Subjective User Experience and Performance with Active Tangibles on a Tabletop Interface

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Abstract. We developed active tangibles (Sensators) that can be used in combination with multitouch tabletops and that can provide multisensory (visual, auditory, and vibrotactile) feedback. For spatial alignment and rotation tasks we measured subjective user experience and objective performance with these Sensators. We found that active feedback increased accuracy in both tasks, for all feedback modalities. Active visual feedback yielded the highest overall subjective user experience and preference scores. Our contribution is that active feedback improves subjectively perceived performance and reduces perceived mental workload. Additionally, our findings indicate that users prefer to be guided by visual signs over auditory and vibrotactile signs.

Keywords: Tangible interfaces · User experience · Tabletop · Multimodal · Active feedback

1 Introduction

Tangible user interfaces (TUIs) provide an intuitive way to interact with digital information through manipulating physical objects. They combine the dynamic qualities typical of digital information with physical affordances. In combination with multi-touch tables TUIs provide passive haptic feedback and visual feedback. Users can handle TUIs similar to everyday objects, which simplifies system interaction and reduces cognitive load. The power of this concept is for instance effectively illustrated by Urp [1], an application for working with architectural elements in the context of urban planning and design, which allows users to move physical models of houses around on a tabletop surface to observe changes in sunlight and shadows.

Frequently quoted benefits of TUIs include eyes-free interaction, spatial multiplexing and bimanualism [2] and the natural affordances of tangible objects [3, 4]. In addition, they can be acquired faster and manipulated more accurately than for instance multi-touch widgets or a mouse in simple control tasks [5, 6].

Active feedback refers to the ability to actively influence the interaction, e.g. by changing the object's position or orientation, or multimodal feedback via the haptic,

N. Streitz and P. Markopoulos (Eds.): DAPI 2015, LNCS 9189, pp. 212–223, 2015.
DOI: 10.1007/978-3-319-20804-6_20

auditory or visual modality. Most TUIs currently used with multitouch tabletops are passive objects that offer no active feedback. If active feedback is provided at all, it is usually only in the visual modality and on the tabletop surface (e.g. in the form of halos or virtual knobs around the tangibles), forcing users to look at the table to see the effect of a manipulation. Actuated TUIs can convey task relevant information through multiple or alternative sensory channels, thus facilitating information processing by simplifying information and guiding user attention. In addition, multimodal feedback has the ability to enhance both objective and subjective performance measures in tasks with high perceptual and cognitive load [7]. Vibrotactile cues can effectively replace visual progress information [8, 9] and visual alerts [10], although they are not effective when replacing visual direction or spatial orientation cues [10]. Audio cues have been found to speed up task performance [11], and can attract attention to tangibles that are outside the field of view. Hence, distributing feedback over different modalities may reduce workload and enable multitasking by reducing within- channel interference [12–14]. In addition, actuated TUIs that are linked to and dynamically represent digital information afford bidirectional interaction while maintaining consistency between the physical interfaces and their representations [15], between remotely coupled TUIs [16, 17], or between TUIs and their underlying digital model [18].

We developed active tangibles (Sensators, Fig. 1) that can wirelessly communicate with for instance a tabletop surface and provide direct visual, auditory, vibrotactile, or multimodal feedback while taking haptic input, thereby allowing an intuitive interaction that stretches even beyond the boundaries of the tabletop surface. In addition, wireless connectivity allows to store information in these objects and reuse them on another tabletop or to superimpose different objects, thus enabling distributed interaction between different users on different tables [19, 20].

Fig. 1. The Sensators. The grey areas are coated with conductive paint and are connected with touch sensors. Left: activated Sensator emitting red light. Right: numbers on top serve to identify the Sensators. Arrows serve to indicate their orientation.

