 6a. The longest delay caused by cold was seen in the device test with the large trackball; the mean acquisition time in the small target subtest in the cold Session 3 was 0.5 s longer than the average of Sessions 2 and 4.

TABLE 3. Coefficients According to Card, Moran, and Newell (1983). The Coefficients of Session 2 and 4 Were Averaged for Comparison to the Cold Session 3

	Sessions 2 and 4 Warm		Session 3 Cold		Difference Cold-Warm	
Pointing Device	k_1	k_2	k_1	k_2	k_1	k_2
Large trackball	**0.86**	0.27	**1.15**	0.31	0.29	0.03
Small trackball	0.96	0.22	**1.12**	**0.24**	0.26	0.02
Thin pen-on-table	**1.15**	**0.11**	0.90	0.20	-0.25	0.09
Thin pen-on-arm	0.51	0.09	**0.42**	**0.14**	-0.09	0.05
Thick pen-on-arm	0.54	0.08	0.52	**0.10**	**-0.01**	0.02
Mouse	0.90	**0.12**	0.97	0.12	0.07	0.00

Effects of devices, target sizes, and cold are illustrated using the coefficients often seen with Fitts' test. We choose the form suggested by Card et al. (1983); $t' = k'_1 + k'_2\,{}^2log(A/W + 0.5)$, and the coefficients are seen in Table 3. The k_1 constants of the thin and thick pen-on-arm were half as big as for the other devices, and participants gained 0.5 s in the pen-on-arm situation where they looked directly at the targets on the template instead of at the targets and the cursor on the screen. The trackball k'_2 coefficients were about twice as high as the coefficients of the other devices. This shows that the trackballs were relatively sensitive to the target size *W*. Effects of cold on acquisition time are seen in Table 3 expressed as the difference between the coefficients of Session 3 and the average of the coefficients of Sessions 2 and 4. The differences show that the trackballs got more difficult to move when the hands were cold regardless of whether the target was large or small, whereas difficulties with the thin pen-on-table and the thin pen-on-arm could be attributed to the target size alone.

The 19 participants made about 19 errors each (in 912 moves), which equals an error rate of 2% so distributed that there were 1.8% errors with the large target and 2.4% with the small one. No error was made with mouse and cold hand. MANOVA based on errors made with the other devices showed one main effect: target size. There were no effects of session. This means that participants did not trade off error against speed in the cold condition but worked with the same accuracy in all sessions. When errors in the two target size subtests were added, MANOVAs on the resulting design (sessions x devices) showed a tendency to interaction between order of participants (as half the participants started with the trackballs and vice versa), which disappeared when Session 1 was excluded, and there were no effects of experience. Women made significantly more errors than men in the small target subtest, when sex and target size were tested alone.

3.3. Observations of Static Work Load and Device Management

The participants were standing as shown in Figure 1. The neck and back posture, arm posture, and handgrip were observed during Sessions 2, 3, and 4. No gender differences were observed. No salient alteration of neck and back posture was noted during the tests; a cold hand had no effect on body posture. There were variations between participants but their individual styles lasted for the whole experiment.

More participants supported the forearm when using the small trackball (18 participants) than when using the large trackball (12 participants), which was reasonable, as the large trackball reached about 2 cm higher up from its holder than the small one. No participant supported the forearm or the hand when using the thin pen-on-arm; a difference from the more relaxed grip of the thick pen, where 8 participants supported the hand on the tablet and 6 supported the forearm. All participants supported the hand or the forearm when using the mouse. Thirteen participants supported the hand. The others worked with the extensor muscles in a static position over the mouse.

There were no instructions on handgrip and fingering. Two fingers were used to roll the small trackball, but two, three, or four to roll the large trackball. When the trackballs and the mouse were used the co-ordination of thumb, fingers, and hand was helped by supporting the hand on the table while the fingers were working. The co-ordination between little finger-thumb-other fingers was accomplished by supporting either the little finger or the thumb while the other fingers worked. This grip, particularly with a cold hand, implied that the three middle fingers worked as a whole partly resting on the mouse or trackballs. In general, when working with a cold hand, the participants pressed the fingers towards each other (adduction), presumably to increase precision and co-ordination. When working with a warm hand, the fingers were not adducted. A thumb-two-finger grip of the thin pen for maximum precision and concentration required static abduction (bent outwards) of the arm. When using the thick pen-on-arm, a thumb-three- or four-finger grip was used, requiring less flexed fingers. At the start of Session 1 all participants but one put one finger on the key of the mouse; this finger was presumably also used for aiming. The 19th participant used two fingers, and showed a better performance. During Sessions 2 and 3 two more participants used two fingers.

