An Exploratory Study on the Effects of Multimodal Feedback in Bimanual Interaction with Active Tangible Interfaces.

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I. Preface

This thesis is the product of more than 6 months of learning, exploring, and experimenting at TNO. But besides being the final deliverable of my graduation project, this thesis also symbolizes the (probable) end of my entire educational career. Over 20 years of learning, exploring, and experimenting, all starting off on the playgrounds: Little Christian, playing with blocks. Via primary and secondary school, I ended up in Eindhoven at the Department of Industrial Design, where I discovered my interests in the human factors of innovative product design. However, I was looking for more structured academic depth. Choosing the Human Technology Interaction Master was therefore a logical next step, and it turned out to be a great choice. My educational career continued and it has brought me to the metropoles of Singapore, Jakarta, Buenos Aires, Rio de Janeiro, Stockholm, and last but not least, Soesterberg, where I ended up at TNO’s ‘playground’…indeed, playing with blocks. Speaking of Innovation..

Looking back, I can say that I enjoyed all HTI aspects; all courses and projects as well as the studytour to Argentina, the international semester in Stockholm and the graduation project at TNO. For this, I have to thank all HTI students (of which some have become good friends) and teachers; Antal Haans and Wijnand IJsselsteijn in particular for supervising me and giving me valuable new insights and feedback throughout the project. Besides them, I would like thank all TNO colleagues for their help and for providing such an interesting and fun experience. In particular, I would like to thank Arnoud de Jong for developing the software for my experiments, Koos Meijer for doing lots of prework with the Sensators, Martijn van den Heuvel for repeatedly pointing out the huge benefits of the Sensators to me, but also for making me think about the real important questions in life, and Tinka Giele for making me think about the important questions with regard to the project…and for the coffee, Obviously. Last but not least, I really want to thank my TNO supervisor Joris Janssen for being supportive all the time, even when we both did not have a clue of what to do with those stupid blocks. Thanks to your interest, ideas, critical questions, and dedication to the project, I left all of our weekly meetings with newfound motivation and inspiration.

Furthermore, I want to thank my parents for supporting me and also for making my time at University – in Eindhoven as well as abroad – possible. I am the first to admit that it took slightly longer than the initially planned five years, sorry for that…but hey, at least it didn’t take me 12.5 years…

I also would like to thank my friends for being such good examples. You guys now have what we all abominated so much: civil lives. It seems to work out pretty well though. Finally, I have to thank Emma for being a mixture of someone who motivated me, someone who was critical, someone who was absolutely not interested, someone who distracted me, and someone who inspired; this was and is the mixture I need..thanks.

After this ‘Academy Award’-like moment, all I can say is that I hope you will enjoy reading this report as much as I have enjoyed working on it!

Christian Willemse
Maarssen, June 2013

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1 For the cynics: this means I hope you will enjoy reading this report a lot.
II. Summary

Technology around us is evolving; computing devices are becoming faster, more efficient and more intelligent over time. Moreover, all kinds of electronic devices are becoming interconnected; the ‘internet of things’. Since technology is becoming more and more embedded in objects around us, styles of interacting with these technologies are evolving as well. These new interaction styles draw upon the user’s skill to interact with the ‘real world’; through speech, bodily movements, and by moving and manipulating physical objects. Within this quest for new interaction styles, the research field of tangible interaction has played a prominent role for the last two decades. Accessing and manipulating digital information by means of physical objects that somehow represent this digital information has proven to be a very intuitive and rich means of interaction. One of the main advantages, when compared with traditional mouse-keyboard interfaces, is that both hands can be used simultaneously in order to provide input to a system. Research has shown that bimanual interaction can not only save a significant amount of time, but that using two hands to carry out a compound task can enhance the understanding of the task at hand.

New advancements in the field of tangible interaction involve the development of active Tangible User Interfaces (TUIs). Traditional TUIs are passive; they only provide information to the user by means of their shape and feel. When a change in the digital world occurs, this change can not be conveyed by the rigid, passive object itself. However, when a TUI contains a certain form of actuation (e.g., moving, or multimodal feedback) changes in the digital world actually can be represented; objects could move autonomously over a surface in order to match the physical setup with the digital, or objects could provide system feedback by means of colour changes or tactile feedback. This might enhance the communication capacity of the tangible system. TNO aims at gaining knowledge and exploring the added value of multimodal feedback within TUIs. To do so, they have developed evaluation tools called ‘Sensators’; generic shaped active TUIs, to be used on a digital tabletop. These TUIs allow the possibility to present the user with extra information about the system and/or the task at hand, by means of visual (colour changes), auditory, and/or vibrotactile feedback. The Sensators – and in particular their visual and tactile feedback modalities –, in relation with bimanual interaction were the starting points for this graduation project. This resulted in the following, rather general, main research question: “How should feedback in generic active tangible objects be designed to facilitate the user in asymmetric bimanual interaction?”

As said, carrying out a task bimanually can result in a higher task efficiency and better comprehension of a the task at hand. In most tasks we carry out bimanually, either in real life or in Human-Computer Interaction, the Kinematic Chain Model as defined by Yves Guiard applies. This is a typical sequence of hand movements with distinctive roles for both the dominant and non-dominant hand. Besides providing stability to the object acted upon, the non-dominant hand provides a coarse reference frame in which the dominant hand carries out its specific and precise tasks. Since each hand has got a specific function and specific characteristics (e.g., temporal precedence of the non-dominant hand, and higher precision of the dominant hand), several questions present themselves with respect to designing active TUIs. First, which sensory modality is most suitable for presenting feedback to each hand, with regard to perception of the stimuli and task performance? Second, might it be beneficial to present each of the hands with a different modality?. Bimanual interaction does not only involve task efficiency, but also cognitive burden. Therefore, these aspects were considered in the evaluation of different combinations of feedback. Besides that, the user experience was evaluated.

In recent years, research on multimodal feedback has received a considerable amount of attention. Presenting information to a user by means of other feedback modalities than vision can enhance time efficiency as well as attention management, especially in data-rich real-world domains in which operators face considerable visual attentional demands. According to the Multiple Resource Theory, people have a limited amount of semi-independent cognitive resources. When more sources of information compete for the same resource, these information channels might interfere with each other, causing a detriment in task performance. To overcome this, it might be beneficial to offload certain information to other sensory modalities, which draw upon different cognitive resources. Moreover, earlier research has demonstrated that the presentation of information in a redundant way
can enhance the task performance even further. With redundant feedback, the user always has the opportunity to offload to another feedback modality when interference between two information channels occurs. Following this Multiple Resource Theory would suggest that it is better to present asymmetric feedback (i.e., each hand presented with a different feedback modality). However, other research suggests that dividing the attention between different sensory modalities involves switching costs, especially with switching to and from tactile feedback. This might cause lower performance. In other words: It is difficult to predict how different combinations of feedback might affect the performance within an asymmetric bimanual task. Moreover, it is unclear how people experience different combinations of feedback with regard to mental load as well as user experience. To get initial insights in these questions, three different studies were conducted in which asymmetric bimanual interaction was induced. Participants were presented with different combinations of feedback.

The first study can be considered a pilot experiment, and was implemented in a Wizard of Oz fashion. A target-finding paradigm was applied in which ‘Sea battle’ was used as cover story. The goal for the participant was to locate an imaginary ship, in which the Sensator in the left hand was used to find the ‘prow’ of the ship and the Sensator in the right hand the ‘stern’. In this way, a different role was emphasized for each hand and simultaneous hand movement was encouraged. Feedback was provided about how close the Sensator was to its accompanying target. Four different feedback combinations were applied; both hands tactile feedback, the left hand tactile and the right visual (and vice versa), and finally both Sensators tactile feedback but with a physical connection between the two Sensators (i.e., a string attached between the two Sensators in order to force simultaneous hand movement). The initial results with regard to the effects of different combinations of feedback pointed to a deteriorating effect of symmetric tactile feedback with which performance was worse than with the other feedback conditions. Moreover, this combination was considered as being more frustrating and difficult than all other conditions. Because we did not include a symmetric visual condition, it could not be determined whether the negative effects of symmetric tactile feedback were mainly because tactile feedback was more difficult to interpret than visual feedback, or because the feedback was symmetric instead of asymmetric. This question was addressed in the remainder two experiments.

For both the second and third experiment, a digital picture manipulation task was designed and developed in which asymmetric hand movement was induced. The non-dominant hand was responsible for creating a frame of reference (in this case locating the picture at a predefined location) in which the dominant hand could carry out the more precise actions (scaling the picture to a desired size). Feedback provided by the Sensators would inform the user with regard to how close the Sensator was to its desired target-location respectively target-size.

The second study too was mainly exploratory. This time, each Sensator provided either visual, tactile or no feedback; resulting in nine different feedback combinations. In line with the earlier results of the Pilot-study, the symmetric tactile condition was considered the least pleasant and most mentally demanding. Moreover, performance (i.e., speed) was worst with this combination. In isolated situations (i.e., conditions in which only one of the two Sensators was presenting feedback), visual feedback resulted in better trial times than tactile feedback (both for the dominant as well as the non-dominant hand). Following this, one would expect that the symmetric visual feedback condition would thus be more beneficial than the asymmetric feedback conditions. However, surprisingly enough, this was not the case; no difference was found and the advantage of visual feedback over tactile disappeared. A possible explanation of this effect could be that two sources of visual information caused more interference than the asymmetric feedback combinations; especially since the latter draw upon different cognitive resources. The fact that asymmetric feedback was not significantly faster could be a consequence of the poor distinctness of the different tactile feedback levels.
The third experiment aimed at three different aspects; first of all, replicating the earlier found detrimental results of symmetric tactile feedback. Besides that, the effects of asymmetric feedback were explored again, but this time with increased distinctness between the different levels of tactile feedback. This is expected to enhance the performance within asymmetric feedback conditions. The third aspect which was explored was the effect of multimodal feedback in the sense that one Sensator would provide multimodal, and thus redundant feedback; both tactile and visual. This redundant information was expected to induce the highest performance, since people would have the option to offload to another sensory channel when necessary. Adding tactile to visual feedback has proven to induce more beneficial effects when compared to replacing visual feedback by tactile.

The results with regard to the third study replicate those of the first two in the sense that despite the increased distinctness, the symmetric tactile feedback caused lower task performance, higher perceived workload, and lower user satisfaction. Contrary to the expectations however, no differences in performance, perceived workload, and user experience were found; neither in comparisons between the symmetric visual condition and the asymmetric condition, nor between the symmetric visual and the multimodal conditions.

An explanation for the absence of differences could be the low task load during the picture manipulation. It could be that the different resources were not fully loaded and thus not interfering. If that is indeed the case, there is no need to offload information to other sensory modalities. Moreover, the fact that the performance within all feedback combinations (except for symmetric tactile feedback) was similar, supports the idea that the task was too easy. Another explanation might be that the symmetric visual condition actually also draws upon different mental resources (just like all other feedback combinations). These different visual resources would consist of foveal vision and peripheral vision. More research is required to investigate the effects in high cognitive load situations; in data-rich environments.

With this study, we have provided several initial insights in the effects of multimodal feedback in bimanual tangible interaction. However, more research is necessary in order to gain a more thorough understanding of the mentioned effects. We have not investigated the fixation strategies of the users during the tasks. Understanding where people mainly look at during a bimanual task, and how these fixation strategies are affected by the presentation of feedback, might provide new insights. Moreover, as described before, an explanation for the absence of effects might be that the task load was too low. An investigation of the effects of multimodal feedback during high task load situations could be useful as well; in particular since the Multiple Resource Theory mainly applies in high load situations. The third direction for possible future research we describe refers to the design of the task and the feedback. Other types of (asymmetric) bimanual movement (such as rotating or lifting the objects) might sort different effects. Moreover, adjusting the shape of the object, the parameters of the tactile feedback (e.g., adjusting frequency instead of amplitude), or the colours applied, could provide a more coherent framework for guidelines regarding multimodal feedback in bimanual tangible interaction.

The implications as derived from the three studies could contribute to the development of active TUI applications, regardless of the application domain. Moreover, this thesis contributes in the sense that it provides an example of how the multi-faceted world of active tangible interaction can be investigated systematically.
### III. Table of Contents

1. Preface ................................................................. I
2. Summary ............................................................. II
3. Table of Contents .................................................. V
4. Lists of Figures and Tables ....................................... VII
5. Abbreviations ....................................................... VIII

1. Introduction ......................................................... 1
2. Related Work ....................................................... 4
   2.1 Tangible Interaction and TNO’s Sensators ............... 4
   2.2 Two-handed Interaction ....................................... 9
   2.3 Multimodal Feedback ......................................... 12
   2.4 Rationale for the Current Study ......................... 15
3. Study 1; Wizard of Oz Pilot study: Sea Battle ............ 17
   3.1 Introduction ..................................................... 17
   3.2 Design ............................................................ 17
   3.3 Participants ..................................................... 17
   3.4 Setting and Apparatus ....................................... 17
   3.5 Procedure ....................................................... 19
   3.6 Measures ....................................................... 19
   3.7 Results .......................................................... 20
   3.8 Discussion ...................................................... 24
4. Study 2; Explorative Experiment: Picture Manipulation .. 26
   4.1 Introduction ..................................................... 26
   4.2 Design ............................................................ 26
   4.3 Participants ..................................................... 26
   4.4 Setting and Apparatus ....................................... 27
   4.5 Procedure ....................................................... 28
   4.6 Measures ....................................................... 29
   4.7 Results .......................................................... 30
   4.8 Focused Analyses Based on Observations .............. 38
   4.9 Discussion ...................................................... 40
5. Study 3; Focused Experiment: Multimodal Feedback .... 44
   5.1 Introduction ..................................................... 44
   5.2 Design ............................................................ 45
   5.3 Participants ..................................................... 45
   5.4 Setting and Apparatus ....................................... 45
   5.5 Procedure ....................................................... 46
   5.6 Measures ....................................................... 46
5.7 Results .............................................................................................................................. 46
5.8 Discussion ....................................................................................................................... 54
6. General Discussion ........................................................................................................... 57
  6.1 Main Findings and Implications .................................................................................. 57
  6.2 Limitations and Future Research .............................................................................. 59
  6.3 Concluding Remarks ................................................................................................. 62
7. References ....................................................................................................................... 63
Appendices ............................................................................................................................. 69
IV. Lists of Figures and Tables

Figure 2-1: An Impression of Iconic and Symbolic Play Pieces (Bakker et al., 2007). .............. 5
Figure 2-2: An Impression of the reacTable. Image by Jordà et al. (2007). ............................ 7
Figure 2-3: Haptic Guidance Application in the Tangible Bots (Pedersen & Hornbæk, 2011). 8
Figure 3-1: A Schematic Overview of the Pilot Study Setting. ................................................ 18
Figure 3-2: Pilot Study: Accuracy Results. ............................................................................... 20
Figure 3-3: Pilot Study: Trial Time Results. ............................................................................. 21
Figure 3-4: Pilot Study: Parallelism Results. ............................................................................ 21
Figure 3-5: Pilot Study: Hand Usage. ....................................................................................... 22
Figure 3-6: Pilot Study: Workload Results. .............................................................................. 22
Figure 3-7: Pilot Study: User Experience Results. ................................................................. 23
Figure 4-1: Study 2: Task Explanation. ................................................................................... 27
Figure 4-2: Study 2: Feedback Working Principles. ................................................................. 28
Figure 4-3: Study 2: Trial Time Results................................................................................... 47
Figure 4-4: Study 2: Parallelism Results. ................................................................................ 32
Figure 4-5: Study 2: Workload Results. .................................................................................. 33
Figure 4-6: Study 2: Mental Demand Results. ........................................................................ 34
Figure 4-7: Study 2: Frustration Results. .................................................................................. 35
Figure 4-8: Study 2: Terrible – Wonderful QUIS Scale Results. .......................................... 35
Figure 4-9: Study 2: Difficult – Easy QUIS Scale Results. ....................................................... 36
Figure 4-10: Study 2: Frustrating – Satisfying QUIS Scale Results. ....................................... 36
Figure 4-11: Study 2: Preference Responses. ......................................................................... 37
Figure 4-12: Study 2: Preferred Feedback Combinations. ..................................................... 37
Figure 4-13: Study 2: Trial Times per Image Location; Both Hands Feedback. ....................... 39
Figure 4-14: Study 2: Trial Times per Image Location; One Hand Feedback. ......................... 39
Figure 5-1: Study 3: Trial Time Results ................................................................................... 47
Figure 5-2: Study 3: Parallelism Results. ................................................................................ 49
Figure 5-3: Study 3: Workload Results. .................................................................................. 49
Figure 5-4: Study 3: Mental Demand Results. ....................................................................... 50
Figure 5-5: Study 3: Frustration Results. ................................................................................ 50
Figure 5-6: Terrible – Wonderful QUIS Scale Results. ........................................................... 51
Figure 5-7: Study 3: Difficult – Easy QUIS Scale Results. ....................................................... 51
Figure 5-8: Study 3: Frustrating – Satisfying QUIS Scale Results. ......................................... 51
Figure 5-9: Study 3: Preference Responses. ............................................................................ 52
Figure 5-10: Study 3: Preferred Feedback Combinations. ...................................................... 52
Figure 5-11: Study 3: Grades for Feedback Combinations. ..................................................... 53
Figure B-1: Sensators. .............................................................................................................. 2
Figure B-2: Sensator Feedback Demonstration Application. ................................................ 3
Figure B-3: Fiducial Marker underneath the Sensator. ............................................................ 3
Figure B-4: Conductive Touch-fields of the Sensator. ............................................................. 4
Figure B-5: An Impression of the Embedded hardware of the Sensator. ............................... 4
Figure B-6: The very first Sensators. ......................................................................................... 5
Figure B-7: Impression of the Second Generation of Sensators. ............................................. 5

Table 3-1: Pilot study Descriptive Statistics of NASA-TLX items. ......................................... 23
Table 4-1: Study 2 Visual and Tactile Feedback Values. .......................................................... 28
Table 5-1: Study 3 Visual and Tactile Feedback Values. .......................................................... 45
Table I-1: Study 2 Descriptive Statistics of the Trial Times. .................................................... 15
Table I-2: Study 2 Descriptive Statistics of the Objective Parallelism Data. ........................... 15
Table I-3: Study 2 Descriptive Statistics of the Subjective Parallelism Data. ........................... 15
Table I-4: Study 2 Descriptive Statistics of the Visual and Tactile Feedback Values. .......... 16
Table I-5: Study 2 Descriptive Statistics of the Workload Scores. ......................................... 16
Table I-6: Study 2 Descriptive Statistics of the Frustration Scores. ....................................... 16
Table I-7: Study 2 Descriptive Statistics for the Terrible - Wonderful QUIS Item. ............... 17
V. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUI</td>
<td>Graphical User Interface.</td>
</tr>
<tr>
<td>HCI</td>
<td>Human-Computer Interaction.</td>
</tr>
<tr>
<td>KCM</td>
<td>Kinematic Chain Model.</td>
</tr>
<tr>
<td>M</td>
<td>Multimodal Feedback (Used in combination with a second letter to represent experimental conditions).</td>
</tr>
<tr>
<td>MRT</td>
<td>Multiple Resource Theory.</td>
</tr>
<tr>
<td>N</td>
<td>No Feedback (Used in combination with a second letter to represent experimental conditions).</td>
</tr>
<tr>
<td>NASA-TLX</td>
<td>National Aeronautics and Space Administration – Task Load Index.</td>
</tr>
<tr>
<td>ns</td>
<td>Not Significant (mentioned after statistical tests)</td>
</tr>
<tr>
<td>QUIS</td>
<td>Questionnaire for User Interface Satisfaction.</td>
</tr>
<tr>
<td>RGB</td>
<td>Red-Green-Blue Value</td>
</tr>
<tr>
<td>T</td>
<td>Tactile (Used in combination with a second letter to represent experimental conditions).</td>
</tr>
<tr>
<td>TTlink</td>
<td>Experimental condition of the Pilot study; both Sensators present tactile feedback and are physically linked.</td>
</tr>
<tr>
<td>TUI</td>
<td>Tangible User Interface.</td>
</tr>
<tr>
<td>V</td>
<td>Visual (Used in combination with a second letter to represent experimental conditions).</td>
</tr>
<tr>
<td>Vd</td>
<td>Visual feedback presented in dominant hand.</td>
</tr>
<tr>
<td>Vn</td>
<td>Visual feedback presented in non-dominant hand.</td>
</tr>
</tbody>
</table>
1. Introduction

“We live in a complex world, filled with myriad objects, tools, toys, and people. Our lives are spent in diverse interaction with this environment. Yet, for the most part, our computing takes place sitting in front of, and staring at, a single glowing screen attached to an array of buttons and a mouse.”

The abovementioned citation reflects the principles of Mark Weiser’s (1991) vision on ubiquitous computing. Computers are forcing human beings to enter the digital world, but would it not be better to develop computers that fit the human world? Weiser states that “the most profound technologies are those that disappear” (p. 94) and aims at computing devices that become embedded in everyday objects and environments, all interconnected, but moving out of the focus of their users’ attention. Following this view, a need for new interaction styles emerged; interaction styles that merge the physical and the digital world and interaction styles that are used in a more intuitive and natural manner as Abowd and Mynatt (2000) proposed. Over the past two decades, many innovative ways of Human-Computer Interaction (HCI) have emerged that draw upon human’s skill of interaction with the ‘real world’. Speech and physical gestures are well-known examples (e.g., Apple’s Siri, Nintendo Wii), but the starting point of this thesis will be interaction with digital information by means of physical objects: Tangible User Interfaces (TUIs). TUIs actually make use of the mentioned myriad objects, tools and toys that fill our complex world.

In tangible interaction, physical objects are used to access and manipulate digital data. By means of physical objects in which technology is implemented, a user can literally grasp the digital information and transform it (Shaer & Hornecker, 2010). A TUI is directly coupled to underlying digital information and can therefore serve as both input and output device, resulting in several advantages over traditional HCI (i.e., Graphical User Interfaces (GUIs) in combination with mouse and keyboard). For instance, TUIs allow multi-person use and parallel, two-handed input. This could expand the expressiveness and the communication capacity with the computer (Fitzmaurice, Ishii & Buxton, 1995) and make tasks more efficient. Moreover, tasks can become more intuitive and comprehensible since two feedback loops are provided in parallel (Shaer & Hornecker, 2010; Ullmer & Ishii, 2000). The object itself provides physical, passive haptic feedback (i.e., basic information retrieved from the shape and feel of an object), which informs the user a certain action in the physical world is completed. Contrary to for instance the traditional mouse, this physical, passive haptic feedback provides information about the specific task at hand. The other form of feedback is provided digitally, by means of visual or auditory feedback with regard to effects in the digital world. This informs the user that his or her physical action is interpreted and processed by the computing device.

