Ease of Juggling: Studying the Effects of Manual Multitasking

Antti Oulasvirta, Joanna Bergstrom-Lehtovirta
Helsinki Institute for Information Technology HIIT
Aalto University and University of Helsinki
PO Box 19800, 00076 Aalto University, Finland

ABSTRACT

Everyday activities often involve using an interactive device while one is handling various other physical objects (wallets, bags, doors, pens, mugs, etc.). This paper presents the *Manual Multitasking Test*, a test with 12 conditions emulating manual demands of everyday multitasking situations. It allows experimenters to expose the effects of design on "manual flexibility": users' ability to reconfigure the sensorimotor control of arms, hands, and fingers in order to regain the high performance levels they experience when using the device on its own. The test was deployed for pointing devices on laptops and Qwerty keyboards of mobile devices. In these studies, we identified facilitative design features whose absence explains, for example, why the mouse and stylus function poorly in multi-object performance. The issue deserves more attention, because interfaces that are nominally similar (e.g., "one-handed input") can vary dramatically in terms of "ease of juggling."

Author Keywords

Multi-object manual performance, human–computer interaction, multitasking, usability, interface design, evaluation.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms

Human factors, design, measurement, experimentation.

INTRODUCTION

We spend most of our waking hours engaged in activities involving physical objects [1,7,20,27,28]: mugs, pens, doors, bags, carts, wallets, steering wheels, packs, etc. (see Figure 1). Dealing with an additional object while one is "supposed to be" doing something else is common even in professional and safety-critical domains. Drivers attend objects such as CDs, A/C controls, and navigation assistance while driving [12] and work in IT companies, hospitals, and airplane cockpits appears to be no exception [5,16,30].

CHI 2011, May 7–12, 2011, Vancouver, BC, Canada.

Figure 1. Everyday multitasking situations often involve simultaneous manipulation of physical objects.

The present paper is the first to analyze *multi-object manual performance in HCI*, which we define as users' ability to maintain high performance upon the introduction of secondary manual demands. To begin with, the issue is nontrivial. For example, Figure 2 presents six ways of holding a medium-sized object while typing text on a mobile device. The issue is also timely. In particular, mobile devices are intended to be usable in the maximum possible number of everyday situations, but observations suggest that users struggle with the physical objects involved [20,28]. Novel user interfaces (UIs) have been proposed to improve multitasking, among them haptic [17], wrist-based [3], hands-free [32], one-handed [18], posture-independent [13], crossmodal [8], and nomadic [24] interfaces. However, the issue's relevance extends beyond mobile use: "ease of juggling" is a desirable quality in many kinds of interactive system from treadmills to calculators.

Unfortunately, the models and methods available in HCI do not touch upon the relevant kinesiological aspects of multitasking, and the models that do, in psychology and ergonomics, overlook the issue of multiple objects. Designers and developers would benefit from a method that quantifies consequences of manual constraints and would help them to see beyond the traditional categories of one-handed versus two-handed interaction.

To address this call, we constructed a brief test, the *Manual Multitasking Test (MMT)*. The MMT consists of 12 conditions informed by statistics on time use [1,7,27] and emulating manual constraints frequent in everyday activities: holding a pen or pack of cigarettes, holding a rail on the subway, pushing a button, holding scissors, opening a door, etc. The test addresses the following manual factors:

- use with the non-preferred hand
- reservation of a whole hand for something else
- reservation of various *parts* of a hand
- application of force in two directions simultaneously
- fixation of finger position
- fixation of index-finger-to-thumb distance
- restricted movement of the shoulder, elbow, and wrist
- protrusion of an object into the work area of a device

The logic is to compare performance affected by manual constraints to unconstrained performance. From the scores obtained, an overall *Manual Multitasking Index (MMI)* is calculated that expresses the "cost" of constraints. The index ranges from 0 (performance floors in every condition) to 1 (top performance reachable with each constraint). MMT is lightweight; it can be run alongside standard usability evaluation. We do not expect a design to be chosen solely based on how well it can be used while holding pens, pushing carts etc., but the issue should be given consideration when 1) manual multitasking is common and, furthermore, 2) uncompromised user performance is desirable.

We applied MMT in two studies for common input devices. Study 1 looked at one-handed use of pointing devices on a laptop computer and Study 2 examined two-handed operation of Qwerty keyboards on a smartphone. Over the two studies, we were able to identify features that prevent negative consequences of manual constraints, such as instability of grip, low acuity of tactual sensing, inappropriate direction of force, and suboptimal movement paths.

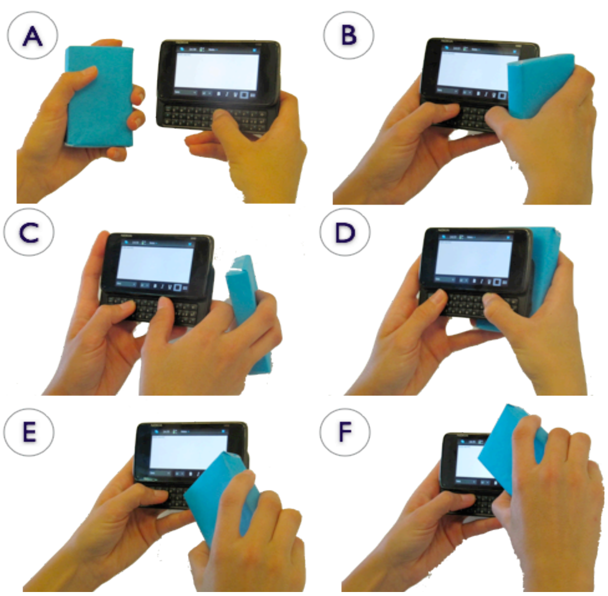


Figure 2. What happens when a pack of cigarettes must be held during texting? A) Switching to a one-handed use, B) palming the pack, C) holding the pack with unused fingers, D) using it as a support surface behind the device, E) using it to press buttons, or F) using it to press the touchpad.