In contrast to passive tangibles, Sensators can actively guide the user and confirm when they have reached a given location and orientation through multisensory feedback. Hence, Sensators have the potential to enhance and intensify the interaction and collaboration experience between users (e.g. on multitouch surfaces) by supporting new interaction styles and techniques. In this study we investigated user performance with Sensators in two spatial tasks: a Movement and a Rotation task. Our first hypothesis (H1) is that both tasks will be performed faster and with higher accuracy (i.e. a lower error rate) when receiving active feedback compared to receiving only passive visual feedback. Our second hypothesis (H2) is that visual feedforward cues signaling which of the Sensators have to be moved will lower task completion timed by reducing search time. Thirdly, we hypothesize (H3) that any form of active feedback will improve subjective user experience by reducing the amount of cognitive effort required to determine the state of the system and the effects of one's actions. Finally, (H4) we expect that active visual feedback will enhance user experience to a larger extent than auditory and tactile feedback, because people are less experienced at being guided by vibrotactile [21] and auditory signs [10, 22, 23], and because vision dominates the auditory and haptic sense in spatial tasks [22, 24].

2 Related Work

Active tangibles have been introduced before in the context of tabletop systems. The Haptic Wheel [25] is a mobile rotary controller providing haptic feedback for eyes-free interaction to reduce cognitive load and visual attention in visually demanding tasks. The SmartPuck [26] is a multimodal tangible interface providing visual, auditory and tactile feedback which has been used to navigate geographical information in Google Earth. Touchbugs [27] are autonomously moving TUIs that can provide haptic feedback and accept haptic input. Tangibles that move autonomously [18] or provide vibrotactile collision feedback [28] have been demonstrated in furniture arrangement scenarios. Active tangibles have also been used for auditory and haptic rendering of scatter plots [29].

However, there are only a few studies on user experience and performance with active tangibles [30, 31]. It appears that active tangibles can effectively support users in solving complex spatial layout problems [30] and in fine-grained manipulation tasks [31] by providing haptic feedback. In this study we further investigate the experience and performance with active TUIs providing multisensory feedback in two spatial tasks.

3 Methods

3.1 Participants

21 adults (10 females, 11 males, mean age = 36.7 years, age range: 20–48 years) were recruited for this experiment. 17 participants were right-handed. None of the participants had any physical disabilities. Participants were compensated €30, - for their participation. All participants used a computer on a weekly basis (M = 30 h per week). 12 participants played computer games on a weekly basis (M = 6 h per week). 20 participants had previous experience with multi-touch technology on mobile phones. One participant had previous experience using a multi-touch tabletop interface.

3.2 Material

A Samsung Surface 40 (SUR 40: www.samsung.com) was used as a multi-touch tabletop computing device. The SUR 40 allows users to directly manipulate digital content using both multi-touch hand gestures and through the manipulation of tangibles. The SUR 40 features a 40 inch Full HD (1080p) display and multiple Bluetooth connections. The active tangibles (referred to as ‘Sensators’ in the rest of this study) used in this experiment were specially developed to be used in combination with an interactive multi-touch tabletop. Each Sensator (6.5 × 6.5 × 5.0 cm) includes an Arduino mini micro-controller and a Bluetooth communication module which enables communication with the SUR 40. The Sensators can convey vibrotactile, visual and auditory feedback through various functional parts. Embedded in their translucent 3D printed housing are two small electronic motorized actuators or tactors. Each tactor can independently produce nine levels of vibrotactile signals. An RGB LED centered on top underneath the housing enables a Sensator to display different colors. An embedded mp3 audio processing shield enables a Sensator to play mp3 audio output signals. A Sensator also contains two independent touch sensors connected to the top of its four sides. See [32] for more details.

In this study each Sensator was marked both with its number (1, 2 or 3) and an arrow symbol (2D orientation), while a fiducial marker was attached to its bottom. This enabled the SUR40 to track both the location and orientation of each Sensator independently. The experiment was performed in a brightly lit room with white walls. The participant stood directly behind the SUR 40. A side table was placed next to the SUR 40 on its right side. A blue A4 paper sheet, attached to the surface of this side table within reaching distance of the participant’s right arm, functioned as a target location during some phases of the experiment. The experimenter stood about 3 m from the participant, and operated a tripod mounted video camera to record the experiments.