For most of the decade after the proposition of TUIs as a means of interaction, research was aimed at the technological possibilities; a proof-of-concept phase in which research was aimed mainly at providing different means of input to a digital system (Shaer & Hornecker, 2010). The physical representation of digital output as envisioned by Ishii and Ullmer (1997) was often neglected, which resulted in a lack of malleability. Contrary to digital information, TUIs were often neither malleable nor versatile; they were rigid instead and could therefore not represent changes in the digital information appropriately. Koleva, Benford, Ng and Rodden (2003) already identified the challenge to create digital artifacts that push back on the physical space and proposed active tangibles. These are tangible objects which can change their appearance based on dynamic changes in the underlying digital world.

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2 Although several different names for basically the same concept have been used throughout the literature (e.g. graspable user interfaces (Fitzmaurice et al., 1995), or props-based interface (Hinckley, Pausch, Goble & Kassell, 1994)), the most common term Tangible User Interfaces as defined by Ishii and Ullmer (1997) will be used throughout this thesis for the sake of readability.

3 The term active tangibles will be used throughout this thesis to refer to tangible objects that communicate changes in the digital world by means of feedback in some form. Other terms (e.g. push-back tangibles (Koleva et al., 2003) or actuated tangibles (Poupyrev, Nashida & Okabe, 2007)) are either referring to the same concept or to a sub-category of active tangibles.
Due to technological advancements as well as the recognition of the lack of malleability, the actuation of tangible objects became one of the main foci within the field of research (Shaer & Hornecker, 2010). Changes in the digital world can be reflected in self-rearranging displays, in which physical objects automatically relocate themselves (Poupyrev, Nashida & Okabe, 2007), or by means of haptic guidance (e.g., Pedersen & Hornbæk, 2011; Patten & Ishii, 2007). Moreover, in line with advancements in other fields of HCI, multimodal interaction in TUIs has gained considerable interest. Multimodal input as well as output can increase the bandwidth of information transfer. Besides that, multimodal interaction can support time sharing and attention management, especially in a variety of data-rich real-world domains (Sarter, 2006). Following the trends in both TUI- and HCI-research, TNO has developed ‘Sensators’; generic shaped active TUIs, which can provide visual (changing colours), auditory (pre-recorded samples), and vibrotactile feedback to its users (see Appendix B). Whereas Sarter (2006) clearly distinguishes between the input and output sides of multimodal systems, TNO’s Sensators provide both in one single object, following Ishii and Ullmer’s (1997) point of view.

With the development of these test- and evaluation tools, TNO aims at gaining new insights in the field of active tangible interaction, without focusing on a specific application domain. Over the years, the TUI research field has evolved from a proof-of-concept phase into a more mature research area with emphasis on conceptual design, testing, critical reflection, theory, and building of design knowledge (Shaer & Hornecker, 2010). Besides that, a vast body of knowledge is gained from research on the perception of multimodal feedback. However, the combination of these two fields is still in its infancy and requires thorough research. Sarter (2006) aptly describes the importance of research on multimodal interfaces: “Multimodal interfaces will likely find their way into an increasing number of complex data-rich environments. It is critical for engineers and designers to be aware of benefits, requirements, and constraints associated with the design of multimodal displays to ensure their effectiveness and avoid pitfalls of this approach to information presentation” (p. 439). The study as described in this thesis will contribute to TNO’s quest.

The developers of new types of interfaces try to translate the user’s skill to interact multimodally with the non-digital ‘real world’ into interaction with the digital world. One of the richest human skills is bimanual interaction and, according to Fitzmaurice et al. (1995), this is one of the main advantages of TUIs as well. It is clear that when designed carefully, bimanual HCI tasks can be more time efficient; two hands can do more than one. Moreover, using two hands simultaneously can enhance the comprehension of a task (Leganchuk, Zhai & Buxton, 1998). However, as Edge and Blackwell (2009) state, the emphasis in TUI-research has never been on bimanual interaction; this was treated as something that comes about naturally, rather than something to be designed for. Considering the principles of bimanual coordination is therefore important. Studies on how people use their hands have demonstrated that in most two-handed tasks, Guiard’s (1987) Kinematic Chain Model (KCM) applies. According to this model, each hand assumes a different functional role. The non-dominant hand provides a frame of reference, within which the dominant hand carries out precise actions. A good example of this asymmetric bimanual interaction is writing a letter; the non-dominant hand holds and moves the sheet of paper, whereas the dominant hand does the writing. Although the KCM initially focused on interaction with real world objects, it has also been applied in HCI. Considering the fact that TUIs intend to merge the physical and digital world, this model seems appropriate. Based on the abovementioned reasons, we chose to focus the research on bimanual interaction with multimodal active TUIs (i.e., TNO’s Sensators).

The graduation project as described in this thesis is carried out in order to explore the opportunities and threats of multimodal feedback in bimanual tangible interaction. The research consists of three main pillars that are very closely related; (active) TUIs, bimanual interaction, and multimodal feedback. However, to our knowledge, these three pillars have not yet been explored in combination with each other. The main research question following from these aspects is therefore: “How should feedback in generic active tangible objects be designed to facilitate the user in asymmetric bimanual interaction?”
The three main pillars of this thesis have been shortly introduced in this introduction. In the next chapter, more elaborate explanations of the respective aspects will be provided and related work will be discussed. The focus will be on those aspects that connect the three main pillars: increasing the performance by time efficiency, decreasing the task load which can result in better task comprehension, and creating a pleasant user experience. The aim of the Related Work section is to provide a more thorough understanding of the several main subjects of this thesis and also to provide an argumentation for the purpose of the research as carried out in this project. The related work serves as basis for three studies that are carried out in order to gain insights and to provide implications for design with regard to the main research question. Implications of each of the studies will be discussed in the respective chapters. These implications eventually lead to an overall discussion in which the work is summarized, the results evaluated, and the opportunities for future research defined.
2. Related Work

Now that the aim of this graduation project has been briefly introduced, it is time to elaborate on the three mentioned starting points of the study: (active) tangible user interfaces, bimanual interaction, and multimodal feedback. In this chapter, each of the three main pillars is described on a conceptual level and this knowledge is supported by practical examples. Moreover, the elements that connect the three main aspects will be discussed. When designed carefully, all three aspects can contribute to the workload and performance within a certain task, resulting in a more pleasant user experience. The related work as described here will eventually provide the rationale for the several research questions posed in this thesis.

2.1 Tangible Interaction and TNO’s Sensators

2.1.1 Concept

As described concisely in the introduction part of this thesis, tangible interaction has become a vast research area over the last two decades. The pioneers in this field, Fitzmaurice et al. (1995) already formulated several opportunities and advantages of TUIs, based on explorations with their ‘Bricks’ system. This exploratory system consists of small blocks, with which underlying digital information can be directly transformed. The objects functioned as graspable handles and moving and rotating the Bricks would move and rotate the digital object accordingly. The underlying digital information is visible on a screen on which the Bricks are placed. These objects have been applied in a drawing and a floor-planning application, mostly as a proof-of-concept. The authors state that traditional interaction styles with mouse, keyboard, and GUIs are *time-multiplexed*. This means that the input device does not have a pre-defined function; the mouse has different functions over time. TUIs, however, offer *space-multiplexed* interaction, in which “each physical object serves as dedicated transducer, occupying its own space” (p. 442). In other words: each single tangible object has got a specific function and link with a certain element of the digital information. This function does not change over time. The TUI can thus be considered a graspable handle of the digital information. This tangible approach would allow for bimanual interaction and thus parallel input specification, which can enrich the communication with the computing device.

One of the goals of tangible interaction was to make interaction more natural and intuitive by making bits (i.e., the digital world) tangible (Ishii & Ullmer, 1997). The kinds of interactions experienced with TUIs are more in line with the way people interact with the everyday physical world. TUIs capitalize on people’s familiarity with the physical world; our innate and well-learned repertoire of physical actions (e.g., grasping, pushing and lifting) in particular (Rogers, Scaife, Gabrielli, Smith & Harris, 2002). To achieve this natural, intuitive and efficient interaction, the shape of the object should convey its intended use, function, and relation with the digital information. In other words: the *affordances* (Ishii & Ullmer, 1997) of the object should be clear. With regard to the shape of the object, Ullmer and Ishii (2000) defined a distinction between *iconic* and *symbolic* objects. Iconic objects refer to the underlying digital information by means of their shape, whereas symbolic objects do not. Fitzmaurice and Buxton (1997) found that iconic objects provided performance advantages over more generic objects in a tracking experiment. They argued that the specialized shapes serve as both visual and tactile functional reminders of the associated tool assignment. Related to this, Bakker, Vorstenbosch, van den Hoven, Hollemans and Bergman (2007) investigated the differences between iconic and symbolic play pieces on a digital tabletop boardgame (see Figure 2-1). They found that the understanding of the game as well as the fun experienced by the players were similar. However, the understanding of the play pieces was higher when playing with iconic objects. Iconic objects were also preferred to play with. Besides the shape, the relations between several different tangible objects should be clear to the user. Ullmer and Ishii (2000) categorized different tangible systems based on the relations between objects. Meaning within an interaction can for instance be derived from the distance and orientation between the objects or by the ability to physically connect several objects. Tangible interaction thus is not only about the relation of one object with its underlying digital representation, it can be a coordinated interplay of different devices and objects (Dourish, 2001), which for instance draws upon people’s bimanual skill.
Ullmer and Ishii’s (2000) vision was mainly aimed at representing digital information physically. Another approach however is to focus on the nature of the link between the physical and the digital world in order to explore and understand the potential richness of these links (Koleva et al., 2003). Fishkin (2004) extended the idea of having different kinds of links between the digital and physical object(s) by framing TUIs along two axes; the metaphor axis and the embodiment axis. The latter axis refers to how close the input and output of a TUI are physically linked; full (i.e., the output device is the same as the input device), nearby, environmental, in which the output is around the user (e.g., sounds), or distant. The metaphor axis on the other hand describes the type and strength of analogy between the interface and real-world actions. To what extent does either the shape of the object or movements carried out with the object correspond with similar real-world actions? Koleva et al. (2003) reasoned in a similar way by defining how different properties of the link between the physical and digital object can enhance the perceived level of coherence between the two. How much of a physical interaction can be sensed by the system and how literal or transformed is a digital reaction to a physical action? How long does a link exist? How configurable is the link? How many digital representations does one physical object have? The most relevant property of the link between the digital and physical with regard to this thesis, is the source of the link. Most of the times the source of a link is the physical object with which an action is performed in order to manipulate a digital object. However, the digital world could also be the source of a link; digital information can be very dynamic and these changes could and should be represented in the physical world as well, by means of the tangibles.

TUIs thus represent the digital world in a physical form, or as Ullmer and Ishii (2000) describe: “Knowledge and structure in the environment, as physical symbols, objects or dimensions, and as external rules, constraints, or relations embedded in physical configurations” (p. 926). However, TUIs often cannot represent digital changes by means of physical changes, preventing bidirectional interaction. Shaer and Horneck (2010) name this lack of malleability as one of the main drawbacks of tangible interaction. TUIs are rigid and are often not capable of representing dynamic changes in the digital information. Digital information on the contrary is more malleable, for instance because it often incorporates undo functionality, a history function, and the option to replay actions. This lack of malleability is strange, especially because Fitzmaurice et al. (1995) named the externalization of traditionally internal computer representations as one of the main advantages of TUIs. Moreover, the initial idea of tangible interaction was to seamlessly integrate the representation of, and control over digital information (Ullmer & Ishii, 2000); the distinction between representation and control should therefore be minimized. A result of having unidirectional interaction instead of bidirectional might be that the tangible object can feel like loosely coupled handles to the digital information, rather than being a physical representation of the information (Pangaro, Maynes-Aminzade & Ishii, 2002). There thus is a need for having some sort of actuation within tangible objects. This would result in a seamless integration of the control (input) and the representation (output) of a digital system and an increased legibility of the system as Ishii and Ullmer (1997) suggested.
However, some tangible objects actually do support this bidirectional interaction; these TUIs are considered active. Koleva et al. (2003) already revealed an asymmetry between the amount of unidirectional, passive tangible interfaces and bidirectional, active interfaces. They identified the challenge to create digital artifacts that ‘push back’ on the physical space (i.e., demonstrate some form of actuation). Shaer and Hornecker (2010) argue in their monograph that the actuation of TUIs is one of the main research areas for now and in the future in the field of tangible interaction. Moreover, Riedenklaau, Hermann and Ritter (2012) argue that actuation and multimodal feedback in TUIs will make the user experience more productive, supportive and assistive, easily understandable, informative and fun; aspects that will recur throughout this thesis.

As van den Hoven et al. (2007) describe, a part of the design research process regarding tangible interaction is the evaluation of prototypes with potential users of the design. In order to improve the usability and to let the user experience new functionalities. Such experiences often lead to new insights that can inspire re-design or ideas for new, related products and applications. With the idea of gaining knowledge in the field of active tangible interaction, TNO – Netherlands Organisation for Applied Scientific Research – has developed their so-called ‘Sensators’. These are generic active tangible objects that can provide visual (colours), auditory (pre-recorded samples), and vibrotactile feedback. Multiple Sensators can be used simultaneously on a digital tabletop (see Appendix B for an elaborate description). Currently, the Sensators can provide input to a digital system by means of their location, movement, orientation, and whether or not they are touched (van Erp, Janssen & Toet, 2011). Moreover, Sensators could perfectly well communicate changes in the digital world by means of one or more feedback modality, in line with what Koleva et al. (2003) have suggested. Besides providing system feedback, the Sensators could display an additional dimension of information, or at least compensate for physical clutter (Fitzmaurice, 1996). TNO does not aim at developing products that are ready for the market, they want to gain knowledge. Therefore, the current Sensators are considered tools to test different ideas and claims regarding active TUIs.

Although the Sensators seem to fit well in the field of tangible interaction, they do lack some of the field’s strengths. This is mainly a consequence of the fact that the Sensators have been developed without an application in mind; they are considered evaluation tools. Because of this, the shape has been kept generic: cubical. This results in a lack of affordance (Ishii & Ullmer, 1997); the shape does neither afford intuitive interactions, nor does it explain something about the object’s function or the relations between several Sensators. None of these aspects have been pre-defined. Moreover, as described before, the richness of tangible interaction also lies in the relation between the digital world and the physical representation as for instance Fishkin (2004) and Koleva et al. (2003) suggested. The digital and physical representations should ideally be developed in harmony, in order to “externalize traditionally internal computer representations” (Fitzmaurice et al., 1995, p. 443). Since there is no digital world yet, not much can be said about the richness of the link between physical and digital, e.g., how metaphoric this link will be. With regard to the embodiment axis as defined by Fishkin (2004), the Sensor system seems to provide full embodiment (i.e., the output is presented within the input device, but also nearby (i.e., the feedback provided by the digital tabletop), and environmental embodiment (i.e., auditory feedback). Research with the Sensors thus either requires an application domain, or the research should focus on a specific type of interaction (i.e., movements of the hand(s) within a specific task). Meijer (2013) has focused on the latter option in his Sensor-work. He investigated the effects of different types of feedback on performance, workload, and user experience in several unimanual precision tasks. In the current project, we elaborate on this earlier work.

4 The Samsung SUR40 digital tabletop, in combination with the Microsoft Surface operating system are used as basis for TNO’s Sensor research. Throughout this thesis, the term ‘Surface’ will be used to refer to this specific digital tabletop computer.
2.1.2 Application Domains

Making digital information physically accessible might thus enrich the interaction in several ways, as long as the design of the object, the relation between several objects, and the relation with underlying digital information are considered carefully. But what does this enrichment actually mean and how are TUIs applied? Shaer and Hornecker (2010) specify several application domains in which TUIs have proven to be successful; many examples are provided in their monograph. Dominant application areas seem to be: learning, support of planning and problem solving, programming and simulation tools, support of information visualization, and exploration, entertainment, play, performance and music, and also social communication. All these domains benefit from one or more characteristics of tangible interaction as defined by Fitzmaurice et al. (1995). It is clear that tangible interaction might facilitate an interaction by making interface elements more direct and manipulable, by means of specialized, context sensitive input devices (i.e., carefully designed objects, interactions, and digital-physical links). These allow parallel and two-handed input, which improves the expressiveness or the communication capacity with the computer. Besides these aspects, the authors define allowing multi-person collaborative use and taking advantage of our keen spatial reasoning skills as important benefits.

The purpose of this thesis is not to provide a complete overview of the work in the field of tangible interaction. However, to provide the gist of the field, the ‘reacTable’ by Jordà, Geiger, Alonso and Kaltenbrunner (2007) – a tangible system which main function is the performance of music – will be explained and discussed. This application (see Figure 2-2) incorporates several of the application domains as described by Shaer and Hornecker and benefits from many of the advantages of tangible interaction as defined by Fitzmaurice et al. (1995).

![Figure 2-2: An Impression of the reacTable. Different Tangible Objects are combined in order to create Music. Relations between Objects are visualized. Image by Jordà et al. (2007).](image)

The basis of the system is a circular shaped digital tabletop on which different tangible objects are to be placed. Each tangible reacTable object has a dedicated function for the generation, modification, or control of sound, resulting in a space-multiplexed application (Fitzmaurice et al., 1995). There are six functional groups of objects, for instance audio generators, filters, and mixers (all identifiable by symbolic shape and symbols), which can all be connected to each other in order to create music. The connections that are made are based on proximity rules; by moving the objects closer together, performers construct and play the instrument at the same time (Jordà et al., 2007). “Since the move of any object around the table surface can alter existing connections, extremely variable synthesizer topologies can be attained resulting in a highly dynamic environment” (p. 143). Moreover, each object can be rotated as if it were a knob, which allows controlling one of the internal parameters of the specific sound (e.g., its frequency or amplitude). This results in a coordinated interplay between different devices and objects, as Dourish (2001) suggested. By means of the tangible objects, the underlying digital information (i.e., the digital synthesizer) can be manipulated directly; either by one hand at a time, but also with two hands in parallel or by multiple users at once. With its multiple dedicated objects in combination with the circular shape of the table, the design of the reacTable clearly follows the guidelines of Hornecker and Buur (2006) for creating a social experience with TUIs. All these aspects enhance the expressiveness of the communication with the underlying digital information, following the advantages of TUIs as defined by Fitzmaurice et al. (1995).
Applications like the reacTable by Jordà et al. (2007), which for instance facilitate collaboration, are also applied for children. Children can benefit a lot from collaboration and imitation and TUIs can facilitate these aspects (Antle, 2007). Moreover, TUIs allow epistemic actions (Kim and Maher, 2008). These are explorative manipulations of physical objects in order to better understand a task’s context; different TUIs can for instance be rotated and arranged, aiming at gaining better insights in the task or problem at hand. Considering the reacTable, this would mean that different objects could be moved and rotated in an exploratory fashion in order to learn about the characteristics of sound. Besides the spatiality of different objects, developers of TUIs could for instance utilize the mass, texture, or malleability of physical objects. Children could explore these physical properties in order to gain valuable conceptual information about the task at hand; traditional interfaces do not allow these forms of exploration (Marshall, 2007). Direct physical interaction with the world is a key component of cognitive development in the childhood (Antle, 2007). Learning by means of TUIs is in line with Fitzmaurice et al.’s (1995) statement that TUIs make use of our keen spatial reasoning skills; with a TUI, tasks can become easier to understand.

With the introduction of dynamically changing physical properties of tangible objects, the design vocabulary of TUIs has expanded enormously (Poupyrev et al., 2007). This statement is in line with the most often cited advantage of multimodal interaction: an increased bandwidth of information transfer (Oviatt, 2008; Sarter, 2006). Three different types of actuation are identified. First there are self-rearranging displays (Poupyrev et al., 2007). Changes in the digital world might result in an incorrect location of the physical object. In such case the object should be replaced to another position in order to overcome inconsistencies between the physical and digital information. With rigid TUIs, the user is required to reposition the object manually, whereas self-rearranging displays can relocate the object autonomously. An example of such a system is the ‘Actuated Workbench’ by Pangaro et al. (2002), which can be considered a proof-of-concept. Other examples include ‘RATI’ by Richter, Thomas, Sugimoto and Inami (2007), with which remote collaboration in TUIs is evaluated, and ‘Madgets’ by Weiss, Schwarz, Jakubowski and Borchers (2010); a set of general purpose tangibles such as buttons, sliders and knobs that can relocate themselves. In haptic guidance applications TUIs apply attraction (‘snapping’) or repulsion (force feedback) in order to make the user move the TUI to (or away from) a specific location or orientation. Examples include ‘Tangible Bots’ by Pedersen and Hornbæk (2011). These are autonomously moving objects that can serve as rotating knobs and that provide force feedback (see Figure 2-3 for an impression). Moreover, ‘PICO’ by Patten and Ishii (2007) also makes use of haptic guidance. This system consists of a planning application in which an optimal spatial layout has to be found; the haptic guidance within the objects helps the user with finding this optimum. The idea of implementing physical constraints like attraction and repulsion corresponds with the vision of Ullmer, Ishii and Jakob (2005), stating that digital constraints (e.g., minimal or maximal values) should have a physical representation.

![Figure 2-3: Impression of the Haptic Guidance Application in Tangible Bots (Pedersen & Hornbæk, 2011).](image)

The third type of actuation in TUIs – the most relevant for this thesis – is defined by applying different modalities of feedback such as changing colours and/or patterns of vibration as was done in ‘Smartpuck’ (Kim, Cho, Park, & Han, 2007). Auditory feedback as was applied in ‘Tangible Active Objects’ (Riedenklau, Hermann & Ritter, 2010). Auditory feedback can serve as means of providing information regarding digital constraints, but also as an extra dimension within the information. The authors applied sounds within tangible objects that represented digital scatter plots. The aim of this development was to facilitate the visually impaired.
Although the reacTable (Jordà et al., 2007) does not incorporate active TUIs, we describe a possible extension of the current system. This is to provide examples with regard to the application of multimodal feedback in tangible interaction. Obviously, the sounds generated by interaction with the reacTable are audible, but other related information is communicated visually by means of the surface table. Representations of the established connections are for instance visible between different functional blocks, as are the accompanying induced waveforms (see Figure 2-2, right side image). Moreover, the auras around the objects provide information with regard to the parameter values and/or configuration states (e.g., is the maximum frequency of a certain tone achieved?). In this case, the underlying screen provides information, but the tangible itself could also convey this information by means of for instance multimodal feedback. The current, rigid tangibles can be rotated infinitely, but the parameter adjusted has got specific minimum and maximum values (i.e., digital constraints). These digital constraints could be represented physically (Ullmer et al., 2005), for instance by changing colours or by vibrotactile feedback as was applied in the ‘Tangible Active Objects’ by Riedenkla (2009).