Relevant Work in HCI Research

The functioning of the human hand—its anatomy, physiology, and motor control—was accorded the status of a topic for scientific research in the late 19th century [10]. At present, it is subject to research in many fields of pure and applied sciences. Modeling work aims at achieving a close fit with human data. The models range from simple point models to simulations of physical properties of joints, skin, bones, and motion [29]. None of the models we know of, however, address performance with multiple objects.

In the HCI context, the topic has been recognized, particularly in the area of novel user interfaces, where several solutions have been presented with the general goal of freeing the user's resources for multitasking [3,8,13,17,18,24,32]. However, to our knowledge, no principle-based approach (either method or model) has been proposed that would address the issue in general:

1. *Analytical methods for assessment of manual tasks* have been proposed, but their focus is on factors causing musculoskeletal extremities, discomfort, fatigue, and strain. A recent handbook [26] presented 15 methods for assessing the physical ergonomics of work postures and manual handling tasks, including such factors as position and flexion/extension of muscles, exertion of force, dynamic and static loads, repetitive loads, and vibration.

Of the other analytical methods we are aware of, a recent adaptation of task analysis for mobile HCI comes closest to what is needed [23]. The method includes "templates" for observation of user behavior, and physical objects are distinguished as a separate category.

2. *Theories of multitasking*, such as the Multiple Resources Theory [31], explain how perceptual, cognitive, and motor resources are organized when multiple tasks are handled. However, we could not find theories of multitasking that cover anatomical and kinesiological aspects of the hand as a factor in multitasking.

3. *Empirical studies of interactive performance* have addressed the contributions of different parts of the motor system when a device is used on its own. Zhai et al. [33], for example, studied the contributions of muscle groups in 6 DOF input, concluding that fingers should be preferred in interface design (on the use of fingers, see also [2][21]), and Gokturk and Sibert [4] studied the index finger as a pointing device. Lee and Su [13] empirically recorded variations in performance, posture, and strain on the hand–arm–shoulder musculature with different input devices. Bimanual versus single-handed interaction was dealt with in work by Guiard [6] and by Leganchuk et al. [14]. Research on typing has exposed many factors (use of the hands, the slope and tilt of buttons, etc.) that affect performance with keyboards [15]. We sought to address many of these factors in the design of the MMT.

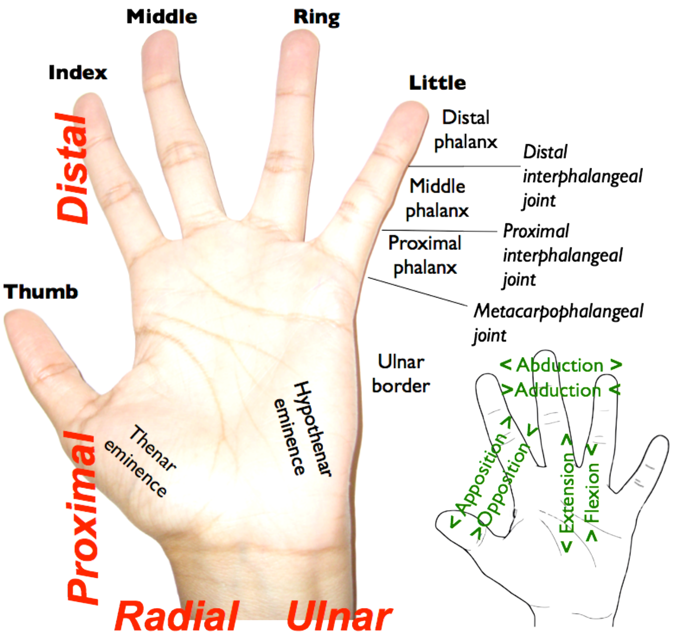


Figure 3. Volar aspects of the hand, with basic anatomical and kinesiological terminology used in this paper [10].

THE MANUAL MULTITASKING TEST

The human hand is a multi-fingered prehensile used for both gross motor skills (grasping) and fine motor skills (picking up a needle). Its capacity for innumerable patterns of action is here analyzed in terms of muscles, joints, receptors, and movements.

The hand has three main muscle groups: the thenar (palm) group acts on the thumb and its metacarpal, the hypothenar group acts on the little finger, and the interossei and lumbrical muscles act "within" the hand. The main joints are metacarpophalangeal joints and two types of interphalangeal joints of the hand and radiocarpal joints and carpometacarpal joints of the wrist. Perception through the hand is based on tactile and somatosensory information, as well as proprioceptive information of hand position and conformation. Because receptors are unevenly distributed to different parts of hand, tactual acuity is uneven, with fingertips being most precise. The basic movements are 1) apposition/opposition of thumb with other fingers, 2) abduction/adduction of digits, and 3) extension/flexion of the palm. In addition, circumduction, rotation, and pronation/supination are enabled by upper limbs.

The basic anatomical and kinesiological terminology necessary for this paper is given in Figure 3. For more background, we refer the reader to a textbook [10].

Developing a Representative Set of Manual Constraints

The Manual Multitasking Test is a set of task conditions developed to study the effects of manual constraints on interactive performance. Our goals in development of the MMT were (in no particular order):

1. Representativeness of daily multitasking situations
2. Coverage of kinesiological conditions
3. Informativeness
4. Applicability to UIs of different kinds
5. Cost-efficiency

The core idea is that of a *manual constraint*: an additional *requirement* (e.g., holding or manipulating a physical object) or a *restriction* to regular performance (e.g., the preferred hand cannot be used). The set of constraints in the MMT were developed in two phases.

First, we examined time-use statistics from the USA [1] and Finland [27]. For example, ATUS [1] reports that waking hours are spent as follows: 5.3 hours per day in leisure and free time, 3.5 h working, 1.8 h in household activities, 1.2 h eating and drinking, 0.8 h purchasing goods and services, 0.5 h taking care of members of the household, and 0.5 h in educational activities. To develop a list of candidates, we enumerated typical objects related to these activities, then grouped similar items, and finally ranked these according to hours spent per day. A caveat is that the available statistics lack data on kinds of objects. In the second phase, we selected a subset that maximally covers factors of hand functioning known to affect manual performance. In addition to the factors we list in Table 1, we considered tasks applied in gerontology to assess the motor capabilities of an elderly person [7]. Based on the review, it was clear that not all factors could be addressed and that "isolating" a factor through a single constraint is impossible if the conditions should also be representative. Our choice was to prioritize representativeness over kinesiological coverage. Consequently, the resulting set is a mix of simple constraints (e.g., `Dominant-Only`) and complex multi-part constraints (see e.g., `Scissors` and `Tongs`).