No general MANOVA was applied to fingering. The measure number-of-fingers was not assumed to mean the same for all devices. Summarised over participants with devices as cases, the Walsh test (Siegel & Castellan, 1998) showed a significant increase in the number of fingers used from Session 2 to Session 3 if the only left-handed participant was left out, and from Session 2 to Session 4 with and without the left-handed participant. Thus, participants used more fingers in Session 3 than in Session 2, and continued to do so in Session 4. Separate significant changes between Session 2 and 3 turned out for the thin pen-on-table and the thin pen-on-arm.

When considering large and small trackballs and thick and thin pens only, male participants, not women, used (insignificantly) more fingers to manipulate the computer devices of larger dimensions. Only 2 participants changed their fingering when working with the mouse, as said earlier, but about half of the participants changed their fingering between each session, and all participants made some adjustments. It seems as if they sought the optimal grip.

3.4. Participants' Ratings

The participants' performance ratings during the experiment referred to the small target subtests. The main effects of device and session were highly significant on the participants' ratings of device appropriateness, acquisition time, and error, but there were no interaction effects. Thus, differences between the devices were recognised by the participants, as well as the effect of cooling on performance, but the notice of selective effects of cold on the use of the devices was insignificant. Further, there was a significant device effect on the ease-to-hit target ratings but only a tendency to significance for the main effect of the session.

The thin and thick pens-on-arm got the highest ratings and were judged as about equally appropriate. The trackballs got the lowest ratings. The mouse and the thin pen-on-table came in between (see Figure 6b). The large versus the small trackball and the thick versus the thin pen-on-arm were tested alone to explore the effects of dimensions. The thick pen-on-arm was the only device not rated as more difficult to use in the cold, which thus caused a highly significant interaction effect between dimension and session.

Participants also rated the keys of the trackballs and the mouse, and rated the former as significantly more difficult to use than the mouse key. The participants seemed to move the trackballs accidentally when pressing the keys. When the participants ranked the devices in order of appropriateness for work with a cold as well as a warm hand after the experiment, these rank orders came out the same as the corresponding order of the appropriateness ratings after Session 3 and Session 4.

Appropriateness ratings correlated significantly with ease-to-hit the target in 14 out of 18 possible times. There were only five significant correlation coefficients with rated time and one with rated errors, so subjective appropriateness of the device was mainly equivalent to ease-to-hit the target. Clicking the keys of the trackballs significantly added to the appropriate ratings in the cold Session 3 according to regression analysis, where all subjective ratings were entered.

Acquisition time ratings and appropriateness ratings correlated in a few instances with acquisition times, but no ratings at all correlated with the number of errors. Both men and women overestimated the number of errors; men by 8 and women by 3.

Participants were asked for comments on their performance after the experiment. Seven participants spontaneously compared the trackballs to the pens, and 5 of them thought that the pens were easier to use because they demanded fewer finger movements. The participant who later was found to have had the lowest acquisition times said, "I use the arm movements anyway" and the participant with the fewest errors, "I tried to work in the same way with a cold as with a warm hand." The slowest participant said, "It was difficult to hold the pen with a cold hand, the mouse and the trackball were better then." The participant making most errors said, "...difficult to hold the pen; [but] you get warmed up by working with the large trackball using the whole hand."

4. SUMMARY OF RESULTS

The main results of the usability of the devices and the detriment of cold were in line with what was learnt from the literature. MANOVAs of performance data showed significant effects of device type, cooling, and target size, and of learning with cold hand. Acquisition times of the trackballs were twice as long as of the pens-on-arm (which were about 1.5 s in the small target subtests), and the pen-on-table and the mouse fell in between. The direct visual feedback available from the use of a template shortened acquisition times by half a second, which is of interest to work in the cold. With a target size equal to the large target used here, participants manage work with the input devices pen and mouse equally well when moderately cold as when warm. Gender or experience did not show up as important features in this study, with the exception that women made more errors than men in the small targets subtests.