3.3 User Tasks

Participants performed two task: a *Movement Task* which involved the displacement of the Sensators to different designated target positions, and a *Rotation Task* which involved adjustment of the orientation of the Sensators to a single designated target site. During the experiments the display of the SUR40 showed an abstract map with a realistic appearance but without any cues that might interfere with the task. A map was used as background since it likely that Sensators will ultimately be applied in the context of geographical information displays.

The three Sensators were placed on their corresponding icons on the SUR40. Prior to the start of each trial the screen showed two buttons: one on left side labeled ‘Start 1’ and one on the right side labeled ‘Start 2’. To ensure that the participant’s hands were in the same starting position for each trial these two buttons had to be pressed simultaneously for 200 ms. After starting a trial a grey button labelled ‘Finish’ appeared in the bottom center of the screen. By pressing this button the participant could finish the trial. White circles labeled H1, H2 and H3 served as a passive visual cues during the experiment, indicating target locations for the Sensators with corresponding labels.

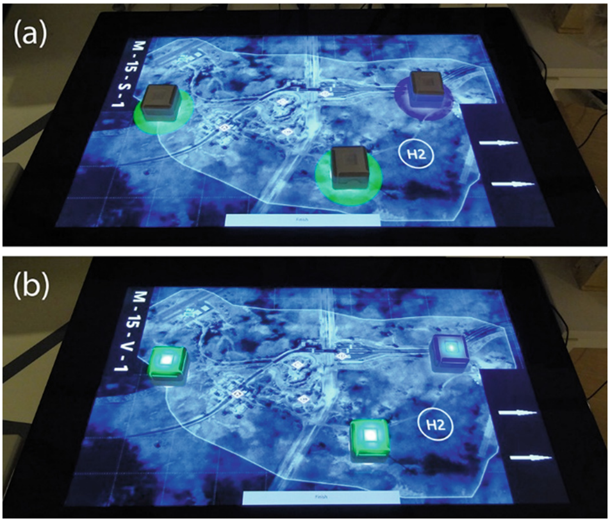

Fig. 2. Tabletop mode (upper) and visual feedback (lower) modes used in the Movement Task. The two Sensators on the left are in their correct positions.

Movement Task. At the start of each experiment the Sensators were placed on icons with corresponding numbers (H1, H2, and H3) shown in the lower part of the SUR40 map display. On each trial up to three target icon positions were updated on the screen, and the participant ‘s task was to move the Sensators with updated target locations to their new positions as accurately and quickly as possible. Participants were asked not to lift the Sensators from the table surface, since the SUR40 needs direct contact with a Sensators’ fiducial marker to track its location and pointing angle. They were allowed to use both hands. Each trial that ended with one or more Sensators not in the correct position was labeled as incorrect.

Performance in the Movement Task was tested for six different feedback techniques, which served to quickly guide the users to the correct target location in a stepwise fashion. Four feedback modes were actively provided by the Sensators: Vibrotactile, Auditory, Visual and Multimodal (= Visual + Auditory + Vibrotactile). In addition, the Tabletop provided visual feedback, and we included no feedback or Baseline condition. In the Vibrotactile feedback mode, the Sensators started vibrating when they came within 300 p (22 p = 1.0 cm) of the target location. At a distance of 200, 100 and 50 p the vibration intensity increased stepwise. Vibration stopped when the Sensator came within 8 pixels (the error margin) of the target location, indicating the correct location had been reached. In the Auditory, Vibrotactile, and Multimodal modes the intensity of the feedback signal increased stepwise while approaching the target and stopped when the Sensator had reached its target position. The Auditory feedback technique was similar to the Tactile technique, but instead of a vibration the Sensator produced a tone that increased in pitch when it approached the target location. In the Visual feedback mode Sensators with an updated target location turned blue. When a Sensator came within the error margin of its target location the Sensator turned green indicating the correct position had been reached (see Fig. 2). The Multimodal feedback technique was a combination of the individual Vibrotactile, Auditory and Visual feedback techniques. In the Tabletop visual feedback mode Sensators with an updated target position were surrounded by a blue disc (R = 140 p) with an opacity of 50 %. This disc (which served as a feedforward cue) remained underneath a Sensator while it was being moved to its new location, and it turned green when the target position was reached (Fig. 2). In the Baseline mode, no feedback was provided and the Sensators acted as passive tangibles. In this case, the users only had the target icons on the tabletop surface as passive visual cues. Participants performed 15 trials per feedback technique.