Handedness: • Switching to the non-preferred hand • Switching from bimanual to one-handed input • Inability to dedicate one hand to supporting the device
Upper limbs: • Constrained contribution of upper limbs to large hand movements • Detraction from synergies among limbs • Unfamiliar viewing and grasping angle • Occlusion of the device display
Hand: • A new, longer, or more complex movement path • New motion requiring more individuation in controlling the fingers • Changing the type of grip • Having to perform motion and use force simultaneously
Fingers: • Changing the direction of force applied • Exerting force when fingers have poor contact • Exerting force when fingers are in flexion/extension • Touching indirectly, via a mediating object • Decreasing the distance between hand and contact • Changing the allocation or number of involved fingers

Table 1. Possible negative effects of manual constraints. Collected from [10] to inform construction of the MMT.

When scoping the test, we made several decisions. First, we excluded biomechanical factors and consequences, such as strain and fatigue, since these are covered in earlier work [26]. Second, in order to dissociate attentional and perceptual demands of tasks as much as possible, we chose to emphasize static tasks over dynamic ones. In (informal) observations of multi-object performance, we noticed that users rarely perform *two* tasks at the same time that involve dynamic and complex motion with the hands. We return to discuss this choice at the end of the paper.

Task Conditions

At the core of the MMT are 12 conditions that emulate demands arising frequently in the real world. The tasks are described in Table 2, with the associated instructions to subjects.

In the test, handedness is studied in `Dominant-Only` and `Non-Dominant-Only` conditions, where only one hand or the other may be used. `No-Support`, where the device is placed on a level surface, addresses the importance of allocating a hand to support the device.

Anatomically, the test covers not only hand constraints but also restrictions to movement of upper limbs: the shoulder (`Big-Object`) and the wrist (`CoffeeMug`). Most of the conditions involve static motion (holding an object), with the exception of `Push-Rail` and `Pull-Rail`, which require isometric motion. They were included because directional application of force is common (opening doors, carrying a bag, holding somebody's hand, etc.). The two variants were included because different parts of the hand are needed to produce force and to balance the bar: the proximal part of the palm and distal parts of the fingers, respectively. `Push-Button` also requires use of force but reserves only the index finger.

The rest of the tasks address *ways* in which the hand is reserved. `Tongs` reserves the "pinch" posture (opposition of index finger and thumb), which is important in tasks requiring tactual accuracy. `Scissors` reserves two fingers, the thumb, and optionally another finger, but it requires keeping their distance constant, which further restricts the degree of freedom in controlling the rest of the palm. The objects in `Medium-Object`, `Scissors`, and `CoffeeMug` are large enough to actually protrude into the work area of an interface held in the hand.

Protocol for Administering the MMT

The MMT is an "analogy experiment": a task is carried out in as natural a fashion as feasible but still in the laboratory, with minimal distraction. The test can be carried out as a supplement to regular usability testing. Given a) two or more interface solutions one wants to compare and b) a task, the outline of data collection is as follows:

1. Decide on the subset of constraints. Not all conditions are representative or informative (for example, the effect may be so strong that it is known in advance).

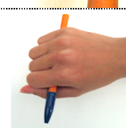
Name	Illustration	Task Instruction
`(Baseline)`		Try to find a way to perform the task that is natural for you.
`Dominant-Only`		Keep your non-dominant hand in your pocket and perform the task with your dominant hand only.
`Non-Dominant-Only`		Keep your dominant hand in your pocket and complete the task with your non-dominant hand only.
`No-Support`		The device is placed on the table. Use it as you like, but do not hold or touch its bottom side or sides.
`Pull-Rail`	3.0–3.5 kg inward force 	Pull the rail (wooden bar) so that it stays between the marked points all the time. The pulling parts of your hands should be at, or outside, the marked points. Pull the rail with your hands – you are not allowed to push with other parts of your arm (forearm, wrist etc.).
`Push-Rail`	3.0–3.5 kg outward force 	Push the rail (wooden bar) so that it stays between the marked points at all times. The pushing parts of your hands should be at, or outside, the marked points. Push the rail with your hands – you are not allowed to push with other parts of your arm (forearm, wrist etc.).
`Push-Button`		Push the button (light switch) with the fingertip of the index finger of your dominant hand. The indicator light for the button press should not turn off during the task.
`Small-Object`		Hold the pen (a BIC ballpoint pen) in your palm so that both ends of it are visible from the sides of the hand.
`Medium-Object`		Hold the box (here, a pack of cigarettes) in the palm, so that the thumb wraps around it and is on the side opposite the other fingers.
`Big-Object`		Hold the basketball / soccer ball under the arm of your dominant hand. Do not let it slip or move down.
`CoffeeMug`		Hold the coffee cup by the handle in your dominant hand, still enough not to spill (a marker is placed 4 cm from the top to signify spilling).
`Tongs`		Keep the clothes peg open in your dominant hand, between the thumb and one of the fingers. There should be no marks of pressure seen in the modeling clay placed between the arms of the peg.
`Scissors`		Hold the scissors in your dominant hand so that your thumb and at least one finger go through the handles. Keep the scissors spread enough that they can't cut a piece of paper placed in between.

Table 2. Conditions in the MMT.

2. Develop a dependent variable (DV) for performance of the main task that is reliable and cost-efficient.
3. Decide on details of the baseline condition (unconstrained) that corresponds to regular usage as much as possible (e.g., sitting or standing, lighting, etc.).
4. Ensure comparable conditions, particularly between interface solutions in the test conditions.