In this first part of the Related Work section, we only scratched the surface of the rich opportunities provided by (active) TUIs, but some of the main purposes have been pointed out. When the representations, the relations with other objects and the underlying digital information, the form of the interaction, and the feedback are designed carefully, (active) tangible interaction can make tasks more natural and intuitive, more time-efficient, more comprehensible, and more pleasant. As described before, TUIs capitalize on people’s familiarity with the everyday physical world; that is, our innate and well-learned repertoire of physical actions (Rogers et al., 2002). One of these physical actions consists of bimanual interaction. However, as Edge and Blackwell (2009) state, the emphasis in TUI-research has never been on bimanual interaction; this was treated as something that comes about naturally, rather than something to be designed for. Therefore, it is important to understand the different roles hands play in a bimanual interaction.

### 2.2 Two-handed Interaction

In HCI with single-handed input, the user has a certain number of degrees of freedom; two-handed input increases that freedom. Because of these degrees of freedom, interaction with two hands offers the biggest power of expression (Chatty, 1994; Fitzmaurice et al.,1995). Two-handed interaction with computing devices can appear in different forms as Chatty (1994) indicates. In HCI with single-handed input, the user has a certain number of degrees of freedom; two-handed input increases that freedom. Because of these degrees of freedom, interaction with two hands offers the biggest power of expression (Chatty, 1994; Fitzmaurice et al.,1995). Two-handed interaction with computing devices can appear in different forms as Chatty (1994) indicates. First, there is independent interaction in which a second pointing device (i.e., a mouse) is added that can be used in the same way as the first. An example of an interaction like this is when one pointing device is used to select tools whereas the other is used to perform actions on an object with the selected tool. Of course, such interfaces can be used with one hand as well, but it can save the user a considerable amount of time when two hands are used. Both hands are used sequentially in this case. Both hands can be used in parallel as well. In fact, our hands are not used to wait for each other before performing operations. In the appropriate context, people are well capable of carrying out the different sub-tasks of a compound task simultaneously using two hands, without additional overhead (Buxton & Myers, 1986). Parallel interaction can take place in an independent fashion, for instance using two different pointing devices to move two different files to the waste basket at the same time. Parallel interaction can also be a combined interaction (Chatty, 1994), in which both hands collaborate to perform one single, compound task.

In this combined interaction, the hands basically can collaborate in two ways; symmetrically and asymmetrically. In compound tasks that are carried out symmetrically, each hand is assigned an identical role (Balakrishnan & Hinckley, 2000) and the hands are used simultaneously. Examples of this type of movement include tying shoelaces, skipping rope, and folding linen or clothing (Latulipe, 2004). Although both hands move in parallel, this does not mean that performance of the hands is identical as well, as Balakrishnan and Hinckley (2000) point out. Despite the fact that the task assigned to each hand is identical, it may occur that one hand’s performance results in poorer accuracy or temporal performance than the other hand’s. The second way of combined interaction is asymmetric interaction. Guiard (1987) observed that in most tasks we carry out bimanually, each hand performs a different role. He proposed the Kinematic Chain Model (KCM), in which the hands are
seen as two motors (i.e., devices to create motion) whose internal complexity is ignored. These motors cooperate “as if they were assembled in series, thereby forming a kinematic chain” (p. 486). Within this kinematic chain, there are several relationships between the dominant and the non-dominant hand. First, besides providing stability to the object acted upon, the non-dominant hand provides a reference frame in which the dominant hand carries out its specific tasks. Second, the resolution of motion of the non-dominant hand is much coarser than that of the dominant hand and therefore the dominant hand can carry out actions that require more precision. The third relation between the two hands is that the non-dominant actions have temporal precedence over the dominant actions since a reference frame has to be set first.

This asymmetric bimanual movement, which is based on compound tasks in the ‘real world’, is often found in HCI as well. Fitzmaurice et al. (1995) already identified the options to have bimanual interaction and providing input in parallel as being two of the main advantages of tangible interaction. Because of the earlier mentioned fact that bimanual interaction offers more degrees of freedom within an interaction, tasks can be carried out more efficient. Hinckley, Pausch and Proffitt (1997) stated that using two hands can offer more than just this time saving; two hands can provide the user with information which one hand alone cannot. Using two hands in a compound task encourages exploration of the task solution space. This exploration leads to reasoning about the most suitable strategy for the task, which in turn can increase both the performance and understanding of the task. Moreover, in unimanual tasks, the user has to visualize and plan a sequence of sub-tasks to achieve a goal, causing a higher cognitive burden. This load can be reduced by a more natural and comprehending bimanual interaction (Leganchuk et al., 1998). This explains why bimanual interaction with TUIs might be so valuable. However, according to Edge and Blackwell (2009), the emphasis in the field of tangible interaction has never been on the bimanual interaction aspect. Other characteristics of TUIs, such as the support of collaboration, have always been deemed more important. Bimanual interaction with TUIs has been treated as something that comes about naturally, whereas it actually is something that requires specific investigation and design. It is important to recognize and understand the different roles hands play in an interaction in order to develop suitable and successful (tangible) user interfaces; in particular when efficiency and understanding are of key importance in a task.

2.2.1 Bimanual Human-Computer Interaction

As Edge and Blackwell (2009) state, the principles of the Kinematic Chain Model account for most of our everyday actions in the real world, in which bimanual cooperation entails both hands operating on the same physical object, in the same physical space. However, our daily actions are becoming more mediated by technology, resulting in interaction with digital objects instead of physical ones. Our hands might be operating on physically independent devices, but still be performing a compound action (that takes place in the digital world). The potential for the actions of our two hands to be conceptually linked in our minds needs to be considered. Balakrishnan and Hinckley (1999) found that the reference principle as defined by Guiard (1987; i.e., the non-dominant hand provides a reference frame in which the dominant hand acts) still applies when the two hands work in separate reference frames (e.g., on two separate WACOM tablets). This applies as long as appropriate visual feedback from the task is present. This implies that different tangible objects indeed can be used in parallel in order to perform a compound task; in particular the Sensators in combination with visual feedback from the Surface table.

Over the years, Guiard’s KCM has been explored and applied in many HCI studies. Several studies focused on evaluating different traditional input devices in bimanual interaction, while considering Guiard’s model. An example of such research is work by Kabbash, MacKenzie and Buxton (1993), who evaluated a mouse, a stylus, and a trackball in the non-preferred hand. Kurtenbach, Fitzmaurice, Baudel and Buxton (1997) focused on the effects of bimanual interaction with two pucks on tablets. Hinckley, Czerwinski and Sinclair (1998) also investigated bimanual interaction by means of puck, stylus, and touchpad in map navigation tasks. Cutler, Fröhlich and Hanrahan (1997) found that users often performed bimanual manipulations by combining two otherwise independent tools in a synergistic fashion. Besides serving as technological proof-of-
concept studies, these studies also supported the KCM within HCI. The studies demonstrate that the non-dominant hand indeed can play an important role in an interaction, especially in tasks that allow coarse movements. Moreover, the several authors distinguish the input devices based on suitability for each hand; a stylus is for instance more suitable for precise tasks with the dominant hand. Besides focusing on the specific input devices and suitability for each hand, different specific computer tasks have been explored considering bimanual interaction. By using both hands, a variety of tasks such as map navigation, sketching, and menu and cursor control can be performed more efficient compared with sequential one-handed input (Brandl, Forlines, Wiegndor, Haller & Shen, 2008).

Since our focus is bimanual interaction, we cannot neglect the relatively recent developments regarding multitouch screens. Multitouch screens allow ‘hands-on computing’; users can directly touch visual representations of their data using both hands and even using multiple fingers, which adds an extra physical quality to the interaction. Moreover, virtual interface objects are often designed in such a way that they exhibit a sense of real-world behavior, in order to create the illusion that one is interacting with real world objects (Wilson, Izadi, Hilliges, Garcia-Mendoza & Kirk, 2008). When digital objects resemble real-world objects, the interaction with these objects becomes intuitive and natural; Guiard’s KCM might thus apply in multitouch tasks as well.

Whereas the earlier studies with regard to bimanual interaction with traditional interfaces mainly involved proof-of-concept technology, multitouch actually has found its way to the market and is now omnipresent. Moreover, Kirk, Sellen, Taylor, Villar and Izadi (2009) state that multitouch undermines some of the advantages of tangible user interfaces; two-handed parallel input is encouraged, interface elements are directly accessible, and collaborative use is supported as well. Moreover, digital objects on multitouch provide the option to carry out actions for which no obvious physical tool exists. For instance generating, reproducing, replaying, merging, and deleting of information. Meanwhile, different tangible objects have got different dedicated functions (i.e., space-multiplexed). Their specifically designed affordances allow for rich and accurate control and TUIs can be used intuitively (for instance without focusing on them). As van Erp et al. (2011) state: “Touch displays feel the same, irrespective of the objects or information they present or the movements or commands the user provides. In other words: as input modality, touch interfaces may be intuitive, but the lack of natural feedback may hamper the intuitiveness of the interaction as a whole” (p. 1-2).

Although this statement is slightly outdated – active touch displays are currently being developed and are finding their way to the market (e.g., Bau, Poupyrev, Israr & Harrison, 2010) – it points out the disadvantages of the omnipresent passive touch displays. Since the touch display changes its functionality over time, interaction with it can be considered time-multiplexed. Lucchi, Jermann, Zufferery and Dillenbourg (2010) demonstrate that for spatial layout tasks, TUIs are more suitable than interacting by means of a touch screen. This is because the interaction is more intuitive and because tangibles provide – besides visual feedback – a second loop of feedback to the user; passive haptic feedback (Shaer & Hornecker, 2010; Ullmer & Ishii, 2000). Moreover, auditory feedback when an object is located on, or moved over a surface, does also contribute to the intuitiveness of an interaction.

What tangible objects lack compared with digital multitouch objects however, is the aspect that manipulation of a digital object on multitouch directly results in visible changes in that specific object (i.e., visual feedback). It therefore seems rather interesting to use the best of both worlds; combining the physical affordances of TUIs with the direct feedback and the malleability as is provided by digital objects. In other words: Exploring the opportunities of active TUIs is necessary. Luckily, this is exactly where TNO aims at with their Sensators. Research on different types of physical input devices has demonstrated that some are more suitable for use in the dominant hand (e.g., a stylus) whereas others are more suitable for the non-dominant hand, but that two hands can be used in parallel when the compound task is designed appropriately (Owen, Kurtenbach, Fitzmaurice, Baudel & Buxton, 2005). Since the most common form of bimanual interaction follows the KCM and thus is asymmetric, this raises the question whether and how feedback should be designed with the different roles of the hands in mind. How should feedback be presented to the non-dominant hand, considering its preparatory and more coarse function, and which form of feedback would be most
effective for the dominant hand with respect to its precise role? Which feedback modalities would be most suitable with regard to performance, workload, and user experience? Could it be beneficial to provide each hand (and thus each role) with a different feedback modality in order to emphasize the two distinct roles? To provide initial insights in questions like these, knowledge in the field of multimodal feedback has to be addressed and applied in an asymmetric bimanual tangible interaction task.

2.3 Multimodal Feedback

As we have seen, tangible user interfaces provide several advantages with regard to the efficiency and understanding of a task; in particular when both hands are used. The question remains whether and how multimodal feedback – as provided by TNO’s Sensators for instance – can enhance this task efficiency and understanding even more. First, the strengths and limitations of both visual and tactile feedback will be discussed and their potential within bimanual tasks will be evaluated. Thereafter, related work with regard to presenting different feedback signals simultaneously will be discussed.

2.3.1 Visual Feedback

Vision is often regarded as the most important perceptive modality during interaction with the environment in daily life (Sigrist, Rauter, Rienar, & Wolf, 2012). The visual modality can process greater amounts of information in a short period of time compared to the auditory and haptic modality (Nesbitt, 2003). Since many active TUIs – Sensators in this case – are used in combination with a digital tabletop, two types of visual feedback are provided: colour changes in the Sensators and task-related on-screen representations. Changes in the hue, saturation, brightness and/or patterns of the colours (Nesbitt, 2003) can convey certain meaningful information within a task, although they have to be considered carefully. First of all, because colours can have semantic meanings and/or associations that might affect the interpretation and/or the performance within a task. Secondly, not every colour is always suitable. As Keller and Keller (1993) describe, colours are not suitable to represent exact data, but are very well capable to communicate sudden changes in quantitative data. Considering colours as being representations of nominal data, the colours applied should be clearly distinguishable. Moreover, when colours represent ordinal data, the colours themselves should also demonstrate a certain order (Trumbo, 1981).

In order to explore the possible benefits of visual feedback within asymmetric bimanual interaction, we need to understand the fixation strategies (or ‘hand-eye coordination’) within such tasks. Hesse, Nakagawa and Deubel (2010) found that bimanual interaction is moderated by fixation strategies. When people are free to move their eyes, bimanual tasks are carried out more sequential than when people had to fixate at a certain point. This implies that people are well capable of carrying out tasks bimanually, without having to look at both hands. Providing visual feedback to both hands could thus affect the time efficiency negatively, since it could induce extra fixation switches. This could apply in particular when both hands are widely separated and/or when a visual link between both hands is lacking (Balakrishnan & Hinckley, 2000). Within bimanual tasks, right-handed people tend to focus visually more on their dominant, right hand (Buckingham and Carey, 2009; Peters, 1981), which would suggest that visual feedback best is provided to the dominant hand. However, the non-dominant hand requires more visual attention in order to guide the hand accurately, as for instance Srinivasan and Martin (2010), and Riek, Tresilian, Mon-Williams, Coppard and Carson (2003) state. This would suggest that visual feedback should be presented to the non-dominant hand.

5 Sensators can also provide auditory feedback, but since auditory feedback is omnipresent and therefore can be perceived regardless of the sound’s orientation (Wogalter, Kalsher & Racicot, 1993), it will not be part of this study. In the case of using two Sensators simultaneously, the source of the sound is difficult to identify. This causes the loss of coupling between the feedback, the Sensator and the underlying digital information which might result in confusion. Moreover, sound comprises many different characteristics (e.g. pitch, timbre, intensity, but also the semantics of spoken texts etc.); this would require specific sound design, which is beyond the scope of this project.

6 Note that the generation of Sensators as used throughout the study only allowed control over the changes in hue.
The literature thus is inconclusive about to which hand visual feedback can best be presented in order to minimize the necessary amount of fixation switches and thus maximize the time efficiency in a bimanual task.

2.3.2 Vibrotactile Feedback
Since the fixation strategy can thus affect the performance (i.e., speed and/or accuracy) within bimanual interaction, it might be beneficial and more intuitive to provide feedback that can be perceived without having to visually focus on it. TUIs already aim at this intuitiveness of interaction by means of providing inherent passive haptic feedback (i.e., the touch and feel of an object; Shaer & Hornecker, 2010; Ullmer & Ishii, 2000), but more system information might be provided by means of active, tactile feedback. Since with this type of feedback, input and output style are matched (Reeves et al., 2004) and because tactile feedback does not require visual attention, this might yield beneficial effects. Moreover, providing information by means of a tactile display could decrease the visual load within a task (e.g., Stockinger & Richter, 2012; Haans & IJsselsteijn, 2006). Vibrotactile feedback is therefore a logical and frequently used application. It is for instance used to alarm the user, direct the user, or communicate with the user (Prewett, Elliott, Walvoord & Coover, 2012). Vibrotactile feedback is relatively easy to implement and it incorporates several physical parameters that can be manipulated.

These parameters include frequency, amplitude, duration of a pulse, waveform, and others such as rhythm and body location (Brewster & Brown, 2004a). Abstract messages can be conveyed by means of vibrotactile icons7, or ‘Tactons’ (Brewster & Brown, 2004b), which are constructed of different manipulations of the tactile stimulus. Tactile feedback has the potential to augment the interaction with traditional GUIs. This can for instance come in useful when the visual display is overloaded, limited in size (e.g., mobile and wearable devices), or not available (e.g., for blind people; Brewster & Brown, 2004a). For single-handed touch input, the addition of synchronous tactile feedback has shown to be beneficial in terms of reducing error rates (Brewster, Chohan & Brown, 2007) and increasing interaction speed (Stockinger & Richter, 2012). Moreover, Scott and Gray (2008) demonstrate that a vibrotactile cue as warning elicits faster responses than visual or auditory warnings.

Prewett et al. (2012) demonstrate with their meta-analysis that vibrotactile feedback added to either a baseline or to visual information in a redundant fashion enhances task performance. However, when (vibro)tactile feedback replaced the visual cue, some effects were attenuated or moderated by cue information complexity. This might be because people are less familiar with tactile cues than with cues in other modalities (Prewett et al., 2012; Nesbitt, 2003). Moreover, the limits on the processing of tactile information seem to be far more restrictive than those of visual (or auditory for that matter) information (e.g., Spence & Ho, 2008; Nesbitt, 2003). As Spence, Ngo, Lee and Tan (2010) describe, vibrotactile interfaces are often tested in the laboratory under conditions of unimodal sensory stimulation. However, in real-life environments, multiple senses are likely to be stimulated simultaneously, in which visual stimuli seem to have priority access to attentional resources. This implies the need for a more real-life study of the effects of tactile feedback within an interaction.

As Prewett et al. (2012) state, people have successfully perceived and responded to vibrotactile cues at various body locations, including the fingers and palms of the hands. However, up to our knowledge, no effects of hand dominance on perception of tactile stimuli in the hands are known. All of the above raises the question whether tactile feedback can be beneficial in bimanual tangible interaction and if so, to which of the two hands should the tactile feedback be provided; the dominant hand, the non-dominant hand, or perhaps to both? The potential of tactile feedback within tangible interaction should thus be investigated, in particular when two channels of feedback are provided to both hands simultaneously.

7 The generation of Sensators as used throughout the project contained two vibration motors with different frequencies. Per motor, nine different amplitudes could be presented. Patterns based on these parameters could be predefined.
2.3.3 Combined Feedback

Both visual and tactile feedback thus have their advantages and disadvantages when one single loop of feedback is provided. However, the question of this thesis concerns two feedback loops, presented simultaneously (i.e., one to each hand). When we consider the roles of each hand as two specific tasks that are carried out simultaneously, Wickens’ Multiple Resource Theory (MRT) (Wickens, 2002; Wickens, 2008) might apply. This theory is based on the idea that people have several cognitive resources divided over several dimensions such as the processing stage (perception or response), whether this perception or response is verbal or spatial, and the input/output modality (e.g., visual or auditory). When two tasks require the same cognitive resource, this causes interference between the two tasks, resulting in cognitive overload which is detrimental to task performance. An example of this is when you are reading and someone is speaking to you at the same time; both input channels draw upon verbal input, causing interference. Although the MRT is not suitable as a model for attention, it can serve as a framework to predict operator performance (Johnson, Proctor & Vu, 2004) and can therefore be valuable in the designing of different HCI tasks and applications. Considering the spatial input and the different output modalities of active TUIs and Sensators in particular, the MRT can turn out to be a relevant guideline.

One of the dimensions defined by the MRT is the sensory modality dimension; dissimilar cognitive resources exist to process information from different sensory modalities. The theory thus states that two tasks can be time shared more efficiently when these tasks make use of different sensory modalities of the user. This would imply that it is more beneficial for both the task performance as well as the cognitive load to let each Sensor present feedback in a different modality (i.e., asymmetric feedback), than to have symmetric feedback (i.e., both Sensors provide feedback in the same modality; either visual or tactile) in bimanual compound tasks. The MRT has been successfully applied in many multimodal interfaces, but as Wickens (2002) states, the model is mostly applicable in high demand multi-task environments such as vehicle driving, overworked secretaries, or commanders in emergency operations mode. In these high load situations, people are more likely to offload information to another sensory channel (Prewett et al., 2012); when for instance the visual load is high, it might be beneficial to replace some of the visual information by means of other feedback modalities or to present the information redundantly by means of different feedback modalities. This can decrease the demands for the visual resource, preventing cognitive overload.

Although the MRT seems to support a multimodal presentation of feedback in asymmetric bimanual interaction, one also has to be aware of the trade-offs in multimodal HCI. Behavioral and neurophysiological data suggest that there are extensive cross-modal links between different sensory modalities (Sarter, 2006), which can cause interference when not designed appropriately. Besides possible effects of modality expectations – responses are slower when information is presented in an unanticipated modality (Spence & Driver, 1997) – there are modality shifting effects (Sarter, 2006). As van Erp et al. (2006) state, there are costs involved (in terms of time) in attention switching between modalities. Spence, Pavani and Driver (2000) suggest that these costs are mainly applicable to switching to and from the haptic channel. This suggestion might oppose the provision of asymmetric feedback in asymmetric bimanual interaction tasks. Even more so because the presence of a stimulus in one modality can affect what people perceive in another modality (van Erp et al., 2006). Bresciani, Dammeier and Ernst (2008) found for instance that the perception of a sequence of target-stimuli (i.e., assessing the amount of presented stimuli) in a certain sensory modality was affected by the presentation of non-relevant sequences of stimuli in another modality (this applied for auditory, visual, and tactile stimuli). Moreover, van Erp and Werkhoven (2004) found that people systematically underestimate the duration of a visual stimulus and/or overestimate the duration of a tactile pulse (presented at the fingertip) in a forced-choice discrimination task.

The theories that seem to be most applicable with regard to how feedback in asymmetric bimanual tasks should be provided seem rather inconclusive. Whereas the MRT suggests that it might be beneficial to present feedback to each hand in a different modality or in a more redundant fashion, other theories oppose this idea since it might involve extra switching costs. These aspects give rise to the need for a further investigation of multimodal feedback in bimanual tangible interaction.
2.4 Rationale for the Current Study

TNO wants to explore the opportunities that multimodal feedback in tangible interaction has to offer and the Sensators are considered evaluation tools for this. The current thesis is part of TNO’s quest, in the sense that it explores the opportunities of multimodal feedback in bimanual tangible interaction. Whereas TUIs, multimodal feedback, and bimanual interaction separately have demonstrated their potential with regard to task performance, task understanding (e.g., intuitiveness and workload), and user experience, this thesis brings the three aspects together in an applied setting. This results in the following main research question of this thesis:

“How should feedback in generic active tangible objects be designed to facilitate the user in asymmetric bimanual interaction?”

This question follows Guiard’s (1987) Kinematic Chain Model, which describes the most common form of bimanual interaction. As described earlier, the model states there is a clear distinction between the role of the dominant and the non-dominant hand within asymmetric bimanual interaction. Throughout this thesis, each hand will be presented with information considering its specific sub-task in the bimanual compound task, resulting in the simultaneous presentation of two distinct feedback signals. This raises the following sub-question:

- What, if any, combinations of feedback facilitate users with asymmetric bimanual tasks in terms of performance (speed, accuracy), user experience, and workload?