Rotation Task. Throughout this experiment the Sensators were at fixed locations, indicated on the SUR40 display by icons labeled with their corresponding numbers (white discs with R = 3.5 cm, labeled H1, H2, and H3). On each trial of the Rotation Task a single red disc (R = 1.5 cm) appeared at a different location on the SUR40 display, and the participants had to rotate all three Sensators to orient their pointing angles to this target as accurately and quickly as possible. They were allowed to use both hands. Each trial that ended with one or more Sensators not correctly oriented was labeled as incorrect.

Performance in the Rotation Task was tested for six different feedback techniques, which served to quickly point the users to the correct target orientation in a stepwise fashion. In the Vibrotactile feedback mode a Sensator started vibrating when the pointing angle of the Sensator came within 50 degrees of the angular direction of the target. At angles of 40, 30 and 20 degrees the vibrating intensity increased until it came within 10 degrees (the error margin), when it stopped vibrating indicating it pointed in the correct direction. Auditory feedback was similar to Vibrotactile feedback, but instead of vibrating the Sensator produced a tone which increased in pitch until it pointed in the correct direction. In the Visual feedback mode all Sensators became blue at the start of each trial and they turned green when the Sensators were correctly oriented. A Sensator that was displaced for more than 5 cm from its start position would turn red. The Multimodal feedback technique was a combination of the Vibrotactile, Auditory and Visual feedback techniques. In the Tabletop visual feedback mode a Sensator that needed to be reoriented was surrounded by a blue disc (R = 140 p) with an opacity of 50 %, which turned green when the Sensator was turned in the correct direction. In the Baseline mode, no feedback was provided and the Sensators acted as passive tangibles. In this case, the participants could only use the target icons on the tabletop surface as passive visual cues. Participants performed 15 trials per feedback technique.

3.4 Experimental Design

The experiment was performed according to a 2 × 6 within-subject design with **Task type** (*Movement Task*, *Rotation Task*) and **Feedback modality** (*Vibrotactile*, *Auditory*, *Visual*, *Multimodal*, *Tabletop*, *Baseline*) as independent variables. Each of the six feedback levels was tested in a separate block of trials. Each participant performed six blocks of 25 trials (150 trials in total). Each block started with 15 trials of the Movement Task (of which the first three were practice trials), followed by 10 trials of the Rotation Task (of which the first two were practice trials).

For each trial in the experiment we logged accuracy and task completion time. Accuracy was defined as the fraction of trials that was correctly performed. Task completion time was the time that elapsed between the start of a trial and the moment the finish button was pressed. To measure perceived workload participants scored two items from the NASA Task Load Index (NASA TLX: “How mentally demanding was the task?” and “How successful were you in accomplishing what you were asked to do?”) on a 20 point scale [33]. Participants also rated their overall experience of the different feedback techniques on two nine point bipolar semantic rating scales from the Questionnaire for User Interaction Satisfaction (or QUIS: respectively item 3.1: ranging from ‘terrible’ to ‘wonderful’, and item 3.4: ranging from ‘difficult’ to ‘easy’ [34–36]). Finally, at the end of the experiment the participants were asked rank order the six feedback modalities for both tasks from ‘most preferred’ to ‘least preferred’. Analysis of variance (ANOVA) was used to test the relationships between the main variables, Bonferroni correction was applied where appropirate. The statistical analyses were performed with IBM SPSS 20.0 for Windows (www.ibm.com).