The rest of the steps follow standard experimental procedures, with the following precautions:

5. Employ a within-subjects design, counterbalancing the order in which 1) the interfaces and 2) manual conditions appear across subjects.
6. Decide on the level of statistical power desired and calculate the sample size required.
7. Design pre-trial instructions and practice so as to ensure that performance under test conditions does not overly reflect the novelty of the situation.
8. After running a pilot, execute the experiment.
9. After preprocessing of outliers and missing data, calculate MMI (see below), and analyze video-recordings.
10. Comparing MMIs across experiments is not advised if different dependent variables and MMT conditions are used.

The manual multitasking index, or *MMI*, is calculated simply as a ratio of the obtained scores:

$$\text{MMI} = \frac{\text{avg. performance in constrained conditions}}{\text{avg. performance in } \texttt{Baseline}}$$

STUDY 1: POINTING ON A LAPTOP

Two studies were conducted with the MMT. Study 1 was a target acquisition experiment where three input devices were compared: Mouse, Trackpoint (also known as a pointing stick), and Touchpad (Figure 4). The difference between the Touchpad and Trackpoint is subtle: both are used with the index finger and thumb, but with the Trackpoint the index finger is fixed in its spatial location, whereas the Touchpad provides greater freedom, thanks to its small working area. Moreover, the Trackpoint is used by exerting directional force from the distal tip of the index finger and the Touchpad is used through planar movements of the index finger on the pad. In this experiment, selection with the Touchpad took place by tapping and with the Trackpoint by pressing of a button with the thumb. The difference between these two and Mouse, which turned out to be the best in unconstrained performance but worst in terms of MMI, is less subtle: Mouse is used by palming the device while the thumb is kept on the side. It contacts most of the palm all the way to the ulnar border.

Figure 4. Input devices (IBM ThinkPad T43) in Study 1.

In Study 1, we did not need to apply the whole MMT, because these devices are operated with one hand and because some conditions (such as `Scissors` and `Push/Pull-Rail`) were deemed atypical of laptop use. Therefore, five constraint conditions were included with the `Baseline`: `Non-Dominant-Only`, `Small-Object`, `Medium-Object`, `Big-Object`, and `CoffeeMug`.

Method

Twelve students (2 F, 10 M) were recruited from a technical university (mean age 24.6 years, SD=2.3). Nine were right-handed. Self-reported daily use of computers ranged from three to 16 hours, with a mean of eight hours (SD=4.7).

The experiment followed a 6x3x5 within-subjects design, with the MMT condition as the first factor, input device as the second, and target radius as the third. The main dependent variable (DV) was *time-to-target.* There were 40 targets for every condition+device combination, yielding, in total, 720 targets per subject. The order of experimental conditions was counterbalanced for MMT conditions by reversing and for input device by rotating.

The experimental task was to select, as quickly as possible, a target circle appearing on the screen. Subjects sat on a chair in an office, in front of a desk on the edge of which we placed the laptop (an IBM ThinkPad T43, with a 15.1" display set to a resolution of 1400x1000 px). A mouse pad (size 17.5x21.5 cm) was placed 1 cm from the edge of the laptop (see Figure 4). The *IDTest Cursor Motion Test Application* [25] was used to control stimuli and measure response times. To get enough spread to targets, the radii of the target circles were set to 3, 28, 53, 78, and 103, while distance-to-target and angle-of-approach were randomized. Display brightness was set to maximum and pointer speed to 7 (from a range of 0–10 in the Windows XP control panel) for all input devices.

The procedure was organized as follows. All subjects were trained to use the input devices and instructed to find their "natural style of use." Subjects were instructed to sit with their back straight and told that none of the computer, table, or chair should be moved. The five (plus baseline) MMT conditions were described, with instructions that the object should not fall during the task and objects should not touch the table or computer or any parts of it during the task, or touch the chair where the subject was seated. In one-hand conditions, the other hand was kept in the lap. `CoffeeMug` used the "official ACM coffee mug" (15 cm tall, radius of 3 cm, glass), filled with water to 4 cm from the rim. In the `Big-Object` condition, we used a size-5 men's soccer ball. Before every MMT condition, the subject had a chance to practice freely. If a user failed in a task – for example, was unable to select any targets – two retries were allowed (only the last attempt was included in the data analysis). The 40 targets were divided into two sets of 20 each, with a short break in between. Each experiment lasted about 1.5 hours.

Results

The results show a crossover between unconstrained and constrained performance. In the unconstrained (`Baseline`) condition, Mouse was the best device, Touchpad second best, and Trackpoint worst (Figure 5, left panel). However, user performance with Mouse was more devastated by the manual constraints: Its MMI was the lowest (0.6). In MMT conditions, the Touchpad was the best and the Trackpoint second best (see Figure 5, right panel).

A closer look at data in Figure 6 shows that there were significant costs found in all conditions. Moreover, reliable differences among the input devices were present in all conditions except `Big-Object`, and they were particularly large between Mouse and Trackpoint. The only condition that did not show a difference between these two was `CoffeeMug`, which was associated with close-to zero performance with both interfaces. Performance with Mouse was distracted from by all constraints. In `Big-Object`, performance was closest to maximum. The two other input devices were much less susceptible to the two other object-holding conditions (`Small-Object` and `Medium-Object`).

There were no strong effects of background variables. Self-reported daily computer use was the only predictive factor: users reporting more than median hours per day showed significantly better unconstrained performance (1.90 s, 95% CI ± 0.05 s) than others did (2.00 ± 0.06 s), but their MMI (0.81 ± 0.07) was not (0.76 ± 0.08).

Qualitative findings are postponed to the end of the paper.

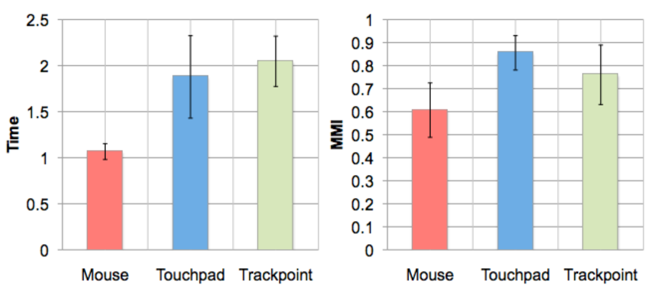


Figure 5. Baseline (unconstrained) performance (left) and MMIs (right) in Study 1. Vertical bars denote 95% confidence intervals (CIs) calculated from Student's t-distribution.