We hypothesize that having feedback (regardless the combinations of modalities) contributes to the performance of a task; to the accuracy in particular. Considering the modality of feedback, one could assume that visual feedback is easier to interpret since the visual modality can process greater amounts of information in a short period than the haptic modality can (Nesbitt, 2003). Moreover, Meijer (2013) concluded that users appreciate visual feedback from the Sensators more than other modalities. However, tactile feedback might come in useful when a certain task is visually demanding. Besides this, the current study differs from earlier work in the sense that two feedback signals are presented simultaneously, which might affect the perception of these signals. Having feedback in the same modality (i.e., symmetric feedback) might be confusing and perhaps overloading that specific sensory modality of the user.

- Does asymmetric feedback (i.e., each hand receives feedback in a different modality) have an advantage over symmetric feedback in terms of performance, user experience, and workload?

Wickens’ Multiple Resource Theory (Wickens, 2002; Wickens, 2008) states that when two tasks are carried out simultaneously, it is better to perceive feedback in different modalities; this prevents sensory overload situations and thus decreases mental workload. As a consequence, task performance will increase. On the other hand, it is known that cognitive switching costs are involved when switching between feedback modalities. This is is especially the case when switching to and from the tactile modality (Spence et al., 2000; van Erp et al., 2006). Following the latter findings, this would suggest a benefit for symmetric feedback.

The questions as defined here form the main part of this graduation project. However, the Sensators are part of a field of research that is still in its infancy; not much is known about the possible effects of multimodal feedback within tangible interaction, let alone within bimanual tangible interaction. Therefore, it is difficult to predict the effects different combinations of feedback modalities have on performance, user experience and workload. For this reason, the current project is set up in an exploratory fashion, in which is aimed at gaining insights in the effects of multimodal feedback and at providing initial guidelines for the development of bimanual active TUI tasks. The project does not initially aim at testing several hypotheses.
Throughout this project, three exploratory studies will be carried out, aimed at providing insights in the earlier mentioned questions. The first study will serve as a Pilot study in order to explore the effects of the simultaneous presentation of two feedback signals in a two-handed task. The goal of this study is twofold; insights with regard to the experimental design will be gained, and initial insights and hypotheses will be formed as starting point for the second study. This second study will consist of a carefully designed asymmetric bimanual task, in which users will be presented with different combinations of feedback modalities. Initial implications for the design of multimodal feedback will be formulated and explained, and a focus for the third study will be defined. The third and final study will elaborate on the second.

As for instance Prewett et al. (2012) point out, the effects of different modalities of feedback on performance and user experience can be very task-specific. The same applies to the effects of different combinations of feedback. In line with earlier research on TNO’s Sensators by Meijer (2013), the effects of feedback with regard to precision tasks will be addressed. However, contrary to his study, the precision task in the current project will thus consist of a compound two-handed interaction task.

Besides the earlier mentioned sub-questions there are two other, more exploratory questions. The first question considers the preference of the user; it might be that option X yields the best performance, but that users prefer option Y. This has to be considered. Moreover, questioning the preference of the user could also provide insights in the relative importance of the measures of performance, workload and user experience:

- **Which combination of feedback modalities is preferred by the user?**

For the final sub-question, the time efficiency aspect is considered in more detail. Bimanual tasks are considered as being more time-efficient since both hands are used in parallel. Throughout this project will be explored whether the combination of feedback modalities affects the amount of parallelism.

- **What are the effects of feedback type on the level of parallelism between both hands (i.e., does the feedback combination have influence on how simultaneous both hands are moved)?**

In several cases, the amount of parallel usage of both hands might also provide insights in the workload of a task. More sequential performance of tasks might imply a higher workload because of the extra switching between the two tasks. However, it is not necessarily the case that more parallel movement is better in a task; this can also be task-dependent.

Concluding, this thesis will address asymmetric bimanual interaction in an applied fashion and will provide initial insights in the claims that Riedenklau et al. (2012) have made earlier, namely that “active TUIs can make the user experience more productive, supportive and assistive, easily usable, informative and fun” (p. 170).
3. Study 1: Wizard of Oz Pilot study: Sea Battle

3.1 Introduction
To gain initial insights into the opportunities and limitations of different combinations of visual and tactile feedback in bimanual tangible interaction, a Pilot study was set up. The aim of this study was to investigate the possible effects of different combinations of feedback modalities on performance, workload, user experience, and parallelism of the hands. Moreover, this Pilot study served as an exploration with regard to a suitable experimental design. A target-finding paradigm has been applied, in which the participant was asked to find two different targets with help from two simultaneously presented channels of feedback. To induce parallel movements of the hands, a cover story regarding ‘Sea Battle’ was applied. In this chapter, we describe the methods applied, the results, and the implications for design and subsequent research.

3.2 Design
In the experiment, a within subjects design was applied, with four different conditions: tactile feedback in both Sensators (TT), visual feedback in the right hand and tactile in the left (TV) and to explore possible dominant hand effects also visual left and tactile right (VT). The order of the conditions varied for each participant to minimize learning effects. The fourth condition consisted of tactile feedback in both Sensators including a physical link between the two (TTlink). As was done before by Patten and Ishii (2007), this condition contained mechanical constraints. It was added in order to force simultaneous movement and to explore possible effects thereof. Due to technical limitations of the available application, the experiment was carried out in a Wizard of Oz fashion (i.e., manually simulating system characteristics that are to be automatized). The feedback as presented by one of the two Sensators was controlled manually by the experiment leader, the feedback presented by the other Sensator was controlled automatically by the Surface. The study was carried out in the weeks before and after the Christmas holidays 2012-2013 during office hours.

3.3 Participants
In total, five participants participated in the study, of which three were male (60%). All participants were employees or interns at TNO, Soesterberg. The mean age was 25.2 years old (SD = 2.77, range: 22-29) and two of the participants (40%) were left-handed. All participants had normal or corrected-to-normal vision and did not suffer from colourblindness.

3.4 Setting and Apparatus
The experiment was carried out in the diffusely lit Demo-room at TNO, Soesterberg, in which a Samsung Surface (SUR40) digital tabletop was located. The Surface displayed an 11x6 square grid (160x160 px per square; fitting a Sensator), two start-buttons, a finish-button and a text-field with participant- and trial-number (see Figure 3-1B). In each experimental trial, two of the cells on the grid were depicted as being the targets (to be found by the participants); these targets were always located in either the same row or the same column of the grid, in line with the original Sea Battle game. We introduced a maximum ‘ship size’ of four cells (i.e., a maximum of two cells between both targets). This was partly based on the rather limited size of the grid and partly on the intention to induce simultaneous movement. When both hands are closer together, they seem to move more in parallel than when further apart (Balakrishnan & Hinckley, 2000). Each target had a dedicated Sensator; one controlled by the surface table, the other controlled manually by the experiment leader.

The location of the Surface-controlled Sensator was tracked automatically; feedback was provided via a Bluetooth connection between Surface and Sensator. The location of the second, manually controlled Sensator, was tracked visually by the experiment leader (a Sony DCR-SR55 camera with wide-angle lens was located above the surface, and its footage was immediately

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8 From now on, the different feedback combinations as presented in the several experiments will be described by means of abbreviations. The first (left) letter refers to the feedback modality presented by the Sensator in the left hand, the second (right) letter refers to the feedback modality of the Sensator in the right hand. ‘V’ = Visual feedback, ‘T’ = Tactile feedback.
displayed on a Samsung 40” television connected to it; see Figure 3-1C). Feedback was presented by means of demonstration software on an Acer A500 tablet computer (see Appendix B).

When the Sensator was more than two cells away from the target, either tactile feedback with a very low intensity (setting 3, see Appendix B), or a grayish blue (RGB: 135,205,250) colour was provided. When the Sensator was two cells away from the target, either tactile feedback of moderate intensity (setting 6) was provided, or light blue (RGB: 0,191,255) visual feedback, whereas the most intense tactile feedback possible (setting 9), or a darker shade of blue/purple (RGB:0,0,255) was presented when the Sensator was only one cell away from the target. When the Sensator was in the same cell as the target, the feedback actuators were switched off. For technical reasons, the Sensator controlled by the Surface was always responsible for tactile feedback. The feedback presented by the Surface was thus always presented real time and correctly, whereas the manually controlled feedback could have suffered from delayed and inaccurate feedback. The applied colours in the visual feedback (see Figure 3-1D) were chosen in line with Trumbo (1981), who stated that ordered categories of colour should be used to represent ordinal data.

In the physical link condition, a string was attached between the two Sensators (see Figure 3-1E). This string had the same length as the maximum distance between the two targets. All Sensators were labeled to make clear in which hand they had to be used during a specific session. During the different sessions, participants wore headphones with the (rather annoying) sound of a lawn mower in order to mask the sounds that are induced by the Sensators when vibrating. This was to make sure the participants focused on the tactile feedback instead of the accompanying sounds.

![Figure 3-1](image.png)

Figure 3-1: A: Schematic overview of Study Setting. B: Participant’s view. C: Screen to monitor Participant’s Actions. D: Visual Feedback Overview. E: Physical Link Condition.
3.5 Procedure
The participant was invited into the Demo-room and was asked to sit down at the long end of the Surface. There, he or she received written instructions (see Appendix C) after which the participant had the opportunity to ask questions if something was unclear. The purpose of the task, as defined in the instructions, was to find the location of an imaginary ship on a grid. The Sensator in the left hand was supposed to find the ‘prow’ of the ship, whereas the Sensator in the right hand was aimed at the ‘stern’ of the ship. A maximum of three practice trials was carried out by the participant to get used to the visual and tactile feedback, the sound presented by the headphones, and the task itself. The experiment consisted of four sessions (each in a different condition) with 9 trials each. Each session started with both Sensators on a predefined location. A trial started at the verbal signal of the experiment leader. At that time, the participant pressed the two start-buttons simultaneously with two hands in order to make sure that both hands had the same starting position each trial. After pressing start, both Sensators were grasped and the participant tried to find both targets based on the feedback provided by the Sensators (either controlled by the Surface or the experiment leader). When the participant thought that both Sensators were located at the locations of the target, he or she could press the finish-button at the bottom of the screen and wait for the next trial. The final locations of the Sensators in a trial were the starting positions for the next trial. The experiment leader did not provide feedback to participant with regard to their performance during the experimental sessions. This was because we did not want to influence the possible effects that were explored.

After nine trials, a session ended, after which the participant was asked to fill out a questionnaire to evaluate the feedback combination he or she has just been presented with (see Appendix D). After the final session and its accompanying questionnaire, a final questionnaire (see Appendix E) was filled out regarding the whole study. Finally, the participant was asked whether he or she had noticed that the experiment leader controlled the feedback in one of the Sensators. After this, the participant was debriefed and thanked. The complete sequence of instructions, practice trials, experimental trials, and questionnaires took approximately 40-45 minutes.

3.6 Measures
3.6.1 Performance
For each trial, the performance was measured by means of execution time (i.e., the time between pressing start and finish) and accuracy (is each Sensator located at the correct location, yes or no?). The logging of the task execution time was done automatically by the Surface application. The accuracy was determined afterwards by means of video analysis.

3.6.2 Parallelism
For each trial, the level of parallelism was measured by means of video analysis making use of Noldus Observer 11 Software. For each Sensator, every movement was coded. When one hand moved with short pauses inbetween, this was considered a continuous movement. We assumed that during this type of movement, the attention was completely focused at that specific hand. The video analysis resulted in three variables: the total duration of movement of the left hand for each trial, the total duration of movement of the right hand for each trial, and the total duration of simultaneous movement for each trial. From these variables, the percentage of the total amount of movement that was dedicated to parallel movement was derived. To explore the parallelism measure more, the participant was asked after each session to indicate the perceived amount of simultaneous movement on a 5-point Likert scale ranging from ‘not simultaneous at all’ to ‘completely simultaneous’.

3.6.3 Workload and User Experience
To measure the perceived workload of each condition, the National Aeronautics and Space Administration – Task Load Index (NASA-TLX) (Hart & Staveland, 1988) questionnaire was applied. NASA-TLX consists of six 20-point scales (i.e., Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration) on which the participant can indicate the perceived level of workload. The higher the score on each scale is, the more demanding that particular type of workload is expected to be.
With regard to the user experience, three items of the Questionnaire for User Interface Satisfaction (QUIS) (Chin, Diehl & Norman, 1988; Harper & Norman, 1993) were used after each condition. The following three 10-point scales (choice options: 0-9) were derived from the overall system satisfaction part of the QUIS: Terrible – Wonderful [Verschrikkelijk – Prachtig], Difficult – Easy [Moeilijk – Makkelijk], and Frustrating – Satisfying [Frustrerend – Bevredigend]. These three items seemed to be the most relevant to the Sensators in relation with the task at hand and were also applied in earlier Sensator research by Meijer (2013).

Besides these standard measures, participants were asked to write down a description of the search strategy applied in order to gain more insight in parallelism, preference for feedback modality and/or feedback-hand preference. Moreover, verbal remarks made by the participants throughout the whole study as well as afterwards were recorded. Finally, participants were asked for their age, their dominant hand and to rank the four conditions regarding which condition was ‘most beneficial for the over-all performance’ [het beste voor mijn algemene prestatie], ‘most pleasant’ [het prettigst], ‘least mentally demanding’ [het minst mentaal belastend], and ‘the most comprehensible’ [het duidelijkst].

3.7 Results

This first study was meant to gain initial insights in the effects of different combinations of feedback modalities in bimanual tangible interaction. Since the study was set up in a Wizard of Oz fashion and because the number of participants was rather low, no extensive statistical analyses and hypothesis tests were carried out. However, we present several results in this chapter in order to provide an indication of possible effects that were studied more extensively in subsequent experiments. Two of the five participants (40%) indicated afterwards that they were aware of the Wizard of Oz setup of the experiment. The focus of the experiment was on the perception and appreciation of feedback instead of on the system itself. Moreover, the feedback controlled by the experiment leader was presented in a similar quality (e.g., similar amounts of delays and mistakes in the feedback) over different conditions and participants. Therefore, we assumed that knowledge about the Wizard of Oz setup did neither affect performance, nor other measures.

Since hand-dominance is one of the fundamentals of the current project, the TV and VT conditions were recoded so that the visual feedback was either in the dominant hand (Vd) or in the non-dominant hand (Vn). Moreover, the data of 16 trials in which technical problems occurred, were removed (8.9% removed). Examples of technical problems include losses of communication between Surface or tablet and accompanying Sensator, which resulted in wrongly presented feedback, or participants that pressed the finish-button unintentionally.

3.7.1 Performance and Parallelism

In 8 of the remaining 164 trials, the final location of one (6 times) or both (2 times) of the Sensators was incorrect. In other words: 10 of the remaining 328 targets were not found (3.05%). In all these 10 cases the wrongly placed Sensator was providing tactile feedback. 8 of the 10 mistakes occurred in the conditions in which both Sensators provided tactile feedback (2 in TT and 6 in TTlink); accuracy results can be found in Figure 3-2.

Figure 3-2: Accuracy Percentages per Condition, per Hand.
Before an analysis of the duration was done, the 8 trials in which mistakes were made were removed, resulting in 156 remaining trials of the possible 180 (13.3% removed in total). For each participant the personal trial duration outliers in each condition were removed (Z-scores > 2 or < -2 were considered outliers), resulting in 5 removed trials. Per condition, mean trial times were computed as can be seen in Figure 3-3.

![Figure 3-3: Trial Duration per Condition (Seconds). Error Bars indicate 95% Confidence Intervals.](image)

Due to the low number of participants as well as the many lost data, no hypothesis tests were carried out. However, when only looking at the means, it seems that the trials in the asymmetric feedback conditions (Vd: $M = 23.7$, $SD = 9.5$; Vn: $M = 25.3$, $SD = 9.9$), on average have been carried out faster than in the symmetric, unimodal conditions (TT: $M = 38.6$, $SD = 29.2$; TTlink: $M = 38.3$, $SD = 23.0$). At first glance, there neither seems to be an effect of hand dominance with regard to performance (i.e., no differences between Vd and Vn), nor does there seem to be an effect of having a physical link between the two Sensators (i.e., no differences between TT and TTlink).

From the video-analysis, the percentage of parallel hand movement was derived. There did not seem to be large differences between the conditions with regard to the mean percentage of parallelism (TT: $M = 45.2$, $SD = 16.3$; Vd: $M = 48.1$, $SD = 17.8$; Vn: $M = 46.1$, $SD = 20.6$; TTlink: $M = 54.8$, $SD = 21.2$). The perceived amount of parallelism did not provide many new insights, besides the idea that a physical link might increase the feeling of parallelism; especially when compared with the TT condition. Figure 3-4 provides an overview of the parallelism data.
Besides the amount of parallelism in the different conditions it is interesting to look at the division of hand usage when not moved in parallel. In Figure 3-5, this division can be found. When not used in parallel, each hand moved approximately 50% of the time. However, when one of the hands was presented with visual feedback, this hand seemed to move relatively less than the other hand (which was presented with tactile feedback). This might imply that visual feedback is easier to understand.

![Figure 3-5: Division of Hand Usage when not in Parallel.](image)

### 3.7.2 Workload

The mean NASA-TLX scores were computed per condition and the scores were compared. Moreover, a weighed perceived workload score was computed based on the assumed importance of each item. Results can be found in Figure 3-6 and Table 3-1. Neither effects of feedback combination on any of the six workload aspects, nor on the weighed average could be identified at this point.

![Figure 3-6: Mean Scores of the NASA-TLX Items. Error Bars indicate 95% Confidence Intervals. Note that the higher the score on Performance, the lower the actual perceived Performance is.](image)

9 NASA-TLX includes a ‘sources of workload’ investigation to assess the relative importance of each of the items, but this investigation was not integrated in the questionnaires as applied in the Study. In discussion with some of the participants, the relative importance of the several items was assessed, which at time of the analyses was the best approach possible.
Table 3-1: Means and SD of NASA-TLX items.

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</tr>
<tr>
<td>Mental Demand</td>
<td>11.80</td>
<td>5.63</td>
<td>10.20</td>
<td>5.54</td>
</tr>
<tr>
<td>Physical Demand</td>
<td>7.00</td>
<td>5.96</td>
<td>5.00</td>
<td>2.35</td>
</tr>
<tr>
<td>Temporal Demand</td>
<td>12.20</td>
<td>4.49</td>
<td>10.00</td>
<td>4.69</td>
</tr>
<tr>
<td>Performance</td>
<td>10.20</td>
<td>5.76</td>
<td>9.60</td>
<td>5.27</td>
</tr>
<tr>
<td>Effort</td>
<td>14.80</td>
<td>2.59</td>
<td>12.80</td>
<td>4.02</td>
</tr>
<tr>
<td>Frustration</td>
<td>14.60</td>
<td>2.41</td>
<td>11.00</td>
<td>4.85</td>
</tr>
<tr>
<td>Weighed Average</td>
<td>12.97</td>
<td>3.23</td>
<td>10.96</td>
<td>4.21</td>
</tr>
</tbody>
</table>

3.7.3 User Experience

Three items from the QUIS scale, which seemed most relevant for the current study, were included in the questionnaire after each condition. Although no hypothesis tests have been carried out, the graph in Figure 3-7 demonstrates a certain trend in favour of the Vn condition (i.e., having the highest absolute scores on all three dimensions).

![Figure 3-7: Mean Scores and 95% Confidence Intervals of QUIS-items.](image)

3.7.4 Remarks and Observations

Besides the predefined measures, the remarks made by the participants were documented. Although not many comments were given, some interesting input was provided. With regard to the tactile conditions (either with or without a link), three participants indicated that these conditions were difficult, frustrating and/or had a deteriorating effect on the performance.

With regard to the visual conditions, two participants indicated they preferred visual feedback in the non-dominant hand and one of them explicitly stated that tactile feedback only worked when presented to his dominant hand; both in terms of performance and convenience. A third participant indicated that having two different modalities emphasized the difference between the two sub-tasks (i.e., finding the ‘prow of the ship’ with the left hand and the ‘stern of the ship’ with the right hand), which made it easier for him to distinguish between the two (sub-)tasks. Besides the condition-dependent remarks, some overall remarks were made, mainly with regard to the performance of the system. Several participants indicated that there seemed to be a certain delay in the feedback and that every now and then the feedback was not accurate.

After each condition, participants were asked to describe their search strategy. In general (i.e., in 16 out of 20 descriptions, 80%) the applied strategy was to start off with both hands simultaneously, making relatively large movements over the grid, until a stimulus (either tactile or visual) was perceived in one of the hands. When this was the case, the Sensator which provided this initial stimulus was positioned at the correct place, after which the second Sensator was located.

23
Contrary to this strategy, one participant indicated that when the feedback was asymmetric, his focus was initially on the dominant hand (regardless of the presented feedback modality). Another participant however indicated that her focus was mainly on the non-dominant hand (but only in the Vn and TTlink conditions). These two participants were the same who indicated a preference for visual feedback in the non-dominant hand and tactile in the dominant.

3.8 Discussion
3.8.1 First Implications

Although there were only five participants, we inferred some initial implications from the results. First of all there are the results with regard to the symmetric feedback conditions (i.e., TT and TTlink); the participants reported these conditions as being more difficult and frustrating than the asymmetric conditions (i.e., Vd and Vn) in their verbal comments. The results of the NASA-TLX and QUIS-questionnaires however did not clearly support these subjective feelings, whereas the results of the task performance actually did. The mean trial times seemed to be higher in the symmetric conditions and all mistakes were made when presented with tactile feedback. These results can have two causes (which are not mutually exclusive): There might be an effect of having tactile feedback in the sense that it is simply more difficult to interpret than visual feedback. In earlier research with the Sensators was found that people performed significantly better with visual feedback (either provided by the Sensator or by a coloured circle displayed on the Surface underneath the Sensator) in a unimanual rotation task (Meijer, 2013). Visual feedback was experienced as being more pleasant as well. Moreover, when not moved in parallel, the hand presented with visual feedback moved for shorter durations than the hand presented with tactile feedback. This could imply that the visual feedback is easier to interpret. This would be in line with Nesbitt (2003) who stated that visual feedback dominates tactile feedback because of experience people have with it and because of the amount of information that can be processed by the visual modality compared with the tactile modality. The other cause might follow Wickens’ Multiple Resource Theory (Wickens, 2002; Wickens, 2008), in the sense that carrying out two (sub-)tasks simultaneously is more difficult when the information regarding the both (sub-)tasks is perceived in the same sensory modality; the two simultaneously presented tactile signals might have interfered with each other.