3.5 Procedures

At the start of the experiment the participants read and signed an informed consent. Then the experimenter explained the multi-touch system and the Sensators and he demonstrated the Movement Task and the Rotation Task. Then six experimental blocks were presented in a randomized order. After each block the participants rated the applied feedback technique for each task using the UEQ. At the end of all six experimental blocks the participants rank ordered the six feedback techniques according to their subjective preference. The experimental protocol was reviewed and approved by TNO internal review board on experiments with human participants, and was in accordance with the Helsinki Declaration of 1975, as revised in 2000 [37].

4 Results

One participant was excluded because of an incomplete dataset. Nine participants reported a lag in the multimodal feedback condition for both tasks, which probably resulted from a software error. Analysis of the videos showed that the lag reached up to 300 ms. Since a lag of this magnitude will significantly affect the results [38] the Multimodal condition was not further analyzed in this study.

The ANOVA showed that for both tasks the mean accuracy scores were significantly lower for Baseline feedback ($p < .001$), while they did not differ significantly between the other feedback techniques. Feedback resulted in an average of 92.5 % accuracy, in contrast to a Baseline accuracy of 70 % (Table 1).

Table 1. Mean (SD) accuracy per feedback condition (N = 20)

Feedback modality	Movement task	Rotation task
Auditory	0.96 (0.07)	0.96 (0.07)
Tabletop	0.93 (0.06)	0.96 (0.08)
Vibrotactile	0.89 (0.07)	0.86 (0.11)
Visual	0.92 (0.08)	0.95 (0.06)
Baseline	0.70 (0.21)	0.66 (0.21)

Incorrect scores were excluded in the calculation of the task completion time and the scores were cutoff at 15.000 ms. For the Movement Task, one-way repeated measures ANOVA revealed no significant difference between mean task completion time in all five feedback conditions. For the Rotation Task, the ANOVA showed that Tabletop feedback resulted in significantly faster task performance than both Vibrotactile and Baseline feedback ($p < .001$), while Visual feedback was also faster than Vibrotactile feedback ($p < .05$). The means for both tasks are given in Table 2.

Table 2. Mean (SD) task completion time (ms) per feedback condition (N = 20

Feedback modality	Movement task	Rotation task
Auditory	8153 (1021)	8388 (1358)
Tabletop	8202 (1241)	7869 (1204)
Vibrotactile	7935 (1139)	9232 (1461)
Visual	8005 (1343)	8183 (1104)
Baseline	7462 (1781)	9324 (1740)

The NASA TLX measured perceived performance and mental workload on two 20 point scales. A Wilcoxon signed-rank test showed that for both tasks participants rated their performance significantly higher in both the Visual and Tabletop feedback modes than in the other modes ($Z = -3.078$, $p < .005$), while performance in the Baseline mode was perceived as worse compared to all other feedback modes. A similar analysis showed that both Visual and Tabletop feedback yielded significantly less perceived mental workload than Vibrotactile and Baseline feedback, while Auditory feedback did not differ significantly from all other feedback techniques. Since there were no interaction effects both scores were combined in Table 3.

Table 3. Mean (SD) NASA TLX scores per feedback condition (N = 20)

Feedback modality	Movement task	Rotation task
Auditory	5.1 (3.2)	6.3 (4.4)
Tabletop	3.9 (2.9)	4.6 (2.9)
Vibrotactile	5.7 (2.7)	7.6 (4.0)
Visual	3.4 (2.3)	4.3 (2.3)
Baseline	9.2 (4.9)	9.0 (5.1)

The QUIS was used to measure user experience on two nine point scales labeled terrible-wonderful and difficult-easy. A Wilcoxon signed-rank test showed that for both tasks participants rated both the Visual and Tabletop feedback as significantly more wonderful than the Auditory, Vibrotactile and Baseline feedback techniques ($Z = -3.467$, $p = .001$). A similar analysis showed that participants found both Visual and Tabletop feedback significantly easier to use than Vibrotactile and Baseline feedback, while there was no significant difference between Visual and Tabletop feedback. Since there were no interaction effects both scores were combined in Table 4.