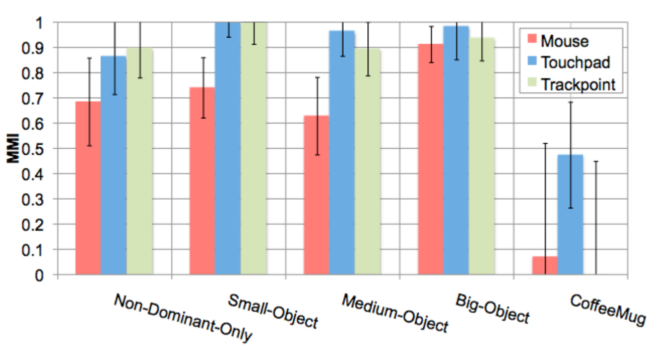


Figure 6. Breakdown of MMIs for the manual conditions in Study 1, calculated as the ratio of constrained to baseline (unconstrained) performance. Vertical bars denote 95% CIs.

Figure 7. Mobile text entry methods compared in Study 2.

STUDY 2: TEXT ENTRY ON A MOBILE DEVICE

Mobile text entry was chosen as the second topic because mobile HCI involves heavy multitasking (e.g., [20,28]) and the race is going on to discover which interaction technology suits mobile use the best. In Study 2, we compared three input devices for text entry on a mobile device: Touchpad-Qwerty, Stylus-Qwerty, and Physical-Qwerty, all on a single device (a Nokia N900; see Figure 7).

The difference between Physical-Qwerty and Touchpad-Qwerty is small, restricted mostly to tactile feedback from button edges and the location of visual feedback. By contrast, the difference from these two to Stylus-Qwerty is dramatic. Stylus-Qwerty demands opposition of index and middle finger with the thumb. And it demands support for the keyboard to hold it steady. For Study 2, we tested the full MMT of Table 2, except for `Small-Object`, which a pilot test determined to be uninformative (the pen was easily held in a way that did not distract from anything).

Method

Twelve students (7 M, 5 F) were recruited from a local technical university (mean age 23.6 years, SD=0.6). Eleven were right-handed. Two were currently using Touchpad-Qwerty, one Physical-Qwerty, and the rest an ITU-12 keypad with T9. Six subjects used touch-typing on their regular PC keyboards. The mean computer usage was 8 h/day. Five subjects reported sending fewer than 10 text messages per week, four 10–20, and three 20–50.

The experiment followed a 12x3 within-subjects design with the MMT condition as the first factor and input device as the second. The order of the two was counterbalanced, via reversal for MMT conditions and by rotation for interfaces. Every subject completed 36 trials. The main DV was *the number of correctly transcribed letters in 30 seconds*.

The experimental task was text entry, or, more precisely, entry of a text message shown on a computer display for 30 seconds (following the method used in [22]). In every trial, five sentences were presented on the display, taken from a set of 500 sentences translated by Isokoski into Finnish [9] from the set of MacKenzie and Soukoreff [19]. No punctuation marks, other special characters, or uppercase letters were used. The Nokia N900's *Notes* application was utilized for recording. The phone was set to the Finnish language with horizontal keyboard layout. Vibrotactile feedback and key-press sounds were set to Level 1 and predictive text entry turned off.

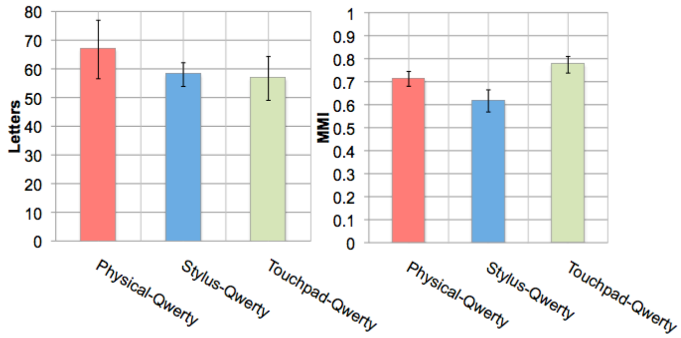


Figure 8. Baseline (unconstrained) performance (left) and MMIs (right) in Study 2 (DV: number of correct letters in 30 s). Vertical bars denote 95% CIs.

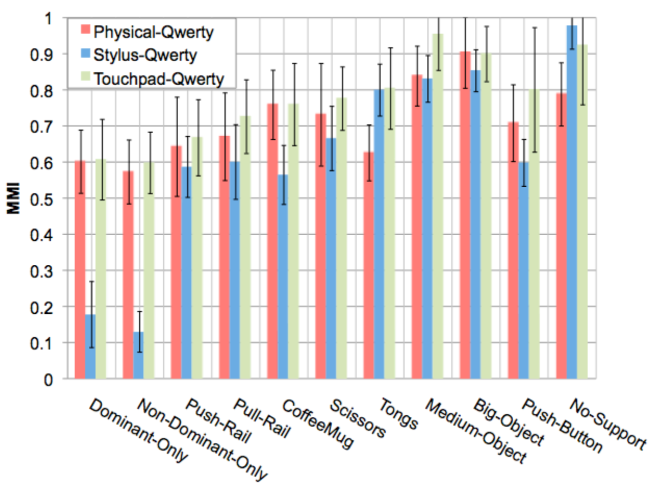


Figure 9. MMIs for manual constraint conditions in Study 2. Vertical bars denote 95% CIs.