The trackballs were relatively sensitive to target size, and cold had a general effect on trackball management. Difficulties with the thin pen when cold could be attributed to the small target alone.

The only experimental effect on errors was the significantly higher number of errors with the small than with the large target. Judged from the performance measures, it should be concluded that participants retained their ambitions to be correct in the cold condition but reduced the work pace as stated by Gentile (1987) and Hammarskjöld (1992).

All participants changed their fingering between sessions, but not their working posture. Data allows for the interpretation that participants learn to work with cold muscles and that fingering influences the results so that synchronous use of fingers is better, and that this is what participants learn when they manage a device in the cold, as well as to use large muscle groups. The rated subjective appropriateness of a device seemed to be synonymous to ease-to-hit the target.

Participants' ratings were not in accordance with measured acquisition times, nor were they with errors. The thick pen-on-arm was the only device not rated more difficult to use in cold.

5. DISCUSSION

Cooling was efficient. The participants tried the devices in two orders and no effects of order on acquisition times were noted. Thus, we assume that the experimental design shows the experimental effects of learning, device, cooling, and target size, as well as effects of gender and practice.

In all device tests the large target subtest preceded the small target subtest. This layout potentially made the results from the large and the small target subtests come closer than should have been the case if the design varied the order, as each time participants tested the small target, they had practice from the large target. Still, target size influenced the results in such a way that we can state that a target with a size similar to a displayed button causes no more problem when the hand is cold than when it is warm, whereas a target of the size of a check box does. An example of a check box size is the closing box of a window or the box used to resize a window.

All participants used the large trackball before the small trackball, and all participants used the thin pen-on-table before they used the thick pen-on-table. When planning the experiment dimensionality was implicitly assumed to be comparable over the devices. Afterwards, this assumption seems less certain. Participants worked faster with the small trackball than with the large one, and faster with the thick pen than with the thin one. The inertia of the large trackball can have played a part. The observed relaxed handgrip of the thick pen, made possible by the larger dimension, seems to have been for the better.

Participants did not take their own estimates of the number of errors into account when judging the appropriateness of the devices. It is possible that participants attribute errors to themselves rather than to devices and conditions. If so, one should be careful to add measurements or observations when evaluating designed tools. The participants' appropriateness ratings were more positive for the large than for the small dimensions of the trackball and the pen in the cold. The participants' appropriateness ratings were not explained by performance data. These two indications make measurements even more important, though preferences should always be noted.

As there were only two target sizes no precise estimate of optimal target size can be offered. In cold environments, pull-down menus should not be smaller than on ordinary computers, and check boxes and radio buttons should be avoided, as their size is similar to the size of the small target. In a cold environment pens could be better than shown here, because they are easily warmed up by the hand, and can be stored in a warm pocket. Trackballs and mice in a cold room would be further cooling the hand. Besides, from the results presented in this study, even if users may rest the wrist they have to raise the hand and thus work with static tensions on the upper side of the hand and the forearm when working with trackballs. It can not be concluded that fine muscle movements are more dependent on direct visual feedback, than the whole positioning of the hand, as suggested by Graham and MacKenzie (1996), as the half-second which users gained per movement when benefiting from direct visual feedback was attributed to *k*'1, the general constant in Fitts' test.

Cold hand conditions had no effect on body posture. There were variations between participants but their individual styles lasted for the whole experiment. The outward deviated wrist, caused by use of the mouse, was also noted by Karlqvist (1997). One explanation could be that participants both want to hold along the mouse and aim with the fingers in the direction of the axes of the virtual room of the computer.

It is noteworthy that fingering varied between individuals, and that the participants changed handgrip. After having noted the various styles, it could be asked whether some participants stress afferent and other participants efferent information. If participants were instructed to hold the devices in specific ways it could perhaps be possible to tell. Fingering seems to play some role according to the tendencies found among correlation coefficients with acquisition times and errors, and because participants changed handgrip so often. Additional reasons for change of handgrip could be dissatisfaction with the performance and nervousness. That in turn means that the devices are not designed so that it is apparent how they should be used.

The program used for measurements worked satisfactory, but it was recognised that HyperCard Player should not be used with faster tasks because it is possible that it not will manage the data storage then.

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