A similar question remains for the conditions containing visual feedback (Vd and Vn), or the asymmetric conditions if you will. Was the seemingly better performance in these conditions a consequence of having asymmetric feedback, resulting in a more clear distinction of the two (sub-)tasks, or was the effect sorted as a consequence of having visual feedback? These questions need to be resolved in future experiments; implementing a symmetric visual condition could provide more insights in these questions.

We did not find any effects with regard to the parallel hand movements. This can imply that there is no effect, but it can also be a consequence of the strategy applied by the participants. In general they indicated to start off with an exploration of the whole grid with two hands. When a stimulus was perceived in one Sensator, the second Sensator was moved closer in order to find the second target in a more confined area. The applied strategy seems to be inherent to the task at hand; in hindsight, the task did not induce asymmetric bimanual interaction as described by Guiard’s KCM (1987). The cover story in which a role was assigned to each hand did not work out as envisioned. It seemed that the two sub-tasks were not integrated into one. A physical link between the two Sensators did improve the perception of parallel movement, but in practice no large increase of parallelism was found. The lack of simultaneous movement might be attributed to the absence of a visual link between both hands. As Brandl et al. (2008) indicate, the necessity of visually linking the tasks of both hands becomes increasingly important when surfaces become larger. When compared with relatively small surfaces such as tablet PCs or graphic tablets, interaction on a digital tabletop requires a visual link in order to support the cognitive integration of two subtasks (Balakrishnan & Hinckley, 2000). Switching the attention between the left and right hand results in highly sequential performance and neutralizes or reverses the advantage of bimanual interaction. Therefore, a future bimanual task should put more emphasis on being one integrative task, instead of two separate sub-tasks.
### 3.8.2 Limitations and implications for follow-up experiments

Just like any other study, this first exploratory study had certain limitations; the most influencing of which will be addressed. With regard to the purpose of the whole project (i.e., exploring the effects of both symmetric and asymmetric feedback in asymmetric bimanual tangible interaction), the Wizard of Oz study was limited in two important ways. First of all, due to technical limitations at this point, a symmetric visual condition was lacking. A VV condition could have provided better insights in the questions that remained after this study: Are the differences in performance between the TT/TTLink and the Vd/Vn conditions a result of the possible worse perception of tactile feedback, or of the possible deteriorating effects of presenting two sources of feedback in the same sensory modality? The second important aspect to consider is the type of the task. Although the task was clearly bimanual and parallelism was encouraged, there was no clear distinction between the roles each hand assumed. In hindsight, the KCM as proposed by Guiard (1987) was not applied well enough; there was no clear collaboration between the two hands.

Since the study was set up in a Wizard of Oz fashion, the experiment leader manually controlled the feedback in one of the two Sensators. This inherently had two consequences. First, errors were made sometimes (e.g., providing light vibrations where heavy vibrations were intended) and second, there was a delay in the feedback. “When feedback is delayed by as little as 100 ms, it can be harmful already when rapid sequences of action are required. Such delays are particularly harmful when the operator is less skilled and thus is more dependent on feedback” (Wickens, Lee, Liu & Gordon Becker, 2004, p. 221). Therefore, the application as used in the subsequent studies should be completely automatized and thus faster and more accurate in its feedback presentation.
4. Study 2; Explorative Experiment: Picture Manipulation

4.1 Introduction
This second study serves as a more elaborate exploration of the effects of different combinations of feedback on performance, workload, user experience, and simultaneous hand movement within asymmetric bimanual tangible interaction tasks. The initial implications as found in Study 1 will be investigated further; a better performance is expected in the asymmetric visual-tactile conditions when compared with the symmetric tactile condition. The question whether this effect is accountable to the specific modalities or to the asymmetric division of the feedback, is to be answered in this study; a symmetric visual feedback condition is implemented for this purpose. In order to explore the effects of the different feedback modalities in relation with hand-dominance, several conditions are implemented in which only one hand is presented with feedback.

Moreover, the lessons learned from the Pilot study with regard to the experimental design will be applied. The task that has to be carried out by the participants will be more comprehensive than in Study 1, and the role distinction of the hands will be more in line with the KCM of Guiard (1987). In line with the example as provided by Casalta, Guiard and Beaudouin-Lafon (1999), the participants will be asked to transform pictures with both hands. The non-dominant hand will determine the location of the picture in order to provide a reference frame within which the dominant hand can carry out a precise task (i.e., scaling of the picture). Each Sensator will provide feedback to the user with regard to its specific sub-task. There is a direct coupling between physical actions with the Sensors and digital transformations of the on-screen image, making it a suitable tangible interaction task (Fitzmaurice et al., 1995). Moreover, a visible link between the two hands is present, resulting in a more comprehensive task (Brandl et al., 2008).

Before the main experiment is carried out, the participants will conduct a small pre-test aimed at finding out how intuitive and how easy to perceive the several stimuli are. Trumbo (1981) stated that an order in data can be represented by means of making colours darker. Does increasing the tactile intensity sort the same effect, and do people intuitively relate a higher tactile intensity to a darker colour? Moreover, the pre-test aimed at finding out how well people were able to discriminate between two different tactile intensities. In this chapter, we will describe the methods for both the pre-test and the main experiment, the results gained, and the implications for design and future research.

4.2 Design
In this picture manipulation study, a within subjects design has been applied with nine different conditions (i.e., feedback combinations). Each of the two Sensors either presented tactile (T), visual (V), or no feedback (N); all possible combinations were evaluated. A latin square was applied to vary the order of the nine conditions over the participants to minimize possible learning effects. The participant was presented with only one feedback combination throughout one experimental block to avoid possible effects of sensory expectations (e.g., Spence & Driver, 1997; Spence et al., 2000; van Erp, 2006).

4.3 Participants
In total, 19 participants took part in the study. Due to technical problems, one person did not finish the experiment. The little data gathered from this participant was left out of further analyses. Of the remaining 18 participants, 10 were male (55.6 %). The mean age of the participants was 34.28 years old (SD = 10.7, range: 18-49). Participants were invited via the participant database of TNO Soesterberg when they met the inclusion requirements for the experiment. Participants had to be right-handed, since the roles for both the dominant and the non-dominant hand were predefined and not configurable. Moreover, the participants could not suffer from colourblindness and both of the participants’ hands should function well. Participants were scheduled on a first come, first served basis. They were paid €30,- for participation and travel expenses were covered.

10 As described before, the different combinations of feedback are represented by means of abbreviations of two letters. ‘N’ refers to ‘No feedback’.
4.4 Setting and Apparatus

Both the pre-test and the main experiment were carried out in the diffusely lit Demo-room at TNO, Soesterberg. For the pre-test, four Sensators (labeled with numbers 1-4) were placed on a table in front of the participant. Sensator 1 and 2 provided tactile feedback, each with a different intensity; Sensator 3 and 4 each presented a different colour. The colours and tactile intensities used in this pre-test were the same as applied during the main experiment (see Table 4-1) and related to each other. When for instance Sensator 1 had tactile intensity 9 and Sensator 2 had intensity 4, then Sensator 3 and 4 assumed the two accompanying colours. The participant was asked to create two pairs of Sensators, each consisting of one Sensator with tactile feedback and one with visual feedback, pure on intuition. There would not be any correct or incorrect combinations. Participants were asked to carry out 6 pre-test trials in randomized order; presentation of the stimuli was controlled by the experiment leader by means of the tablet computer (see Appendix B).

For the main experiment, the Samsung Surface table (SUR40) was used. Specially designed software ran on the Surface, in which images could be manipulated by means of the Sensators. The layout of the Surface screen can be seen in Figure 4-1A; the bottom of the screen contained two start-buttons (replaced by one finish-button during a trial), on the left of the screen a bar with trial-number, condition and participant number was visible, and the right top corner contained a miniature representation of the Surface screen, in which a target-image was displayed. The remainder of the screen was applied as being the area for the actual picture manipulation. The participant was asked to manipulate the image on screen in such a way that it would match the relative location and size of the displayed target-image.

![Figure 4-1: Layout of the Screen. A: Initial state. Sensators located on Surface, Target-image visible. B: After Participant presses the two Start-buttons simultaneously, the Image appears coupled to the Sensators. C: The Participant moves both Sensators in order to match the Image with the Target-image and when satisfied he or she presses the finish-button. D: The manipulated Image disappears and a new Target-image becomes visible.](image)

In each trialblock (i.e., each condition), the same sequence of 12 trials was carried out; 2 practice trials to let the participant get used to the feedback combination and 10 experimental trials. The Sensator in the left hand was coupled to the lower left corner of the image. The Sensator in the right hand was coupled to the top right corner of the image. When a Sensator was moved over the Surface, the accompanying corner of the image moved along, resulting in a non-uniformly scaled...

11 During pilot sessions of the experiment, it became clear that the absence of a representation of the finish-button, the miniature screen and the text-field within the miniature screen was confusing. To solve this issue, small pieces of tape were sticked on the Surface, in order to create a visual representation of these fields.
image. The reason for choosing non-uniform scaling was twofold: First, the interaction was more intuitive and second, the coupling between Sensator and digital information (i.e., the image) was very clear and direct; an important characteristic of tangible interaction. The different trials varied in the size of the image (ranging from 300x200 px to 975x650 px) and the location. Although the size varied, the target-image’s proportions remained the same.

Each Sensator provided either visual or tactile feedback with regard to its specific role. A third option was that a Sensator did not provide any feedback. In one condition (the baseline condition), no feedback was applied. The feedback in the Sensator in the left hand communicated the distance to the target-location. The Sensator in the right hand communicated whether the current size of the image corresponded with the size of the target-image. A consequence of this setup was that the location of the image could be incorrect, but at the same time, the scale of the image could be completely corresponding to the target-scale. Note that when only the left (location-)Sensator was moved, the scale of the image changed. This resulted in changes in the feedback presented by the right (scale-)Sensator. Table 4-1 displays the feedback values of the visual and tactile feedback and Figure 4-2 gives a graphical overview of how the feedback was provided.

In the conditions in which one or both Sensators provided tactile feedback, the participants were asked to wear hearing protection in order to mute the sounds the Sensators make when vibrating. All trials were recorded on video as means of information backup.

<table>
<thead>
<tr>
<th>Distance in px to target-location (and target-scale)</th>
<th>RGB Value</th>
<th>Tactile intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-35</td>
<td>(0,0,0) (LED turned off)</td>
<td>0</td>
</tr>
<tr>
<td>36-100</td>
<td>(0,255)</td>
<td>9</td>
</tr>
<tr>
<td>101-190</td>
<td>(40,90,255)</td>
<td>7</td>
</tr>
<tr>
<td>190-280</td>
<td>(50,191,255)</td>
<td>5</td>
</tr>
<tr>
<td>&gt;280</td>
<td>(135,205,250)</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4-2: Visual Representation of Feedback Mechanism. A: The Red Dot represents the Target-Location. Around this Location several invisible Rings were implemented. When the Left Sensator was positioned on one of these Rings, the accompanying Feedback was provided. B: The Feedback with regard to Image Size and thus the Sensator in the Right Hand worked similar. However, in this case, the ‘Feedback-Rings’ were located relative to the current Location of the Left Sensator (which thus served as a Reference Frame); the ‘Feedback-Rings’ for Image Size moved along with the Sensator in the Left Hand.

4.5 Procedure

Each participant was invited into the Demo-room and asked to sit down at the long end of the Surface. There, he or she received written participant information and was asked to sign an informed consent form (see Appendix F). Next, the six trials of the pre-test were carried out (within approximately 3 minutes). Next, written instructions of the main experiment (Appendix G) were provided to the participant, after which he or she could ask questions when something was unclear.
After the introduction, seven practice trials were carried out in order to become familiar with the task, the Sensators, and the feedback modalities. The experiment leader carried out the very first trial to explain the task in detail. After this trial, the participant could carry out the remaining six practice trials (two trials VV, two trials TT and two trials NN). After this block of practice trials, the participant was asked whether he or she had any other questions and the actual experiment was started.

As described before, every experimental block started with two practice trials, in which the participant could get used to the feedback combination presented during that specific block. Additionally, the practice trials made sure that the starting location for both Sensators was roughly the same during each block. The target-image was already visible in the miniature screen. The participant was asked to press both start-buttons on the screen in order to start a trial; two start-buttons were implemented to make sure that both hands were off the Sensators when a trial started. Once the trial was started, the image that had to be manipulated became visible and was directly coupled to the location of the Sensators. The participant was expected to grasp both Sensators and transform the image as fast and accurate as possible in such a way that it would match the target-image. When the participant thought the image was manipulated correctly, he or she pressed the finish-button on the screen. The end locations of the Sensators in one trial were the starting locations for the consecutive trial. After each experimental block, the participant was asked to fill out a questionnaire with regard to the condition he or she just experienced (see Appendix D). After the ninth and final condition-specific questionnaire, participants were asked to fill out a concluding questionnaire (see Appendix H). Finally, the payment-administration was arranged, after which the participant was shortly debriefed and thanked. The complete sequence of experimental trials and questionnaires took approximately 75 minutes. Another 15 minutes were reserved for instructions and the pre-test before the main experiment.

4.6 Measures

4.6.1 Pre-test

During each of the six trials, the participant was asked to make two pairs of Sensators and to write down the combinations. Afterwards, the participant was asked to describe on what basis the different Sensators were paired. This description was the measure for the intuitiveness; when participants answered as hypothesized (i.e., higher intensity relates to darker colours), the number of trials in which the pairs corresponded with this hypothesis, were counted.

4.6.2 Performance

For each trial, the performance was measured by means of execution time (i.e., the time between pressing start and finish). The accuracy was logged per Sensator; it tells how many pixels the location of the Sensator deviates from the intended location at the moment of pressing finish. From this was derived whether a Sensator has been located correctly or not. Both the trial time and the accuracy were logged automatically within the Surface application.

4.6.3 Parallelism

The amount of simultaneous movement of both hands was stored automatically for each trial. On a 200 ms interval base was checked whether the current location of a Sensator was different than its prior location (with a 2 px threshold to compensate for possible deviations in the Surface’s tracking accuracy). The total amount of intervals was counted as well as the total amount in which either the left Sensator moved, or the right Sensator, or both. From these total amounts, the percentage of simultaneous movement could be derived. To gain more insight in the amount of parallelism, the participant was asked to indicate the perceived amount of simultaneous movement on a 9-point Likert scale12 ranging from ‘not simultaneous at all’ to ‘completely simultaneous’ after each experimental block.

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12 A 9-point Likert Scale was applied in this study, whereas a 5-point Likert scale was applied in the Pilot study. This change was made in order to allow more nuance in the ratings.
4.6.4 Workload and User Experience

As was the case in the Pilot study, the perceived workload and user experience were measured. The user experience was measured using the same three items as in the Pilot study. The following three 10-point scales (choice options: 0-9) were derived from the overall system satisfaction part of the QUIS (Chin, Diehl & Norman, 1988; Harper & Norman, 1993): Terrible – Wonderful, Difficult – Easy, and Frustrating – Satisfying. These three items seemed to be the most relevant to the task at hand and were also used by Meijer (2013) in his earlier work on the Sensators.

With regard to the workload, the NASA-TLX questionnaire (Hart & Staveland, 1988) was applied after each experimental block. Contrary to Pilot Study 1, participants of the current study were asked to indicate which aspects of the NASA-TLX scale had most influence on their overall workload. 15 Comparisons between two NASA-TLX scales were made (i.e., all possible combinations between the six items); participants had to indicate which of the two was of higher influence on their perceived overall workload. Knowing the so-called ‘sources of workload’ for each participant is helpful to come to a more meaningful weighted average of the perceived workload.

These ‘sources of workload’ comparisons were part of the concluding questionnaire, as were the demographic questions (age, sex). Although we did not explicitly address this aspect earlier, we wanted to explore whether gender could have an influence on the other measures. Moreover, for each sub-task (i.e., moving and scaling) the participant was asked to indicate which modality of feedback (visual, tactile, or no feedback) they considered as being ‘most beneficial for the over-all performance’, ‘the fastest’, ‘the most accurate’, ‘the most pleasant’, ‘the most comprehensible’, and ‘the least mentally demanding’.

Besides gathering all the mentioned data, the experiment leader observed the participant and wrote down striking aspects such as applied image manipulation strategies, and how the Sensators were used. Moreover, verbal comments made by the participants were listed.

4.7 Results

4.7.1 Pre-test Results and Implications

11 out of the 17 (65%) responding participants indicated that they coupled the higher intensity of vibration to the darker colour; in line with how it was applied in the main experiment. Another explanation, which recurred 5 times (29%), was that the brightest colour of the two was coupled with the more intense vibration. The pairs created by the 11 people who responded in line with the main experiment setup were checked for consistency. On average, each of these 11 persons made 4.27 correct combinations (out of 6; $SD = 1.35$). This implies that it is sometimes difficult to distinguish between two different tactile intensities. The differences in intensity between the two tactile stimuli varied over the trials. However, in one trial the difference between the intensities was only 1 level (see Appendix B for more information about the different intensities). Participants seemed to have more problems with that specific trial.

Although the results of the pre-test demonstrated that the coupling between a higher intensity and darker colours as applied in the main experiment was not the most intuitive for every person, it was for the majority. We did not consider the results with regard to the tactile intensity distinction as being problematic; in particular because in the main experiment, the vibrations were applied in a different fashion. That is, the participant would move his or her arms and the intensity would as a consequence gradually increase or decrease. The task of the main experiment was not to make distinctions between the intensity between two different Sensators, but to identify changes in intensity in each of the two Sensators. To overcome possible influence of these aspects, participants were clearly instructed on the different stimuli in the main experiment, and practice trials were carried out in order to become more familiar with the feedback and its respective meaning.
4.7.2 Pre-processing

The 18 participants carried out a total amount of 1620 experimental trials. Due to problems during several trials, 121 trials (7.47%) were considered invalid. Invalid trials were mainly caused by technical problems; the locations of the Sensators were sometimes not recognized appropriately by the Surface, resulting in images that did not transform along with Sensator movement. Another recurring problem was that participants let their forearms rest on the Surface, thereby unintentionally pressing the finish-button.

Per condition, all trial times that exceeded the condition’s mean trial time +/- 2 SD were removed. It appeared that all removed trials exceeded the mean trial time + 2 SD (no trial times were faster than the mean – 2 SD). Sometimes, participants seemed to be distracted and not completely focused on the task; they were playing with the objects and/or the image, or searching for the right target-location in a completely wrong area of the Surface. Although there were no technical problems during such trials and these trials could thus be considered valid, we considered them as being atypical for the specific condition. The performance in such trials was lower than what can be considered typical – and sometimes even highly unrealistic (e.g., trial times over 4 minutes) – and were therefore removed. Removal of the outliers thus resulted in different, but more representative, mean trial times for each participant in each condition. The removal of outliers resulted in a decrease of the mean trial times of each condition, but this decrease was not similar for every condition (see Appendix section I-1). Therefore, the removal of outliers also affected the interpretation of the custom hypothesis tests. Moreover, excluding the outliers resulted in normally distributed data. Since the removed trial times were not considered as being representative, the accompanying accuracy data (i.e., how many pixels does the final Sensor location deviate from the target-location?), and the parallelism data were removed as well. Data of another 55 trials (3.4% of the total) were removed. After removal of the outliers, the trial times, parallelism, and accuracy data were aggregated per participant.

Before we carried out the several analyses, some data were recoded. The accuracy data (i.e., the measured distances between the final location of each of the Sensors and the accompanying target-locations) were recoded into either ‘0’ (correct location; distance <= 35 px) or ‘1’ (incorrect location; distance > 35 px). Moreover, for each valid trial, the percentages of parallel movement of the two hands were computed based on the ratio ‘total amount of intervals in which both Sensors got a new location’ / ‘total amount of 200 ms intervals during a trial’. For the subjective parallelism measure, the Likert scale results were transformed into percentages as well.

4.7.3 Manipulation check

To find out whether the picture manipulation task could be carried out without any form of feedback, the (recoded) accuracy data were analyzed. A Repeated Measures ANOVA was applied, in which one planned comparison was carried out; the comparison between having feedback (conditions VV, TT, VT, TV) and having no feedback (condition NN). For the left hand, this resulted in a significant effect ($F(1, 17) = 573, p < .001$) in favour of having feedback (i.e., significantly less errors). For the right hand, the effect was similar ($F(1, 17) = 334.53, p < .001$). These results tell that the task could not be carried out successfully (i.e., accurately) without having feedback.

4.7.4 Trial Times

To check for possible main and/or interaction effects of gender, a 2 (male-female) x 9 (conditions) Mixed Design ANOVA was carried out on the trial time data. Neither a significant main effect ($F(1, 16) < 1, p = .988, ns$), nor a significant interaction effect was found ($F(3.52, 56.322) < 1, p = .953, ns$) (a Huynh-Feldt F-Test was applied, since the assumption of sphericity was violated according to Mauchly’s test: $\chi^2(35) = 96.71, p < .001$). Since there were no gender effects, it was safe to carry out planned comparisons without gender as distinguishing factor.

A Repeated Measures ANOVA omnibus test was carried out to demonstrate the presence of a main effect of feedback combination on trial times. Since the assumption of sphericity was violated according to Mauchly’s test ($\chi^2(35) = 102.82, p < .001$), the Huynh-Feldt correction was applied
There was a significant main effect of feedback combination on trial times ($F(3.321, 56.322) = 14.65, p < .001$). Since the current study has got an exploratory fashion, several planned comparisons were carried out in order to understand what actually happened as a result of having different feedback combinations. First of all, the anticipated negative effect of TT was explored. Figure 4-3 shows the mean trial times per condition and this graph already implies a negative effect. Planned comparisons were carried out in which TT was compared with the other combinations in which both hands received feedback (i.e., VV, VT and TV combined). Moreover, TT was compared with only VV, respectively with the two asymmetric conditions combined. On all three comparisons significant differences were found which indeed demonstrated that TT was slower. A mean difference of 10.1 seconds in trial time was found between TT and VV-VT-TV ($F(1, 17) = 13.77, p = .002$). Similar differences (10.25 and 9.99 seconds respectively) were found between TT and VV ($F(1, 17) = 20.55, p < .001$), and between TT and asymmetric feedback ($F(1, 17) = 10.66, p = .005$).

One of the main questions of this project was to find out whether it could be beneficial to emphasize the different roles each hand assumes by providing asymmetric feedback. A comparison between symmetric and asymmetric feedback (VV and TT vs VT and TV) indicated that asymmetric feedback resulted in faster trial times ($F(1, 17) = 5.04, p = .038$), but as demonstrated before this was mainly caused by the TT condition. A comparison between the symmetric visual condition and both asymmetric conditions seemed therefore appropriate and this resulted in a non-significant effect ($F(1, 17 < 1, p = .877, ns$). With regard to the performance, there thus did not seem to be a difference between asymmetric and symmetric visual feedback.