In all MMT conditions, users were standing still in a lab room. The following specifics apply to the MMT in this study: The `Push-Rail` and `Pull-rail` conditions used a 2.5-centimetre-thick, 80-centimetre-long wooden rail, so that the hands were at least 8 cm apart from each other. The rail was positioned 1 meter above the floor, and the user had to keep it constant in the range of 3–3.5 kg of force, measured with a digital fish scale. `Scissors` used a standard pair of plastic-handled scissors designed for paper, with a piece of paper placed between the blades, so that the shortest distance between the ends of the handles should be 5 cm in order that the piece of paper not be cut. The `Big-Object` condition used a size-7 (men's) NBA basketball. The `Push-Button` condition used the MacBook trackpad's button, positioned vertically so that the hand could be kept in the normal pointing posture.

The procedure was organized as follows. Subjects were first trained to use each keypad and told to find a way to use them that "feels natural." They were told to hold the device with just the hands; it was not to be placed on lap or on the table, except in `No-Support`. Users had a chance to practice with each MMT condition. Again, three attempts were allowed. NASA-TLX was administered after each 30-second task. One experiment lasted about 1.5 hours in total.

Results

A crossover was seen here for two of the input devices: Physical-Qwerty was the best in unconstrained performance, but Touchpad-Qwerty was the best in terms of MMI (Figure 8). The stylus was the worst in MMI conditions.

Looking more closely at MMIs from the MMT conditions in Figure 9, one can see that all constraints were effective. There were differences among the devices in all conditions except `Big-Object` and `Push-Rail`.

As in Study 1, an effect for a background variable was found. Previous experience had an effect on MMI: Four subjects who had prior experience with Touchpad-Qwerty had a higher MMI for this device than for the other devices (mean MMI of 0.85, 95% CI ±0.04, as compared with 0.77±0.02).

There was a moderate correlation (r=-0.54) between MMI and workload (avg. of mental, physical, frustration, and effort components in NASA-TLX). In other words, high workload was associated with low MMI (Figure 10).

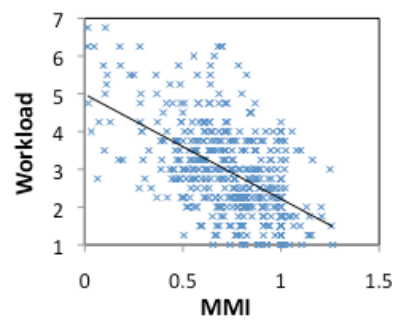


Figure 10. A moderate correlation of *r*=-0.54 was found between MMI and Workload in Study 2. MMIs > 1.0 may occasionally take place when users perform better than in the baseline condition.

OBSERVATIONS OF POSITIVE DESIGN FACTORS

Among the general observations is that no interface was superior in *all* manual conditions; instead, each was associated with both positive and negative outcomes. Analyzing the video recordings, we identified four design factors that had a positive contribution to multi-object performance.

1. Enabling commanding with only one part of the hand: In Study 1, Mouse suffered significantly in both the `Small-Object` (25%) and the `Medium-Object` (35%) condition, while the Trackpoint and Touchpad were virtually unaffected. The reason is that moving a mouse requires simultaneous control by two parts of the hand: proximal parts (eminence) push it "forward," and the distal phalanges of the fingers pull it back. This simultaneous contribution of many muscle groups may explain why the mouse is superior in *unconstrained* performance. However, if either part of the hand cannot contact the mouse cover properly, control suffers. Touchpad, by contrast, only reserves the index finger; the remaining capacities of the hand can be used for the secondary object. Figure 11 illustrates the difference.

Figure 11. When the pen was to be held in the palm, pointing was more difficult with Mouse than the Touchpad (Study 1).

2. *Affording one hand supporting and manipulating simultaneously*: Having to switch from two-handed input to one-handed input caused an average decrease of about 50% in Study 2. However, comparing data from No-Support and the one-handed conditions (Dominant-Only and Non-Dominant-Only) revealed an interesting pattern: in the former, Stylus-Qwerty was the best, while in the latter it was the worst. The reason is that for Touchpad-Qwerty and Physical-Qwerty, a single hand can both hold the device and exert force on the interface. By contrast, Stylus-Qwerty demands a secondary hand or a static surface on which the device is placed. Stylus-Qwerty requires a long distance (3–6 cm) be maintained between the display surface and the fingers controlling the pen. Figure 12 illustrates three strategies to cope with this demand in one-handed use.

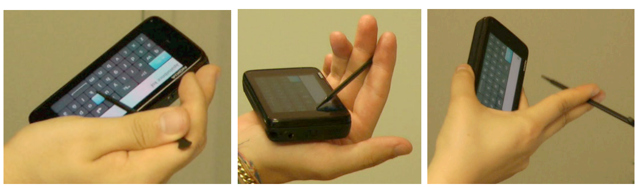


Figure 12. Three strategies observed in one-handed use of Stylus-Qwerty (Study 2).

3. *Enabling input with minimal force from the fingertips*: To our surprise, although similar in most respects, in its MMI Touchpad-Qwerty was better than Physical-Qwerty in four conditions: Tongs, Medium-object, Push-Button (borderline-significant difference), and No-Support. The reason is that Physical-Qwerty requires application of force from the fingertips, which is difficult if the secondary task requires force to be applied *elsewhere* [11] (see Figure 13, left panel). Tongs, for example, requires applying force in the "pinch" posture (index finger and thumb opposed), making it difficult to apply the required force to the buttons at the same time.

Performance in the No-Support condition suffered from a related symptom. The problem with Physical-Qwerty is that the force from two fingers pressing down the buttons should be *even*; otherwise, the N900 sways and is unstable (see Figure 13, right panel). *Force-matching*—matching of the force produced by individual fingers—is known to be difficult [11]. By contrast, the Touchpad-Qwerty interface does not require downward force nor force-matching to the same extent and is therefore easier to operate.

Figure 13. Physical-Qwerty was poor in conditions that required simultaneous application of force elsewhere (left) or force-matching from one finger to another (right).

4. *Enabling input without "caging" the palm*: A key problem with the stylus is that pen grip is required. In effect, this grasp cages the rest of the hand, which hampers holding of other objects and causes a direct conflict when another object should be held in the palm. Both CoffeeMug and Scissors involve a physical object that cages the palm (Figure 14, left). In addition to restricting use of the palm, the pen grip competes for the index finger. This explains the poor performance of Stylus-Qwerty in the Push-Button condition. Here, the response of half of our users was to change the inputting hand (Figure 14, right panel).