Table 4. Mean (SD) QUIS scores per feedback condition (N = 20)

Auditory	4.9 (2.0)	6.3 (1.7)
Tabletop	7.2 (1.2)	7.3 (1.6)
Vibrotactile	5.4 (1.7)	5.2 (1.6)
Visual	7.5 (0.9)	7.6 (1.0)
Baseline	4.3 (2.1)	3.8 (2.0)

Since there were no interaction effects between both tasks, we combined their raking scores for the different feedback techniques (Table 5). Wilcoxon signed-rank tests showed that Visual feedback was rated significantly higher than Auditory, Vibrotactile and Baseline feedback ($p < .001$), while Tabletop feedback was rated significantly higher than both Auditory and Baseline feedback ($p < .005$). There was no significant difference (at the Bonferroni corrected alpha level of .005) between Auditory, Baseline and Vibrotactile feedback ($p = .04$).

Table 5. Mean (SD) rank scores per feedback condition (N = 20)

Feedback modality	Rank
Auditory	4.0 (1.2)
Tabletop	2.1 (1.4)
Vibrotactile	3.9 (1.4)
Visual	1.9 (0.9)
Baseline	5.0 (1.1)

5 Conclusions and Discussion

Hypothesis H1 (both - Movement and Rotation- tasks will be performed faster and with higher accuracy with active feedback) was only partly confirmed. Active feedback had no effect on task completion time for the Movement Task. For the Rotation Task however, both Visual and Tabletop feedback yielded significantly faster task performance than Vibrotactile feedback, while Tabletop feedback also resulted in shorter task completion times than Vibrotactile feedback. Also, all active feedback modes significantly increased accuracy for both tasks, while there was no significant difference between the accuracy in the different active feedback modes.

Hypothesis H2 (visual feedforward cues signaling which Sensators have to be moved reduce search time and thereby task completion time) could not be tested due to software errors.

Hypothesis H3 (active feedback improves subjective user experience) only holds for the Visual and Tabletop feedback modes. Participants rated their performance significantly higher in these feedback modes than in the other feedback modes while performance in the baseline mode was perceived as worse compared to all other feedback modes. Visual and Tabletop feedback also significantly reduced perceived mental workload compared to Vibrotactile and Baseline feedback, while Auditory feedback did not differ significantly from all other feedback modes in this respect.

Finally, hypothesis H4 (active visual feedback enhances user experience more than auditory and tactile feedback) was also partly confirmed. Visual feedback was rated significantly higher than Auditory, Vibrotactile and Baseline feedback, while Tabletop feedback was rated significantly higher than both Auditory and Baseline feedback. There was no significant difference between Auditory, Baseline and Vibrotactile feedback.

Summarizing, we found that all active feedback techniques increased accuracy in both tasks. Active visual (Visual and Tabletop) feedback yielded the highest accuracy in both tasks, fastest performance in the Rotation task, and overall highest subjective user experience and preference scores. Without active feedback (Baseline condition) subjectively perceived performance was lowest and perceived mental workload was highest. Although Visual and Tabletop feedback performed equally well in most cases, Visual may be preferable, since visual feedback from the tangible itself reduces clutter and occlusion on the display surface, and the signal remains visible when the tangible is used beyond the boundaries of the tabletop. Future work should investigate the potential added value of auditory or visual feedback in attracting attention to Sensators that are outside the SUR40 surface, and further investigate optimal combinations of multimodal feedback (in bi- and tri-modal combinations) and the effects of feedforward cues on task completion time.

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