Interesting to note is that there was a difference of 3.1 seconds between the two asymmetric conditions, which is in favour of the VT condition ($F(1, 17) = 5.02, p = .039$). This result raises the question whether the effect could be mostly attributed to having the tactile feedback in the dominant (right) hand, or by having the visual feedback in the non-dominant (left) hand. To further explore this question, two extra comparisons were made. First, visual feedback was compared with tactile feedback in the dominant hand (with no feedback in the non-dominant hand; NV vs NT), and second, the same comparison was made for the non-dominant hand (with no feedback in the dominant hand; VN vs TN). The performance of the hand to which no feedback was provided was assumed to be a constant factor, not affected by the feedback modality presented to the other hand. In both comparisons, a significant effect was found in favour of visual feedback. Trial times were 2.28 seconds faster when visual instead of tactile feedback was provided to the dominant hand ($F(1, 17) = 8.89, p = .008$) and 3.29 seconds for the non-dominant hand ($F(1, 17) = 10.42, p = .005$). These results did not directly explain the difference between TV and VT, but they did lead to another interesting observation: Since the task was performed faster with visual than with tactile feedback, regardless of the hand, an advantage of VV over VH and HV would have been logical. However, as described before, no differences between VV and asymmetric feedback were found. An overview of the descriptive statistics of the trial times can be found in Appendix I.1.
4.7.5 Parallellism

The main effect of gender on parallelism as well as possible gender*parallelism interaction effects were explored by means of a 2 (male-female) x 9 (conditions) Mixed Design ANOVA. Since Mauchly’s test of sphericity indicated a violation of this assumption, the Huynh-Feldt corrected F-statistic was applied ($\chi^2(35) = 64.56, p = .003$). Neither a significant main effect of gender ($F(1, 16) < 1, p = .798, ns$), nor a significant interaction effect ($F(5.112, 81.785) < 1, p = .802, ns$) were found. Moreover, no significant main effect of feedback combinations on the amount of parallel hand movement were found ($F(5.112, 81.785) = 1.97, p = .09, ns$). This implies that the amount of parallel hand movement was not affected by the (combination of) feedback modalities provided to the hands.

After each experimental block, in which the participant was presented with one feedback combination, he or she was asked to indicate the perceived amount of parallel movement of both hands. Scores from the 9-point Likert scale were transformed into percentages. Results can be found in Figure 4-4, in which the results for both objective and subjective parallelism are visualized. Interesting to see are the relatively large differences between the objective and subjective measures. As described before, no effects were found in the objective measures. With regard to the effects on the subjective measure, the comparison between having no feedback (NN) and having feedback in both hands (VV, TT, VT and TV) demonstrated the most striking result. People had the impression that having feedback in both Sensators decreased the amount of parallel movement ($F(1, 17) = 14.68, p = .001$); on average the score on perceived parallelism was 22.2% higher in the NN condition. The descriptive statistics for both the objective and subjective parallelism data can be found in Appendix I.2.

![Figure 4-4: Percentages of Parallel Hand Movement in each Condition. Both Objective and Subjective Measures are displayed accompanied by 95% Confidence Intervals.](image)

4.7.6 Subjective Workload

Based on the ‘sources of workload’ comparisons that were presented to the participants in the concluding questionnaire, a weighed summated score was computed for each participant in each condition. As done before, possible effects of gender on the weighed scores were analyzed by means of a Mixed Design ANOVA. No significant effects were found for gender; $F(1, 16) < 1, p = .73$ (ns) for the main effect, and $F(3.757, 60.119) = 1.77, p = .150$ (ns) for the interaction effect (a Huynh-Feldt F-Test was applied, since the assumption of sphericity was violated according to Mauchly’s test: $\chi^2(35) = 80.18, p < .001$). The weighed scores are displayed in Figure 4-5; the higher the scores, the higher the perceived workload.
The same planned comparisons were carried out for the weighed workload scores as were done for the trial times. It turned out that the workload in the TT condition was significantly higher than in the other conditions in which both hands received feedback (VV, TV and VT); $F(1, 17) = 8.76, p = .009$. The same applied for TT compared with the two asymmetric conditions ($F(1, 17) = 5.52, p = .031$), and for TT compared with VV ($F(1, 17) = 12.08, p = .003$). The differences between the mean scores were respectively 2.5, 2.3 and 3 on a scale from 0 to 20.

Participants did not experience a different workload between the symmetric and the asymmetric conditions (VV and TT vs VT and TV); $F(1, 17) = 1.05, p = .321, ns$. When comparing only VV with the asymmetric conditions, no effects were found either ($F(1, 17) < 1, p = .446, ns$). The two asymmetric conditions did not differ from each other either with respect to the workload; $F(1, 17) = 2.63, p = .123, ns$. For the workload, the isolated effects of feedback modality per hand were explored and this resulted in a significant respectively marginally significant effect in favour of visual feedback. The comparison between visual and tactile in the dominant hand, while no feedback was presented to the non-dominant hand, resulted in a 1.38 difference ($F(1, 17) = 5.73, p = .028$). This difference was 1.25 between visual and tactile in the non-dominant hand ($F(1, 17) = 4.28, p = .054$, marginally significant).

Besides the overall workload scores, two of the NASA-TLX items were explored more in depth; Mental Demand and Frustration. Based on verbal comments of the participants, these were considered most relevant with regard to the task at hand. Results are displayed in Figure 4-6 and 4-7.
For the Mental Demand item, the results implied that VV was less demanding than TT ($F(1, 17) = 9.54, p = .007$). Moreover, asymmetric feedback was considered as being less demanding than TT ($F(1, 17) = 5.53, p = .031$). No differences between asymmetric conditions and VV were found ($F(1, 17) = 1.85, p = .192, ns$). When both feedback modalities were compared with each other secludedly (i.e., only one hand is presented with feedback), there were no differences between the mental demand of the modality (visual vs tactile in the dominant hand: $F(1, 17) < 1, p = .411, ns$; non-dominant hand: $F(1, 17) = 4.11, p = .059, ns$).

With respect to the Frustration item, there was also a difference between VV and TT ($F(1, 17) = 11.62, p = .003$), where TT was more frustrating. Interestingly, there was no significant difference anymore when TT was compared with asymmetric feedback; $F(1, 17) = 3.66, p = .073, ns$. No differences between asymmetric conditions and VV were found either ($F(1, 17) = 1.18, p = .293, ns$). The secluded effects of feedback modality suggested that the frustration level did not differ between having visual or tactile feedback in the dominant hand ($F(1, 17) = 3.73, p = .07, ns$). However, when focusing on the non-dominant hand, visual feedback actually was considered less frustrating than tactile; $F(1, 17) = 7.38, p = .015$. An overview of the descriptive statistics with regard to the overall workload and the Mental Demand and Frustration items can be found in Appendix I.3.

### 4.7.7 User Experience

With regard to the user experience, three items of the QUIS scale were used; Terrible – Wonderful, Difficult – Easy, and Frustrating – Satisfying. First, the three items were analyzed on possible gender effects to find out whether women experienced the different conditions differently than men. This was not the case. Mean scores for each of the three items can be found in Figure 4-8, 4-9 and 4-10.
Testing the suggestion that TT was the least pleasant condition according to the participants, demonstrated that this was indeed the case. When comparing TT with the other conditions in which both hands received feedback, it turned out that TT was more terrible ($F(1, 17) = 8.48, p = .01$), more difficult ($F(1, 17) = 12.22, p = .003$), and more frustrating ($F(1, 17) = 10.33, p = .005$). Comparisons between the asymmetric conditions and the symmetric visual combination did not demonstrate any significant effects for either of the QUIS-items.

The contrasts between tactile feedback and visual feedback for the dominant hand indicated that visual feedback was considered easier ($F(1, 17) = 13.66, p = .002$) and more satisfying ($F(1, 17) = 10.35, p = .005$), whereas there was no difference in the terrible-wonderful scores ($F(1, 17) = 3.24, p = .09, ns$). The contrast between visual and tactile feedback for the non-dominant hand revealed that visual feedback was considered more wonderful ($F(1, 17) = 5.06, p = .038$) as well as easier ($F(1, 17) = 4.5, p = .049$), whereas there was no difference between the two modalities with regard to the frustration-satisfaction level ($F(1, 17) = 3.66, p = .073, ns$). The descriptive statistics of the user experience data is provided in Appendix I.4.

Besides the three QUIS items that were investigated after each experimental block, the participants were asked to indicate which feedback modality they preferred for each hand with regard to different aspects of the task (i.e., overall performance, speed, accuracy, convenience, comprehensibility, least mentally demanding). An overview of the responses can be seen in Figure 4-11.
These percentages indicate that in general, the visual feedback modality was preferred in either of the hands, especially in comparison with the tactile modality. With regard to speed and mental demand, having no feedback at all was often preferred as well. When the responses of the participants were interpreted as a choice for the preferred combination of feedback modalities with regard to the specific task aspects, the results became as Figure 4-12 depicts.

These bars imply that in most cases the VV condition was preferred by the participants. With regard to speed, more participants indicated that having no feedback at all resulted in the fastest trial times. The same applied for the mental demand. This was logical, since in the NN condition, the participants only could guess the target-locations of the Sensator; this did not require any focus on feedback stimuli. Despite the perceived speed and mental demand advantages of NN, the participants indicated that having feedback is necessary for the accuracy.
4.8 Focused Analyses Based on Observations

The different participants were observed throughout the experimental sessions and remarks made by them were noted. Whereas only a few remarks were made with regard to the user experience (some in favour of symmetric visual feedback, others in favour of either of the asymmetric combinations), relatively many remarks were made with regard to the location of the image. Several different people indicated that “the task seems easier when the image is on the right side of the Surface”. Moreover, the experiment leader had the impression that some specific trials were carried out faster than other trials. These impressions were the basis for further analyses with regard to the influence of feedback combinations on trial times and parallelism. Since the two respective tasks of the hands were related to the location and the size of the image, two follow-up analyses were carried out with focus on either of these aspects. Following Balakrishnan and Hinckley’s (2000) findings, the distance between both hands could indeed have affected the performance and/or the parallelism. Moreover, since bimanual interaction is moderated by fixation strategies (Hesse et al., 2010), the location of the image might as well have affected the performance and/or parallelism. In the first analysis, a distinction was made based on the size of the image, whereas in the second analysis a distinction was made based on the location of the image: images in the left side, the center, or the right side of the Surface screen. The main question for the analyses was whether there would be any interaction effects between respectively image size and condition and between image location and condition.

4.8.1 Image Size

A distinction between the 10 recurring experimental trials was made based on the size and the accompanying hand movements in particular. When a picture in an experimental trial was larger than its predecessor, this resulted in an outgoing movement of the hands (this was the case for 5 trials). Was the picture smaller than the picture before, both hands moved towards each other and an ingoing movement thus took place (applicable to the remaining 5 trials). Trial times for both ingoing and outgoing movements were aggregated per person for each feedback combination. A 2 (outgoing – ingoing movement) x 9 (Feedback Combinations) Repeated Measures ANOVA was carried out on the trial times as well as on parallelism (N = 17; the new distribution of trial times resulted in missing data for one participant). Mauchly’s Test of Sphericity turned out to be significant for both the Feedback Condition factor (χ²(35) = 97.54, p < .001) as well as the Size*Condition interaction (χ²(35) = 64.18, p = .003), considering the trial times. The sphericity assumption was violated and therefore the Huynh-Feldt Correction was applied. Not surprisingly, a main effect of Feedback Combination was found (F(3.236, 51.772) = 12.11, p < .001). Besides that, a main effect of size was found; on average, trials in which both hands moved towards each other were carried out 2.3 seconds faster than trials in which the hands moved away from each other (F(1, 16) = 10.95, p = .004). No interaction effect Size*Condition was found; F(5.378, 86.047) < 1, p = .688, ns. Since no interaction effect was found, no further analyses on the trial times were carried out.

Although no significant effects were found with regard to the parallelism over the different conditions, it would be interesting to see whether a distinction between different trial-types sorted any effects. Again, the assumption of sphericity was violated according to Mauchly’s Test (χ²(35) = 73.51, p < .001 for the main effect of Feedback Conditions and χ²(35) = 51.11, p = .049 for the Size*Condition Interaction. The Huynh-Feldt F-test was therefore applied. As was the case for the analysis without image size as factor, no main effect was found for the feedback conditions; F(4.427, 70.825) = 2.08, p = .086, ns. However, it seemed that the participants used their hands slightly more simultaneous when the hands moved towards each other; a 2.36% increase in parallelism (F(1, 16) = 12.78, p = .003). No interaction effect between condition and image size seem to occur; F(7.646, 122.343) < 1, p = .756, ns. No further contrast analyses were carried out.

4.8.2 Image Location Left-Right

For the analysis based on the image location, the trials were divided amongst three categories; left (3 images), center (5 images) and right side (2 images) of the screen. The x-coordinate of the target-image’s centre served as determinant for the distinction over the categories. Trial times were aggregated per participant. Since the division of trial times based on image location led to a lot of
missing data, and because the little remaining data was not distributed normally, we decided to only explore the means of the trial times instead of carrying out hypothesis tests. We investigated the plots of the data in order to get a gist of the effect of image location on task performance.

As can be seen in Figure 4-13, there seemed to be an effect of image location on the task performance when feedback was presented to both hands. The NN condition (i.e., the baseline) did not demonstrate such an effect; the performance was constant over the different locations. This implied that the variations in performance over the different locations was affected by the feedback modalities. Trials in which images had to be moved to – and scaled on – the right part of the Surface seemed to be carried out faster consequently when feedback was involved. When visual feedback was provided to the non-dominant hand (i.e., VV and VT), the decrease in trial times appeared when the left hand was moved to the right side of the screen completely; there did not seem to be differences between the left side and the center of the screen for both these conditions. For the TV and TT conditions however, the decrease in trial times seemed to be more linear over the different locations. Moreover, for these latter two conditions the difference in performance between left and right seemed to be larger than for the VV and VT conditions. With regard to the isolated effects (in which only one hand was presented with feedback), Figure 4-14 demonstrates again that trials on the right side were carried out faster.

Figure 4-14: Mean Trial Times (ms) per Image Location for the Conditions with Feedback in only One Hand. NN was added as Baseline.
Interesting to see is that the two conditions in which feedback was presented to the non-dominant hand (VN and TN) demonstrated a similar pattern over the different image locations, as did the conditions in which feedback is presented to the dominant hand (NV and NT). However, the location of the image seemed to have a larger effect when feedback was presented to the left hand.

4.9 Discussion

4.9.1 Implications

The aim of this study was to explore the effects of the different combinations of feedback on task performance, parallel usage of the hands, workload, and user experience. Participants were asked to carry out a task in which the functional roles of the hands were clearly distinguished; the creation of a reference frame with the non-dominant hand (the left hand in this case) and carrying out precise actions with the right, dominant hand. This role division corresponded with Guiard’s (1987) KCM. Moreover, as Brandl et al. (2008) suggested, a visible link between the hands was created by means of the to-be-transformed image, in order to make the two sub-tasks more coherent. Feedback was provided with regard to each specific sub-task and analysis of the errors that were made demonstrated that feedback was essential in order to fulfill the task successfully.

As the name of the Kinematic Chain Model suggests, it defines a concatenation of movements of the two hands, in which the non-dominant hand has got precedence over the dominant hand. This might explain why the amount of parallelism – despite the presence of a clear role division and a visual link between the hands – seemed rather low. It might have been the case that participants first created the frame of reference, after which they carried out the precise actions; moving the non-dominant hand first, and then the dominant hand. This could be explained as being in line with the temporal precedence principle as defined by Guiard (1987). However, the idea of this principle was that the non-dominant hand starts moving before the dominant hand starts; during the major part of the interaction, the hands would move simultaneously. Another explanation for the low amount of parallelism could be that participants carried out the task sequentially (e.g., first a movement of the left hand, then the right, then the left again, etc), thereby continuously switching their attention between the two sub-tasks. This could imply a higher workload (Balakrishnan & Hinckley, 2000). Unfortunately, the data did not provide insights in whether participants indeed moved the dominant hand after the non-dominant, or whether they continuously switched attention between both hands.

Based on the earlier results of Study 1, a higher performance for asymmetric feedback than for symmetric tactile feedback was expected. This turned out to be the case. Following on these results, the question was raised whether this effect was caused by the asymmetric division of feedback, or by the presence of visual feedback. A difference between symmetric and asymmetric feedback was found, but this was mainly caused by the negative influence of symmetric tactile feedback. When this TT condition was left out of the analysis and asymmetric feedback was thus compared with visual symmetric feedback only, the advantage of asymmetric feedback disappeared. From these results, it can be concluded that symmetric tactile feedback had a negative influence on task performance. People seemed to be less capable of interpreting two tactile signals than either two visual signals or one visual and one tactile signal simultaneously. This was also reflected in the subjective measures; the perceived workload was significantly higher for the symmetric tactile condition than for the other bimanual feedback conditions. Moreover, when tactile feedback was presented to both hands, the amount of frustration and mental demand were higher and the combination of feedback was considered more terrible and difficult.

The question is whether the negative effect of symmetric tactile feedback can be attributed to the feedback modality in itself (i.e., tactile is more difficult to interpret, people are not familiar with it, etc.), or to the idea that signal interference occurs since one single mental resource is addressed for two (sub-)tasks simultaneously. The results seem to point in both directions. When looking at the effects of feedback modality in which only one hand was presented with feedback, results imply that the type of feedback actually had an effect. People tended to perform better when presented with visual than with tactile feedback, regardless of the hand to which it was presented. Moreover, they appreciated visual feedback more than tactile as the results of the subjective measures (i.e., QUIS and
NASA-TLX) demonstrated. These results correspond with earlier work on the Sensators by Meijer (2013), in which two types of unimanual tasks were carried out. Both performance as well as user experience were higher in visual feedback conditions than in tactile feedback conditions. This might be a result of the fact that people are less familiar with tactile than with visual feedback in terms of perception and interpretation (Prewett et al., 2012; Nesbitt, 2003). Another explanation for the higher appreciation of visual feedback might be a consequence of the distinctness between the several intensities of the signal. Although the feedback was applied in a different setting, the pre-test demonstrated that in some cases the distinction between different levels of tactile feedback was difficult to make. As van Erp (2002) states, not more than four different levels of intensity (i.e., amplitudes) should be applied to encode information between the detection threshold and the comfort/pain threshold. Since the applied amplitudes did not stretch this complete range, it might have been too difficult to identify differences between two consecutive intensity levels.

Besides the effect of the tactile signal itself, the negative influence of symmetric tactile feedback can also partly be attributed to Wickens’ Multiple Resource Theory (Wickens, 2002; Wickens, 2008). This theory applies because participants had to carry out two (sub-)tasks simultaneously. This is more difficult when information regarding the two sub-tasks is presented to one single sensory modality. Since the visual modality can process greater amounts of information in a short period of time compared to the haptic modality (Nesbitt, 2003), the symmetric visual condition might be less subject to this intramodal interference than the symmetric tactile. However, there still seems to be an effect. The comparisons between conditions in which only one hand was presented with feedback demonstrated that visual feedback was significantly better with regard to the performance. This applied for both the dominant hand as well as the non-dominant hand. Based on this, one would expect that the performance of VV would be better than either TV or VT. This expectation would be in line with the findings of Prewett et al. (2012), who stated that vibrotactile direction cues are not effective when they are replacing (instead of added to) visual direction cues. Interestingly enough, these expectations were not supported when looking at the conditions in which both hands were presented with feedback; asymmetric feedback (in which one of the visual cues was replaced with a tactile one) did not decrease task performance as was to be expected. This implies that there might be an effect of intramodal interference in the VV condition, which is in line with the Multiple Resource Theory. Despite the fact that the visual modality can process much information simultaneously, a certain interference between the two visual feedback channels (in combination with the visual task at hand) may have occurred.

One of the main research questions for this project was whether asymmetric feedback would have benefits over symmetric feedback. The results seem to imply that both symmetric feedback conditions are subject to intramodal interference, although symmetric tactile more than symmetric visual feedback. When following this reasoning, asymmetric feedback might thus be beneficial, and in particular the situation in which the non-dominant hand is presented with visual feedback and the dominant hand with tactile feedback. The reason that the asymmetric conditions were not significantly better than the VV condition can be a consequence of the unfamiliarity with the tactile feedback as well as the difficulty with the discrimination of different feedback levels. Increasing the distinctness of the tactile feedback levels might enhance the performance within the asymmetric feedback conditions. Another option to increase task performance is to present information redundantly (i.e., providing the same information in two different sensory modalities at the same time). In their meta-analysis over many different studies, Prewett et al. (2012) found that when a vibrotactile cue was added to an existing visual cue, this enhanced task performance. When vision requires too many resources, it might be beneficial to offload to another feedback modality; tactile in this case.

The effects of the different feedback combinations as described are not subject to changes in the distance between the hands and/or the location of the image. In line with the findings of Balakrishnan and Hinckley (2000), the performance and parallelism were higher when images were smaller and the hands thus were closer together. However, no interaction effects of feedback combinations were found.

41
4.9.2 Limitations

Besides the earlier mentioned distinctness of the different feedback levels in the tactile modality, there were some other aspects of the study that might have biased the results, or which at least should be considered in future studies. First of all, the task aimed at emphasizing the different roles each hand has according to Guiard’s Kinematic Chain Model; it followed the asymmetric bimanual task example as provided by Casalta et al. (1999). The task was designed for right-handed people in order to limit the scope of the study as well as the development time. However, it would be interesting to verify whether the task indeed corresponds with the hand division as described in the KCM. This could be done by inviting left-handed participants.

A second possible limitation of the study that requires more consideration, appeared when several focused analyses were carried out, based on observations and comments of the participants. Although not statistically proven, there seemed to be a large effect of the position of the image on the Surface. The performance within all conditions (except for the no feedback condition) seemed to be far better when an image was to be manipulated on the right side of the screen. The most plausible explanation for this is that the miniature screen containing the target-image was located at the top-right of the screen. The time required for shifting the visual focus from the image that is being manipulated to the target-image and v.v. is shorter when the distance between these two images is smaller. Since each condition consisted of the same sequence of trials, we assumed that this did not influence the effects with regard to feedback condition. However, the location of the target-screen should be carefully considered in future research, since shifting the visual focus more often might result in a decrease of bimanual performance (Balakrishnan & Hinckley, 2000; Hesse et al. 2010).