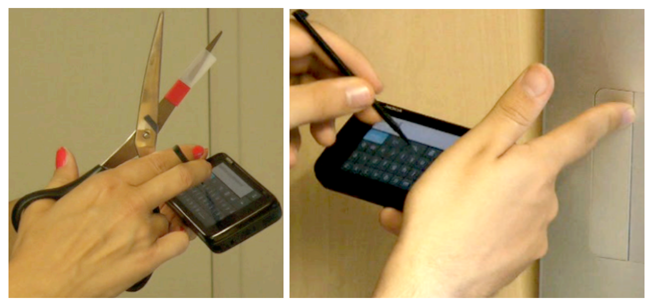


Figure 14. Manual conditions in Study 2 that disrupted the pen grip of Stylus-Qwerty: Scissors and Push-Button.

Four other observations are worth mentioning:

- *Handedness*: Having to switch from the preferred hand to the non-preferred hand resulted in a decrease of about 20% (Study 1). Interestingly, Mouse suffered proportionately more (about a 30%) than other interfaces did.
- *Upper limbs*: The upper limbs contribute specifically to large movements with the hand. Performance with Mouse was somewhat hampered (about 10% decrease) by having to hold a large object (soccer ball) under the armpit.
- *Simultaneous application of force with the fingertips and parts of the palm*: Having to apply force with the proximal or distal part of the hand and simultaneously using the fingertips for interaction quite uniformly detracted from performance. We observed a roughly 33% decrease in the Push-Rail and Pull-Rail conditions, although not all of it can be attributed to this factor alone.
- *Restricted movement path of middle and proximal phalanxes:* Entering text while holding a pack of cigarettes was difficult with Physical-Qwerty, because depressing

the buttons requires middle and proximal phalanges of fingers to contribute, which was compromised by the object. By contrast, touching the Touchpad display requires almost no force from the fingertips.

DISCUSSION

There is a blind spot at the intersection of two important areas of HCI—manual performance and multitasking. This paper has examined a novel approach to study the richness, flexibility, and importance of the human hand in multitasking. We proposed a test for studying "ease of juggling" or, the other way around, the "vulnerability" of interaction to manual constraints. The *Manual Multitasking Test* (MMT) allows an experimenter to quantify performance costs across a wide variety of conditions emulating everyday demands. The test is reasonably lightweight and it requires no special equipment. Because the MMT is task-based, it can be run alongside usability testing.

The two studies provide positive indications for sensitivity. Each MMT condition turned out to be effective in the sense that at least one significant cost was found across the tested UIs. Moreover, the crossover effects observed suggest that performance with manual constraints is not trivially predicted by unconstrained performance. Manual flexibility was also associated with subjective workload (Study 2).

The strength of the MMT is its systematicity: It draws attention to factors that would not be considered by accident. The most surprising of our findings was that touch-based interaction emerged as a "winner." Haptic feedback from button edges and presses has been shown to be important for users' ability to use a device without looking at it (e.g., [22]). The present results suggest that the requirement to produce force counteracts performance in situations like `Tongs` and `No-Support` that demand force simultaneously elsewhere.

Proceeding from findings like this, we were able to identify four beneficial design factors. Indeed, the goal of the test is not just to rate techniques, but also to help with designing better ones. However, the opportunities for design must be quite considerably larger than what the MMT exposed here. When we conducted Study 2 with the (almost) full set of tasks, our initial plan was to look for redundancies among conditions, to create a minimal set of constraints for maximum information gain. Instead, it is likely that *more* conditions will be needed. The present MMT can serve as a starting point for creating variants to serve any domain of human activity from surgical theaters to information work. If one disagrees with a particular condition, the test can be amended, extended, or modified.

For designers applying the method, we recommend that performance costs greater than 20% (MMI < 80%) be taken seriously. In Study 2, the average cost for Stylus-Qwerty was about 40%, whereas for Touchpad it was only a little over 20%. Generally, drops of more than 20% were observed in situations where interaction was uncomfortable, unnatural, cumbersome, or laborious. In Study 2, a drop of 20% in MMI was associated with a 0.55 drop in workload (full range 1-7). Such effects must be reflected in users' willingness to use these devices also in real-world multitasking. However, our manual constraints were imposed fairly rigidly and left little room for clever circumventions that might occur in real situations. Consequently, a low index should be interpreted as indicating not that something is *impossible* but that the familiar way of doing it is. On the other hand, one could argue that the MMT *under*estimates costs, because in a laboratory test users are more willing to be inventive and invest effort in finding alternative ways of using a device.

For developing the MMT further, one area that calls for further study is the interplay of manual factors with attentional and perceptual factors, which contributed decidedly little in the design of the MMT. Our assessment was that adding these demands would have overly complicated the administration of the test, requiring analysis of the speed–accuracy tradeoff in not one but two tasks. Also of concern should be that the method focuses on effects of short-term overloading, but in the future we cannot ignore the issue of biomechanical effects due to sustained postures. We conclude that, while the strength of the method is that it simplifies a complex phenomenon, future work must ask whether added realism is needed.

As a final note, we want to point out that multi-object manual performance is a safety issue. How well, for example, do MP3 players mix with bicycling? Or would a roofer trying to reply to a message while standing on a ladder be better off with an ITU-12 keypad than with Qwerty? Anecdotally, bans on hand-held-phone calls during driving were imposed without critical consideration of how "free" the hands actually are with hands-free interfaces. We hope that research on this topic will eventually enable designers and policymakers to transcend naïve categorization of interfaces as "one-handed," "two-handed," or "hands-free."

ACKNOWLEDGEMENTS

This work was funded by the Tekes project Theseus2 and by the Emil Aaltonen Foundation. We thank Céline Coutrix, Yanqing Cui, Stephen Brewster, Poika Isokoski, Anna Shefl, Jari Laarni, Miikka Miettinen, Tuomo Kujala, Sami Ronkainen, and Eve Hoggan for help and comments.

REFERENCES

1. American Time Use Survey ATUS. *Tables for 2009.* United States Department of Labor, Bureau of Labor Statistics. http://www.bls.gov/tus/tables/a1_2009.pdf
2. Balakrishnan, R., and MacKenzie, I. Performance differences in the fingers, wrist, and forearm in computer input control. In *Proc. CHI'97*, ACM Press (1997), pp. 303-310.
3. Crossan, A., Williamson, J., Brewster, S., and Murray-Smith, R. Wrist rotation for interaction in mobile con-

texts. In *Proc. MobileHCI'08*, ACM Press (2008), pp. 435-438.

4. Gokturk, M., and Sibert, J. An analysis of the index finger as a pointing device. In *Ext. Abst. CHI'99*, ACM Press (1999), pp. 286-287.
5. González, V., and Mark, G. Constant, constant, multi-tasking craziness: Managing multiple working spheres. In *Proc. CHI'04*, ACM Press (2004), pp. 113-120.
6. Guiard, Y. Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *Journal of Motor Behavior 19* (1987), 486-517.
7. Haley, S., Jette A., Coster WJ, et al. Late Life Function and Disability Instrument: II. Development and evaluation of the function component. *Journal of Gerontology: Medical Sciences 57* (2002), 217–222.
8. Hoggan, E., and Brewster, S. Designing audio and tactile crossmodal icons for mobile devices. In *Proc. ICMI'07*, ACM Press (2007), pp. 162-169.
9. Isokoski, P., and Linden, T. Effect of foreign language on text transcription performance: Finns writing English. In *Proc. NordiCHI'04*, ACM Press (2004), pp. 109-112.
10. Jones, L.A., and Lederman, S. *Human Hand Function.* Oxford University Press, USA, 2006.
11. Jones, L.A., and Piateski, E. Contribution of tactile feedback from the hand to the perception of force. Experimental Brain Research 168 (2006), 298–302
12. Klauer, S.G. et al. An analysis of driver inattetion using a case-crossover approach on 100-car data: Final report. *National Highway Traffic Safety Administration*: DOT HS 811 334, USA, 2010.
13. Lee, Y., and Su, M. Design and validation of a desk-free and posture-independent input device. *Applied Ergonomics 39*, 3 (2008), 399-406.
14. Leganchuk, A., Zhai, S., and Buxton, W. Manual and cognitive benefits of two-handed input: an experimental study. *ACM TOCHI 5, 4* (1998).
15. Lewis, J., Potosnak, K., and Magyar, R. Keys and keyboards. In Helander et al. (Eds.), *Handbook of Human-Computer Interaction*, Lawrence Erlbaum (1997), NJ, USA, pp. 1285-1315.
16. Loukopoulos, L., Dismukes, R., and Barshi, I. Cockpit interruptions and distractions: A line observation study. In *Proc. International Symposium on Aviation Psychology*, Columbus: Ohio State University (2001).
17. Luk, J., Pasquero, J., Little, S., MacLean, K., Levesque, V., and Hayward, V. A role for haptics in mobile interaction. In *Proc. CHI'06*, ACM Press (2006).
18. Lyons, K., Starner, T., Plaisted, D., Fusia, J., Lyons, A., Drew, A., and Looney, E. Twiddler typing: One-handed chording text entry for mobile phones. In *Proc. CHI'04*, ACM Press (2004).
19. MacKenzie, I., and Soukoreff, R. Phrase sets for evaluating text entry techniques. In *Ext. Abst. CHI'03*, ACM Press (2003).
20. Mainwaring, S.D., Anderson, K., and Chang, M.F. Living for the global city: Mobile kits, urban interfaces, and ubicomp. In *Proc. Ubicomp'05*, Springer-Verlag (2005), pp. 268–286.
21. Oakley, I., Sunwoo, J., and Cho, I. Pointing with fingers, hands and arms for wearable computing. In *Ext. Abst. CHI'08*, ACM Press (2008), pp. 3255-3260.
22. Oulasvirta, A., and Bergstrom-Lehtovirta, J. A simple index for multimodal flexibility. In Proc. CHI'10, ACM Press (2010), pp. 1475-1484.
23. Ronkainen, S., Koskinen, E., Liu, Y., and Korhonen, P. Environment analysis as a basis for designing multi-modal and multidevice user interfaces. *Human-Computer Interaction 25*, 2 (2010), 148-193.
24. Sawhney, N., and Schmandt, C. Nomadic radio: speech and audio interaction for contextual messaging in nomadic environments. *ACM TOCHI 7*, 3 (2000).
25. Smith, B. *IDTest Cursor Motion Test Application*, 1999, http://www.almaden.ibm.com/u/basmith/testapp.html.
26. Stanton, N. *Handbook of Human Factors and Ergonomics Methods*. CRC Press, 2005.
27. Statistics Finland Time Use Study 1999-2000. http://pxweb2.stat.fi/Database/StatFin/klt/akay/akay_en.asp
28. Tamminen, S., Oulasvirta, A., Toiskallio, K., and Kankainen, A. Understanding mobile contexts. *Personal and Ubiquitous Computing 8*, 2 (2004), 135-143.
29. van Nierop, O., van der Helm, A., Overbeeke, K., and Djajadiningrat, T. A natural human hand model. *Visual Computer 24*, 1 (2008), 31-44.
30. Westbrook, J., Ampt, A., Kearney, L., and Rob, M. All in a day's work: an observational study to quantify how and with whom doctors on hospital wards spend their time. *Medical Journal of Australia 188*, 9 (2008).
31. Wickens, C.D. Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science 3*, 2 (2002), 159-177.
32. Witt, H., Nicolai, T., and Kenn, H. Designing a wearable user interface for hands-free interaction in maintenance applications. In *Proc. Pervasive Computing and Communications Workshops*, IEEE (2006), pp.-655-659.
33. Zhai, S., Milgram, P., and Buxton, W. The influence of muscle groups on performance of multiple degree-of-freedom input. In *Proc. CHI'96*, ACM Press (2006).