Another possible limitation with regard to the design of the experimental application that might have had an effect on the results was the parallelism measure. It might be the case that there indeed is no effect of feedback modality combination on the amount of parallel hand usage, but another option could be that the measure applied was not suitable enough. At an interval of 200 ms, it was checked whether a sensator had moved from its previous position. Based on the amount of intervals in which this was indeed the case, a score for parallelism was computed. A smaller interval might have provided more nuance in the data. Another aspect which was lacking in the movement tracking data is the sequence of movements. This could have provided insights in on which hand the attention is focused; first the non-dominant hand and than the dominant, or moving back and forth between both hands?

The final remark with regard to the experiment are possible learning effects; the order of the different conditions was randomized over participants and several practice trials were presented to the participants in order to overcome this effect as much as possible. However, there might still have been an effect of learning; people are getting more familiar with the task, develop specific strategies, and/or get more acquainted with the different feedback modalities. In general, people are not familiar with tactile feedback. When they perceive tactile feedback throughout several conditions, the increase in performance might be steeper than for visual feedback, which could result in biased data. More elaborate training could prevent from this.

4.9.3 Conclusions and Future Research

From this second study, which mainly served as exploration, several tentative conclusions can be drawn. The first conclusion is that it is not desirable to provide tactile stimuli to both hands simultaneously when only the amplitude of the signal varies. In future research, more attention could be paid to increasing the distinctness of the tactile signals; both to the differences in signal between the two hands as well as to the differences between the feedback-levels. Besides varying the amplitude of the signal as was done in the current study, vibrotactile feedback offers other parameters such as frequency, pulse, duration and patterns (Brewster & Brown, 2004a) which can be adjusted in order to convey information. The interference effects of these parameters when applied in TUIs could provide valuable information with regard to the design and implementation of tactile feedback.
Another tentative conclusion which requires more elaboration was that symmetric visual feedback seemed to be subject to some sort of interference as well. This might be because two different visual sources compete for the same cognitive resource. Considering the results of this study, we expect that this interference can be overcome by providing asymmetric feedback; provided that the tactile element within the asymmetric feedback is implemented carefully. In other words: When we increase the distinctness of the different feedback levels – in line with van Erp (2002) – Asymmetric feedback can demonstrate its value. Moreover, it could also be beneficial to provide one of the hands with visual feedback and the other with multimodal redundant information. Prewett et al. (2012) have demonstrated amongst others, that adding vibrotactile feedback to a visual cue in a redundant fashion can result in higher task performance.
5. Study 3; Focused Experiment: Multimodal Feedback

5.1 Introduction

One of the main research questions of this project is whether asymmetric feedback might have a beneficial effect on performance (and user experience). The results of the previous study are not conclusive in this respect. When presented with asymmetric feedback, participants seemed to perform equally well as when presented with symmetric visual feedback. The absence of a difference between these two types of feedback was rather surprising considering the beneficial effects of visual feedback when presented to only one hand. There could have been an intramodal interference in the symmetric visual condition, which would be in line with the Multiple Resource Theory (Wickens, 2002; Wickens, 2008). When this is indeed the case, providing asymmetric feedback could indeed become more beneficial in asymmetric bimanual tasks when the tactile part would be implemented more carefully. This is the starting point for this third experiment; we increased the distinctness of the different tactile feedback levels and evaluated the effects of both the symmetric and the asymmetric feedback combinations.

In this third study, the same picture manipulation task as used in Study 2 is applied, but instead of an exploratory fashion, we have defined some concrete hypotheses:

- Despite the increased distinctness, people will perform the worst when presented with symmetric tactile feedback (i.e., TT), since two tactile signals will interfere with each other. This lower performance will also be reflected in the subjective appreciation of the feedback combination.
- People will perform faster when presented with asymmetric (VT and TV) feedback than with symmetric visual feedback. This will be a result of the increased distinctness of the tactile signal.
- Within the asymmetric feedback conditions, people will perform better when presented with tactile feedback in their dominant hand and visual in their non-dominant than vice versa. This result would replicate the effects found in the first picture manipulation study.

With this third study, we thus aim at confirming and replicating earlier found results. However, besides these hypotheses, we introduce a new aspect: Multimodal feedback (M\textsuperscript{13}) which consists of redundant visual and tactile stimuli presented by one Sensator. Prewett et al. (2012) stated that performance does not increase when visual feedback is replaced by tactile feedback, but when tactile feedback is added to a visual signal, performance does increase. Other studies have demonstrated that multimodal feedback indeed can increase task performance (e.g., Vitense, Jacko & Emery, 2003; Rovelo, Abad, Juan & Camahort, 2012). The reasoning behind the beneficial effects of redundant stimuli is that different visual stimuli might compete for the same mental resource. Presenting the same information by means of another sensory modality (tactile feedback in this case) might reduce the demands of the visual resource; people can offload to another sensory channel. In this experiment, tactile feedback will be added to visual feedback, which is in line with Prewett et al. (2012). We defined the following hypothesis:

- The performance of the asymmetric multimodal conditions (VM and MV) will result in even higher performance than the asymmetric unimodal conditions. We expect this because providing multimodal redundant information has proven to be a successful application (Prewett et al., 2012).

In the previous study, the plots indicated that trial times were lower when images were presented at the right side of the Surface screen. This can probably be attributed to the fact that the miniature version of the screen was located in the top-right corner of the screen. To overcome this

\textsuperscript{13} From now on, the multimodal condition will be depicted with the letter ‘M’. VM will thus mean: visual feedback presented to the left hand and multimodal feedback (haptic and visual combined) to the right hand.
issue, the miniature screen has been relocated to the top center of the screen. We do not expect any effects of image location on performance any more after this adjustment. No interaction effect between feedback combination and image size on performance and/or parallelism is expected either, in particular since no interaction effects have been found before\textsuperscript{14}. Although no effects are hypothesized, the dimensions and locations of all experimental trials will be carefully categorized in order to be able to conduct well-structured analyses.

5.2 Design

In this second picture manipulation study, a within subjects design has again been applied with six different conditions: VV, VT, TV, TT, VM, and MV. The experiment consisted of 6 experimental blocks and within each block, one feedback combination is evaluated. The order of the blocks varied per participant in order to minimize learning effects; a latin square was applied for the distribution of the conditions over the participants. When compared with the previous explorative study, a more extensive set of practice trials was to be carried out; all possible combinations of feedback modalities were presented to the participants. The reason for this was twofold: First, participants became more familiar with the several feedback modalities and combinations, as well as with the task. Secondly, filling out the questionnaires after the first couple of experimental blocks became easier for the participants. That is, in Study 2, participants indicated that it was difficult to answer the user experience questions, since they had nothing to compare their experiences with.

5.3 Participants

In total, 19 participants took part in the study. 9 of the participants were male (47.4 %). The mean age of the participants was 29.74 years old ($SD = 9.02$, range: 21-46). Participants were invited via the participant database of TNO Soesterberg when they met the inclusion requirements for the experiment. Again, participants had to be right-handed since the functional roles for both the dominant and the non-dominant hand were predefined and not configurable. Besides this, the participants could not suffer from colourblindness and both of the participants’ hands should function well. Moreover, participants who already participated during the first picture manipulation study could not take part in this second experiment; they could benefit from earlier experiences. Participants were paid €30,- for participation and travel expenses were covered. The selection took place on a first come, first served basis.

5.4 Setting and Apparatus

For an elaborate description of the application used, its settings, and the space in which the experiment took place, please see chapter 4.4 of this thesis. The application as used in this third study was basically the same, although adjusted on four aspects, which will be addressed here.

First of all, instead of having the miniature screen in the top right corner of the application, it has been moved to the top center in order to minimize the influence of the position on the trial times. Second, the settings with regard to the feedback have been changed; the distinctness of the different levels of tactile feedback has been increased. Due to the capabilities of the current version of the Sensators, this resulted in the removal of one level of feedback as can be seen in Table 5-1. Moreover, it resulted in changes in the tactile intensities and some of the RGB-values of the colours applied.

\begin{table}[h]
\centering
\caption{Visual and Tactile Feedback Values with regard to Location and Scaling Tasks.}
\begin{tabular}{|c|c|c|}
\hline
Distance in px to target-location (and target-scale) & RGB Value & Tactile intensity \\
\hline
0-35 & (0,0,0) (LED turned off) & 0 \\
36-100 & (0,0,255) & 9 \\
101-190 & (67,103,253) & 6 \\
>190 & (135,205,250) & 4 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{14} In line with Balakrishnan and Hinckley (2000), a better performance is expected when both hands are located closely together. This however, is not relevant with regard to the effects of different combinations of feedback modalities and will therefore not be formulated as being an hypothesis.
The third change when compared with the previous study were the conditions applied. The baseline condition of the previous study (i.e., no feedback) has been replaced with a multimodal condition in which visual feedback was presented in combination with the accompanying tactile feedback. The final change involved the trials; in each block, the same sequence of 18 trials was carried out, of which the first two were practice trials. Locations and image sizes were less random than in the previous study. Five images were located on the left side of the screen, five on the right side, and two in the center. These 12 images all were small (i.e., varying between 300x200 px and 600x400 px), but all in proportion. The images in the other six trials of each sequence were large and out of proportion (i.e., occupying the largest part of the width of the Surface).

5.5 Procedure

The procedure as applied during this study was similar to that of the previous study. Upon arrival, participants had the option to read TNO’s general participant information. Since most participants already were familiar with this information, it was often not read. After a general introduction of the Sensators, participants were asked to sign an informed consent form (see Appendix F). Written instructions of the main experiment (Appendix G) were provided to the participant, after which he or she could ask questions when something was unclear. After the instructions, 13 practice trials were carried out; the first by the experiment leader to explain the task, the remaining 12 (two in each condition) by the participant to become familiar with the task and all feedback combinations. The questionnaire after each experimental block was the same as used in the previous study (see Appendix D). The final questionnaire was slightly extended (see Appendix H and chapter 5.6). The complete sequence of experimental trials and questionnaires took approximately 70 minutes. Another 15 minutes were reserved for instructions, practice trials, and other formalities.

5.6 Measures

The measures for performance, workload, and user experience as applied in this third study were the same as applied in the previous study. See chapter 4.6 for a more elaborate description of these measures. The parallelism measure was adjusted in order to better assess the amount of simultaneous movement of the hands. The measuring principle remained the same (i.e., checking on a predefined interval whether or not the position of the Sensator has changed), but the measurement interval was reduced from 200 ms to 100 ms.

In the concluding questionnaire, one extra question was introduced in order to gain better insights in user preferences. Participants were asked to provide a grade (between 1-10) to each of the feedback combinations applied. In providing this grade, participants were asked to take all aspects of the interaction and their performance with the Sensators into account (i.e., speed, accuracy, ease of use, and comprehensibility).

5.7 Results

5.7.1 Pre-processing

Each of the 19 participants finished the complete experiment, which resulted in 1824 experimental trials. Of these trials, 128 (7.02%) were considered invalid due to technical problems. These problems were similar to those of Study 2; unintentionally pressing the finish-button as well as problems with the system detecting the Sensators’ locations on the table.

An outlier analysis was carried out to remove unrepresentative trials for each condition from the dataset. For the same reasons as in Study 2 (i.e., participants sometimes seemed to be distracted, causing untypical, lower performance), trial times that exceeded the mean time of a specific condition by +/- 2 standard deviations were removed. Accompanying parallelism measures were removed as well, since we considered the whole trial as being unrepresentative. A total of 81 trials (another 4.44%) was removed. The remaining 1615 trial times and parallelism data were aggregated per participant per condition. Removal of the outliers did not yield different interpretations of the results, but we considered the values after removal as being more representative for the effects. Therefore, the results after outlier removal will be reported.
Since the trial times as well as the parallelism data were not normally distributed in every condition, we carried out transformations on the data. A logarithmic transformation \((\log_2)\) was applied on the trial times in every condition, resulting in normalized data suitable for further analyses. With regard to the parallelism data, a square root transformation was applied. Although both the Shapiro-Wilk \((W(19) = 0.887, p = .028)\) and the Kolmogorov-Smirnov \((D(19) = 0.217, p = .019)\) tests of normality still indicated a deviation from normality in the TV condition, the square root transformation yielded the best approximation of normality possible. Analyses were carried out on the original as well as on the transformed data. This neither led to different interpretations of the results for the trial times, nor for the parallelism measures. For this reason we decided to report the analyses of the original, non-transformed results. This made the results easier to interpret and the presented numbers (e.g., milliseconds) more meaningful.

For the extra analyses with regard to image location, the trial time data of each feedback combination (after removal of outliers) were divided over three categories; images left (5 images), images center (2), and images right (5). The trial times were aggregated. Although the location of these 12 images differed, their sizes were all similar (i.e., small). For the image size analysis, the trial times of these 12 images were aggregated. Trial times of the remaining six large images were also aggregated per participant in order to make an analysis on image size possible.

The error-margins for both Sensators was measured, but these were not analyzed further. The reason for doing so was that we already demonstrated in Study 2 that feedback was necessary to carry out the task appropriately. Moreover, the specific amount of pixels between the final Sensator location and the intended target-location was not relevant when all locations below a certain threshold are considered correct. Participants did not finish a trial before both Sensators were placed correctly.

5.7.2 Trial Times

Similar to Study 2, a 2 (male-female) x 6 (feedback combinations) Mixed Design ANOVA was carried out on the trial time data in order to explore possible main and/or interaction effects of gender. None of these effects were found (main effect: \(F(1, 17) < 1, p = .779, ns\); interaction: \(F(5, 85) < 1, p = .525, ns\)). A main effect of feedback combination was found within the data \((F(5, 85) = 5.5, p < .001)\). Therefore, planned comparisons were carried out to explore the found main effect and to test the hypotheses; gender was not considered an extra factor.

![Figure 5-1: Overview of the Mean Trial Times (ms) for the Six Feedback Combination. Error Bars indicate 95% Confidence Intervals.](image)
The first hypothesis with regard to the trial times was that the symmetric tactile condition would result in the lowest performance. As can be seen in Figure 5-1, the TT feedback combination seemed to be the slowest. Custom hypothesis tests (TT vs the five other conditions) within a Repeated Measures ANOVA supported the hypothesis: $F(1, 18) = 14.2, p = .001$. When splitting up the other five conditions and carrying out more specific planned comparisons, the effects were similar. The comparison between the two symmetric conditions results in significant faster results for VV: $F(1, 18) = 11.61, p = .003$ (5.5 seconds faster). The comparisons with the asymmetric unimodal conditions (i.e., TT vs TV and VT; $F(1, 18) = 9.99, p = .005$), and the multimodal conditions (i.e., TT vs VM and MV; $F(1, 18) = 13.59, p = .002$) demonstrated performance differences of 4.1 respectively 5.9 seconds. The descriptive statistics of the trial time data can be found in Appendix J.1.

The second hypothesis stated that as a result of the increased distinctness of the tactile signal, the performance in the asymmetric conditions would be higher than in the symmetric visual condition. The results of the planned comparisons did not support this hypothesis; no differences were found ($F(1, 18) = 1.15, p = .298, ns$). Moreover, contrary to the hypothesis, no difference was found between the two unimodal asymmetric feedback conditions; performance in VT was not higher than in TV ($F(1, 18) < 1, p = .723, ns$).

The hypothesis with regard to the two multimodal conditions (i.e., VM and MV) stated that these would result in the highest performance. When comparing these conditions with the four other conditions, the results indeed supported this hypothesis; $F(1, 18) = 7.32, p = .014$. However, this effect could be mainly explained by the negative influence of the TT condition. When comparing the multimodal feedback combinations with the VV condition ($F(1, 18) < 1, p = .742, ns$), and with the asymmetric combinations ($F(1, 18) = 3.23, p = .089, ns$), no significant differences were found.

Based on the results of Study 2, no interaction effect between image location and feedback combination was expected. In a 2 (left-right) x 6 (feedback combination) Repeated Measures ANOVA, again no interaction effects were found ($F(5, 90) < 1, p = .951, ns$). Despite changing the location of the miniature screen in the application, a significant main effect of image location was found. On average, trials with images on the right side of the screen were carried out 1.75 seconds faster than trials on the left side ($F(1, 18) = 7.37, p = .014$).

A 2 (small-large) x 6 (feedback combination) Repeated Measures ANOVA was conducted to test for possible interaction effects between image size and feedback combination on the performance data. No significant interaction effect was found ($F(5, 90) < 1, p = .469, ns$), meaning that performance differences between trials with large and trials with small images were equal over the different conditions. Trials with larger images seemed to be more difficult, since it took participants on average 2.24 seconds more to finish these ($F(1, 18) = 14.63, p = .001$).

### 5.7.3 Parallelism

A 2 (gender) x 6 (feedback combination) Mixed Design ANOVA was carried out to investigate the effects of parallelism. No main effect of parallelism was found for the different feedback combinations ($F(3.871, 65.811) = 1.92, p = .120, ns$). A Huynh-Feldt F-Test was applied, since the assumption of sphericity was violated according to Mauchly’s test: $\chi^2(14) = 35.99, p = .001$. A comparison between male and female participants did not demonstrate significant differences on the parallelism data either; $F(1, 17) < 1, p = .372, ns$. Since no main effect of feedback combination on parallelism was found, no further tests were carried out on the objective parallelism data.

Figure 5-2 displays both the objective and subjective parallelism data; the descriptive statistics can be found in Appendix J.2. Participants indicated they did not experience a different amount of parallel hand movement between the conditions; the differences between the perceived parallelism and the observed parallelism however were rather large.

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15 Scores of the subjective parallelism measure were recoded into percentages.
Subjective Workload

A weighed summed workload score was computed based on the NASA-TLX scores and the 'sources of workload' comparisons in the final questionnaire. Possible effects of gender on the weighed scores were analyzed by means of a Mixed Design ANOVA. No significant effects were found for gender; $F(1, 17) < 1, p = .337$ (ns) for the main effect and $F(5, 85) < 1, p = .585$ (ns) for the interaction effect. Therefore, gender was not included in the subsequent analyses on the weighed summed workload scores. Figure 5-3 displays the scores for the six feedback combinations.

We defined one hypothesis with regard to the workload, namely that the symmetric tactile condition would negatively affect the perceived workload. This hypothesis was supported with a custom hypothesis test in which the TT condition was compared with the remaining five conditions; $F(1, 18) = 23.19, p < .001$. This corresponded with an average difference of 2.9 points on a 20-point scale.

Although no hypotheses were defined with regard to other possible effects, more planned comparisons were carried out in an exploratory fashion. No significant differences were found between VV and asymmetric unimodal feedback conditions (i.e., VT and TV; $F(1, 18) = 3.81, p = .067$, ns), between VV and the multimodal conditions ($F(1, 18) = 1.36, p = .259$, ns), or between the asymmetric and multimodal conditions ($F(1, 18) = 1.55, p = .229$, ns).
As was done in Study 2, the dimensions Mental Demand and Frustration were explored more in depth. With regard to the mental demand of the different feedback combinations (see Figure 5-4), a custom hypothesis tests suggested that again TT was more demanding than the other five combinations of feedback ($F(1, 18) = 16.74, p = .001$). Additional planned comparisons were carried out (similar to Study 2), but again no significant differences were found between VV and the asymmetric conditions ($F(1, 18) = 3.07, p = .097, ns$), and between VV and the multimodal conditions ($F(1, 18) < 1, p = .82, ns$). A comparison between the asymmetric feedback conditions and multimodal feedback conditions however resulted in a small significant effect; on average people did consider the multimodal conditions as less mentally demanding (1.16 points difference) than the asymmetric conditions ($F(1, 18) = 4.56, p = .047$).

![Figure 5-4: Mean Scores on Mental Demand per Condition. Error Bars indicate 95% Confidence Intervals. Note that the Maximum Score of the Scale is 20.](image1)

The mean scores for Frustration can be found in Figure 5-5. Again, the scores were not in favour of the TT condition; the amount of frustration was significantly higher (3.77 points on a 20-point scale) than the average of the five other conditions ($F(1, 18) = 21.94, p < .001$). Further planned comparisons between VV and the multimodal combinations ($F(1, 18) = 1.76, p = .201, ns$), and between the multimodal and asymmetric conditions ($F(1, 18) = 1.35, p = .26, ns$) did not yield significant results. However, a marginally significant difference of 2.16 points in favour of the VV condition was found when compared with the two asymmetric conditions ($F(1, 18) = 4.21, p = .055$, marginally significant).

![Figure 5-5: Mean Scores on Frustration per Condition. Error Bars indicate 95% Confidence Intervals. Note that the Maximum Score of the Scale is 20.](image2)

The descriptive statistics with regard to the three NASA-TLX items that were analyzed can be found in Appendix section J.3.
5.7.5 User Experience

The user experience was measured with three items of the QUIS scale; Terrible – Wonderful, Difficult – Easy, and Frustrating – Satisfying. Mean scores for the three items are displayed in Figure 5-6, 5-7 and 5-8.

The hypothesis with regard to the user experience was that the symmetric tactile condition would yield negative effects. Custom hypothesis tests for all three items supported this hypothesis. On the Terrible – Wonderful scale, the TT condition was rated with 1.7 points less on a 0-9 scale than the average of the other five combinations ($F(1, 18) = 18.23, p < .001$), the score on the Difficult – Easy scale was on average 1.8 points lower (i.e., more difficult; $F(1, 18) = 37.91, p < .001$), and on the Frustrating – Satisfying scale, the score of TT was 1.6 points lower ($F(1, 18) = 14.31, p = .001$).

Other planned comparisons between respectively VV and asymmetric feedback, VV and multimodal feedback, and between asymmetric and multimodal feedback were carried out for the three QUIS-items in order to explore possible other differences, but no significant effects of the feedback combinations on user experience were revealed.

Besides applying the QUIS-items for measuring the user experience, the participants were asked to point out their overall preferences for feedback in the concluding questionnaires. As can be seen in Figure 5-9, most participants indicated either a preference for visual feedback or for multimodal feedback. Differences between preferences for the left and right hand were generally not
large, except for the overall performance; more people preferred multimodal feedback in the left hand over the right when overall performance was at stake. Another remarkable aspect which is worth mentioning is that not a single participant indicated to have a preference for tactile feedback in his left hand on each of the three user experience items (i.e., Most Pleasant, Most Comprehensible, or Least Mentally Demanding).

Figure 5-9: Overview of the Preference Responses.

The preferences for feedback presented to both the left and right hand were also combined in order to explore what would be the preferred feedback combinations of the participants. The results are depicted in Figure 5-10. Since the participants were asked to indicate the preference for each of the hands and not specifically for a preferred feedback combination, preferences for feedback combinations that have not been tested (i.e., TM, MT and MM) could appear.

Figure 5-10: Overview of the Preferred Feedback Combinations with regard to different Task Aspects. Note that Feedback Combinations which have not been tested could also show up.

For the overall performance most people would opt for either the VV or the MV feedback combinations; rather interesting since MV was not considered one of the fastest or one of the most accurate combinations. These were respectively the VV and the (hypothetical) MM conditions. The VV combination was also considered the most pleasant and the least mentally demanding, whereas the hypothetical MM condition had the preference with regard to which combination made the task most comprehensible.
Finally, participants were asked to grade each of the presented feedback combinations with a grade from 1-10. The results can be found in Figure 5-11.

![Figure 5-11: Average Grades for each of the Feedback Combinations. Error Bars indicate 95% Confidence Intervals.](image)

Again, a Repeated Measures ANOVA was carried out and this analysis demonstrated a significant effect of feedback combination on grade ($F(3.589, 64.598) = 10.16, p < .001$). A Huynh-Feldt F-Test was applied, since the assumption of sphericity was violated according to Mauchly’s test: $\chi^2(24) = 28.69, p = .012$. Planned comparisons demonstrated that what Figure 5-11 suggests was indeed the case; the TT feedback combination was rewarded nearly 2 points lower than the other five combinations on average ($F(1, 18) = 36.41, p < .001$) and is the only combination that scored insufficient ($M = 5.37, SD = 1.212$). The VV and both multimodal feedback combinations scored equally well ($F(1, 18) < 1, p = .424, ns$). However, when the VV condition was compared with both the asymmetric conditions, VV scored significantly higher; almost 1 point on average ($F(1, 18) = 6.54, p = .02$). And although not significant, the difference of 0.7 points in favour of the multimodal conditions when compared with the asymmetric conditions seemed to indicate a trend ($F(1, 18) = 3.65, p = .072, ns$).

The descriptive statistics concerning the three QUIS-items as well as the grades the participants gave to each feedback combination they were presented with, can be found in Appendix section J.4.
5.8 Discussion

5.8.1 Implications

Based on the earlier found results and the tentative conclusions drawn in the second study, we formulated several hypotheses for this third study. The feedback as provided in the picture manipulation task was adjusted in the sense that the different feedback levels were more distinct. The envisioned result of this adjustment was that the tactile feedback in particular would be easier to interpret. Van Erp (2002) defined in his design guidelines for tactile feedback that people are only capable of distinguishing between four different tactile feedback intensities. Moreover, Nesbitt (2003), Prewett et al. (2012), and Spence and Ho (2008) stated that the processing capacity for tactile information is far more restrictive than for visual information. For these reasons, increasing the distinctness of the tactile feedback levels seemed appropriate.

Despite this increased distinctness, we expected a negative effect on performance and overall appreciation caused by the symmetric tactile feedback combination. This hypothesis was supported: In line with the results of both Study 1 and 2, participants performed significantly worse when two channels of tactile feedback were presented simultaneously. Moreover, participants experienced a higher workload, higher mental demand, and a higher frustration level in the TT condition. This combination of feedback was also considered more difficult and terrible than the other combinations. The simultaneous presentation of two tactile feedback signals seemed to cause interference. This interference could have taken place at a physical level, meaning that for instance the tactile signal presented in the left Sensator was transduced by the Surface and resonated in the right hand; causing perhaps confusion. Resonance was explicitly mentioned as being one of the main pitfalls of vibrotactile feedback by van Erp (2002). Besides physically, the interference might also have taken place at a more cognitive level which would be in line with the MRT (Wickens, 2002; Wickens, 2008). In that case, the presentation of information regarding two sub-tasks simultaneously in the same sensory modality would have caused a sensory overload resulting in deteriorated performance.

The results of the three studies conducted all suggest that presenting symmetric tactile feedback within asymmetric bimanual interaction tasks is not suitable. The question remains which of the remaining feedback combinations actually would be the most suitable. The results of Study 2 seemed to point to possible beneficial effects of presenting asymmetric feedback; the negative effect of tactile feedback when presented to only one hand seemed to disappear when applied in asymmetric conditions. We suggested that asymmetric feedback could have beneficial effects, but required a careful implementation of the tactile aspect. In line with van Erp (2002), we increased the distinctness between two consecutive tactile intensity levels. Based on these earlier results and the increased distinctness of the tactile feedback, the second and third hypotheses were formulated: The performance in asymmetric feedback conditions would be better than in the symmetric visual condition, and in particular when tactile feedback would be presented to the dominant hand and visual to the non-dominant hand. The results of this third study however, did not support these hypotheses. No differences between the asymmetric and the symmetric visual conditions were found; not in performance, not on the user experience, and not on overall workload measures. A marginally significant effect was found for the frustration level, in favour of the VV condition, but this effect was not supported by the QUIS item on frustration. Moreover, contrary to expectations, no significant differences were found in the performance, workload, and user experience between the VT and TV feedback combinations; these results thus did not replicate the earlier found effects. However, although no differences were found between asymmetric feedback and symmetric visual feedback with regard to performance, workload, and user experience, the preference data point to a higher appreciation of the symmetric visual condition. This did not correspond with the QUIS measures for user experience.

Besides the adjustments to the distinctness of the stimuli, another aspect related to feedback was evaluated in this third experiment. Based on earlier findings by for instance Vitense et al. (2003), Prewett et al. (2012), and Rovelo et al. (2012), we formulated the hypothesis that the multimodal feedback conditions (i.e., VM and MV) would yield the highest performance and user appreciation. Presenting the same information redundantly to different sensory modalities could provide users with
the option to offload certain information to another sensory channel in high load situations. The results with regard to the performance did not support the hypothesis; the small differences found were not significant.

Since no differences were found – except for the symmetric tactile feedback combination – it might be the case that a ceiling effect has occurred. The best performance possible has been achieved in that case. When this would indeed be the case, the question should not have been which combination of feedback increased the performance the most, but which combination of feedback deteriorated the performance the least. According to the results, only symmetric tactile feedback affected the performance (and with that the perceived workload and user experience) negatively.

In line with the results of Study 2, as well as with the findings of Balakrishnan and Hinckley (2000), trials were carried out faster when the hands were closer together. Surprisingly enough, despite the relocation of the miniature screen, images on the right side of the Surface screen were still carried out faster than images on the left side. This effect deserves a more thorough investigation. Although we found main effects of image size respectively image location on performance, we did not find any interaction effects between respectively image size and feedback combination, and image location and feedback combination. The differences in performance between different image sizes (or locations) were not affected by the feedback combinations. This is in line with our final hypothesis.

5.8.2 Limitations and Future Work

In Section 4.9.2, several limitations with regard to Study 2 are described. Whereas some of these possible biasing effects, such as possible learning effects, were considered more carefully in Study 3, others were not. We address the most influencing and suggest several opportunities for future research. An increased distinctness of the feedback signals, as proposed by van Erp (2002) did not sort the anticipated effects. It might have been the case that the difficulties with the distinctness were not as severe as we assumed. It is tempting to verify this by comparing the results of Study 2 and 3 with each other. However, since not only the distinctness of the feedback was adjusted, but also for instance the trials and the parallelism measure, such a comparison would not be fair.

Although the measure for the amount of parallel hand movement was adjusted in order to provide more nuance, this change did not sort any new insights: No effects of feedback combination on the amount of parallelism were found. However, the amount of parallel movement in Study 3 again seemed rather low. As mentioned before, it would be interesting with regard to future research to analyze the sequence of hand movements in asymmetric bimanual tasks in more detail. This could be carried out in combination with an analysis of the fixation strategies, as Hesse et al. (2010) suggest. This would perhaps provide more insights in the amount of parallelism within the asymmetric bimanual task as was carried out in the current experiments, and thus in how well the Kinematic Chain Model (Guiard, 1987) actually applied. Moreover, the suggested more detailed analyses could provide explanations for the performance differences between picture manipulations in the left and the right side of the screen. A comparison between left-handed and right-handed people would be a useful extension as well, in order to verify the asymmetric component in the task.

A final limitation of this third experiment followed from the preference data. The reason for not implementing the MM – and the TM and MT condition was the expectation that the tactile element of the multimodal feedback in one Sensator would interfere with the tactile information presented by the other Sensator; similar to the evaluated TT condition. Moreover, tactile information added to visual feedback can enhance performance as for instance Prewett et al. (2012) stated; adding visual information to tactile stimuli was not mentioned. This is perhaps because vision is the most important perceptive quality (Sigrist et al., 2012) and because it can process more information than other sensory modalities (Nesbitt, 2003). However, many participants implicitly16 indicated a

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16 Note that preference was investigated for each hand separately; some of the participants indicated a preference for multimodal feedback in the left hand, as well as for multimodal feedback in the right hand. Participants thus did not explicitly state a preference for the hypothetical MM condition.
preference for the not-presented MM condition; in particular with regard to the accuracy in the task and the comprehensibility of the feedback. Since relatively many people indicated a preference for multimodal feedback in both the dominant and non-dominant hand, it might be worthwhile to explore the possible effects of the MM combination (and TM and MT for that matter) on performance, perceived workload, and user experience. It would be of particular interest to investigate to what extent the hypothesized interference indeed takes place when people have the opportunity to offload to the visual channel.

5.8.3 Conclusions

In this third study we demonstrated again that it is not desirable to present two channels of tactile feedback simultaneously; at least not when only the amplitude of the signals varies. Presenting tactile feedback to both hands in asymmetric bimanual interaction deteriorated the performance with regard to speed. This is not desirable, in particular because time efficiency is often considered one of the main advantages of both tangible and bimanual interaction. Moreover, not only performance was negatively affected by the symmetric tactile feedback. The user experience as well as the workload were also negatively affected by simultaneously presented tactile stimuli. These findings thus provide additional support for our statement about the undesirability of symmetric tactile feedback. However, tactile feedback has proven to be a successful means of communicating specific information; it might therefore be worthwhile to investigate the effects of symmetric tactile feedback when other parameters – such as frequency, waveform, or rhythm (Brewster & Brown, 2004a) – of the tactile stimulus are adjusted, instead of only the amplitude. When adjusting these parameters, the interference effects – both physical resonance (van Erp, 2002) and cognitive interference (e.g., Wickens, 2002) – of the two tactile signals could be different.

With regard to the other feedback combinations as presented in this third experiment, we can not provide well-founded conclusions. Despite expectations, no differences between the remaining feedback combinations were found with regard to performance. This could imply a certain ceiling effect, meaning that the task could not be carried out faster. Moreover, the results of the user experience measures and the perceived workload are inconclusive as well.
6. General Discussion

Van den Hoven et al. (2007) describe that an important part of the design research process of TUIs is the evaluation of prototypes with potential users and to let them experience new functionalities. Such experiences often lead to new insights that can inspire re-design or ideas for new, related products and applications. With a similar approach in mind, TNO has developed their Sensators; active tangible objects that can provide multimodal feedback. Active TUIs comprise one of the main research directions for the future with regard to tangible interaction, according to Shaer and Hornecker (2010). Since multimodal interfaces will likely find their way to many complex data-rich environments, it is critical to be aware of the strengths and weaknesses of multimodal displays (Sarter, 2006). However, whereas Sarter makes a clear distinction between input and output, the Sensators combine the two within one single object, following Ishii and Ullmer’s (1997) view on tangible interaction. From this merging of input and output follows the global research question of TNO: How can and should multimodal feedback be implemented in tangible user interfaces in order to facilitate the user in some way?

Bimanual interaction is often cited as one of the main advantages of tangible interaction (Fitzmaurice et al., 1995), but is also often considered as something that comes about naturally. Edge and Blackwell (2009) however, consider bimanual interaction as something that requires careful investigation and design. The most common form of two-handed interaction in the real world is described by Guiard’s KCM (1987), but this model also applies in HCI. To specify and narrow down TNO’s research question, we took bimanual interaction as starting point, which resulted in the following main research question: “How should feedback in generic active tangible objects be designed to facilitate the user in asymmetric bimanual interaction?”

6.1 Main Findings and Implications

In a Pilot study and two subsequent experiments we tried to integrate the three main pillars of the study: TUIs, asymmetric bimanual interaction, and multimodal feedback. Each aspect in itself has demonstrated to have beneficial effects on both task efficiency and understanding. However, with developing successful TUI applications as eventual goal, the three pillars need to be properly integrated and evaluated. Within asymmetric bimanual precision tasks – Study 2 and 3 based on Casalta et al. (1999) –, the effects of different combinations of feedback on performance (in particular on speed), perceived workload, and user experience were investigated. These measures are closely related to the mentioned task efficiency and understanding. Moreover, an extra, exploratory measure with regard to the amount of parallel hand movements was introduced.

The first three research sub-questions as defined in Section 2.4 all referred in some way to which combination of feedback would be the most suitable in asymmetric bimanual interaction. The results of the three studies do not provide a proper conclusion with regard to this question. In Study 1, asymmetric feedback (i.e., visual in one sensator, tactile in the other) seemed to induce a beneficial effect, but there was no symmetric visual feedback condition to compare with. In Study 2 and 3, no differences with regard to performance were found between the symmetric visual condition and the asymmetric feedback conditions; even despite an increased distinctness of the tactile stimuli in Study 3. The found advantage of VT over the TV asymmetric combination as found in Study 2 could not be replicated in Study 3. Moreover, contrary to the expectations, the introduction of redundantly presented information in Study 3 did not sort the expected beneficial effects on performance either. With regard to perceived overall workload, mental demand, frustration levels, as well as user experience, no clear conclusions can be drawn either. These subjective evaluations of the different feedback combinations did not yield any differences between either the symmetric visual condition and the asymmetric conditions, or between the symmetric visual condition and the multimodal feedback conditions. Only a small advantage of multimodal feedback over asymmetric feedback with regard to the mental demand was found in Study 3, as well as a slightly higher grading of the multimodal conditions (although not significant). Although the results do not point to one feedback combination as being the most suitable, the majority of the participants seemed to have a preference for the symmetric visual feedback combination. When asked to indicate their preferred feedback modality for each hand separately, most participants indicated to prefer visual feedback; in particular...
with regard to speed, pleasantness, and mental demand. The grading of the several combinations in Study 3 supported this finding. This can be related to earlier research on the Sensators by Meijer (2013), in which visual feedback was also preferred over other sensory modalities. However, many people considered multimodal feedback as being the most suitable with regard to comprehensibility and accuracy.

The lack of an advantage of symmetric visual feedback over asymmetric feedback is rather surprising considering the effects we found in the secluded conditions in Study 2. Corresponding with earlier work by Meijer (2013), when only one of the two hands was presented with feedback, an advantage for visual feedback was demonstrated; in particular with regard to performance, but also for the majority of the subjective measures. This advantage can be explained by the larger communication capacity of – as well as the familiarity with – visual feedback (Nesbitt, 2003; Sigrist et al., 2012). Since visual feedback sorted better effects than tactile, regardless of the hand to which it was presented, an advantage of symmetric visual feedback over asymmetric feedback seemed a logical inference. However, we did not find such an advantage. The absence of this effect was interpreted as a possible interference effect of the two visual stimuli, in line with the MRT (Wickens, 2002; Wickens, 2008). Following this theory, it was assumed that presenting feedback in an asymmetric form would prevent this interference, in particular when the tactile element would be presented with care. In the third study, we increased the distinctness of the different tactile feedback levels, following van Erp (2002). However, this did not yield the anticipated results.

The absence of the anticipated effects can have several reasons. The first explanation being that the MRT did not apply because the task was too easy. Wickens (2002) states that the MRT is mostly applicable in high cognitive load situations; situations in which one of the available resources is fully loaded. Offloading information to another sensory modality can then have a positive effect on performance. Since the participant’s only task was the manipulation of an image – no time pressure, heavy thinking, or far-reaching consequences involved –, it seems reasonable to assume that the task load was too low for the MRT to become relevant. In other words: Due to the low task load, the different sensory resources were not fully loaded and thus not interfering. This would also explain why the multimodal conditions did not yield the expected beneficial effects; there was no need to offload to another sensory modality.

Another, although related, explanation for the absence of any differences in performance between asymmetric and symmetric visual feedback could be that the symmetric visual condition in itself also draws on different resources. A later extension to the original MRT (Wickens, 2008) included an extra dimension nested in the visual resources; visual channels. A distinction is made between foveal and peripheral vision. This would imply that visual feedback in the hand on which one is focused would be processed by foveal visual resources, whereas feedback in the other hand might be processed by peripheral visual resources. According to the MRT (Wickens, 2008), information presented to both visual channels in parallel can be processed simultaneously without causing interference. This would imply that every feedback combination presented throughout this study draws upon multiple resources, except for the symmetric tactile feedback combination. This implication corresponds with the results found. The absence of a clear conclusion with regard to the most suitable feedback combination asks for a further investigation of effects. In particular the effects in high load situations, or data-rich environments as Sarter (2006) names these more realistic settings.

Despite the fact that not one specific feedback combination can be considered the most suitable one, the results of the three studies clearly demonstrated that the symmetric tactile combination is the least suitable. Presenting two tactile feedback signals simultaneously has proven to deteriorate the performance of a task. This negative effect was also reflected in the appreciation of this particular feedback combination. With regard to the subjective measures, the results of the Pilot study already suggested that symmetric tactile feedback was appreciated less. Participants told they experienced this combination as being more difficult and frustrating. In both subsequent experiments, these suggestions were supported by statistical tests. The negative effects can perhaps be explained by the relatively low communication capacity of tactile feedback (Nesbitt, 2003) and/or the lack of
familiarity with tactile stimuli (Sigrist, 2012). However, no negative effects occurred when only one tactile stimulus was presented. Therefore, it seems more reasonable to explain the negative effect as a consequence of interference of the signal. This could be a resonance effect (van Erp, 2002), in which the tactile signal in one Sensator is physically transferred to the other one. Another option is interference of the two tactile signals at a cognitive level, in line with the MRT (Wickens, 2002; Wickens, 2008). This would imply that the sensory resource for tactile signals is overloaded. The suggestion that this sensory overload already occurs in low load situations is in line with findings by for instance Spence and Ho (2008) and Nesbitt (2003), who state that the processing capacity of tactile information is more restrictive than that of visual information.

Throughout the three studies, the amount of simultaneous hand movement was explored. Whereas this amount seemed to be rather low in general, it has not been affected by the different combinations of feedback. Besides parallelism measures, we carried out extra analyses on the effects of image size (i.e., varying the distance between both hands) and image location. These analyses were based on observations as well as suggestions by the participants. Trials on the right side of the Surface yielded higher performance, as did – in line with Balakrishnan and Hinckley (2000) – trials in which both hands were closer together. However, the effects of the different feedback modalities did not interact with these factors. In other words: The earlier described effects of different feedback combinations were neither different for larger or smaller images, nor for images at different locations.

Tangible interaction can be applied in many different settings and application fields as Shaer and Hornecker (2010) for instance describe. Regardless of the application domains, developers of new active TUI applications can benefit from the findings of this study. In particular when the task involves (asymmetric) bimanual interactions. Although tactile feedback has demonstrated to be a very suitable means of communication, we now know that presenting two channels with tactile feedback simultaneously in bimanual tasks is not recommended. Besides that, the results with regard to the remaining feedback combinations seem to imply that for bimanual tasks that do not lead to high task loads, it does not really matter in which sensory modalities the information is presented; as long as the feedback does not incorporate two simultaneously presented tactile stimuli. This tentative implication however requires further investigation. Considering the preference of the participants, a choice for either symmetric visual feedback or for redundantly presented information seems to be the safest option.

6.2 Limitations and Future Research

We defined several implications with regard to the presentation of different forms of feedback in asymmetric bimanual tangible interaction. It might be useful to provide some nuance in the results in order to better understand and value our findings. Moreover, we suggest several opportunities for future research, in order to come to more well-founded design guidelines.

Whereas Study 1 can be considered a preliminary investigation of possible effects, the task as carried out in Study 2 and 3 is actually based on the Kinematic Chain Model (Guiard, 1987). This model was used since this form of bimanual interaction is the most common and natural form of bimanual interaction and because it is also applied in HCI. Moreover, the reference principle as defined in the KCM has proven to apply also when both hands manipulate separate objects (Balakrishnan & Hinckley, 1999), as long as a visual link is present. The task that we designed followed one of the examples of Casalta et al. (1999) about how the KCM is applied in HCI. Moreover, the necessary visual link (Brandl et al., 2008; Balakrishnan & Hinckley, 2000) between both hands was present (i.e., the image on the Surface). Therefore, the task as applied in Study 2 and 3 seemed an appropriate abstraction of asymmetric bimanual interaction in HCI. Needless to say is that the picture manipulation was applied in order to trigger bimanual interaction, instead of being a representative, real-world application. In hindsight, several remarks can be made about the interaction in itself and about how we designed this specific experimental task. First of all, the interaction was limited to the displacement of both the TUIs on a horizontal plane; it might be interesting to investigate other types of movement. For instance when a third dimension is added to the interaction and people can move the objects in a 3D-space, or when one or both Sensators (or other active TUIs)
are being rotated instead of being moved, as Meijer (2013) for instance explored. Whereas asymmetric bimanual interaction is the most common form, it is not the only form of bimanual interaction. It might be interesting to explore how the effects apply in symmetric bimanual interaction in a compound task, or even when two independent tasks are carried out simultaneously. Although the latter is difficult to achieve, it has been named by Fitzmaurice et al. (1995) as one of the possible advantages of tangible interaction.

These possible additions to the present research do not only point solely to the interaction in itself. The seemingly low amount of parallel hand movement throughout the studies might have resulted in a more sequential perception of the two feedback signals. Other forms of bimanual interaction as proposed before, might induce more parallel movement of the hands and following from that, more parallel perception of sensory stimuli; resulting perhaps in more thorough results. In hindsight, the asymmetric bimanual interaction as described in the KCM might not have been the most appropriate form of bimanual interaction for the investigation of simultaneous perception. In particular because of the temporal precedence aspect of the model: The model states that the dominant hand starts after the non-dominant hand has started moving, eventually leading to simultaneous movement (Guiard, 1987). In our studies, it nearly seemed that the dominant hand started moving after the non-dominant hand had finished. When a task is easier, more intuitive or more natural (Leganchuk et al., 1998), both hands are used more simultaneously. When different forms of bimanual interaction are evaluated in combination with several combinations of multimodal feedback, this might yield more thorough results.

Another remark with regard to how we applied the KCM in the picture manipulation task concerns the resolution of the hands. Guiard (1987) states that the resolution of motion of the non-dominant hand is much coarser than that of the dominant hand and therefore the dominant hand can carry out actions that require more precision. In the task as applied, the accuracy thresholds for both hands were the same (i.e., when the Sensator was located within a range of 35px from the target coordinate, it was considered as located correct). The different resolutions of each hand were thus not considered specifically. When the accuracy requirements for the Sensator in the non-dominant hand would be set lower, more coarse movements would be allowed. This could result in several new implications. First because adjusting the accuracy requirements for the non-dominant hand might affect the amount of parallelism and second, because it might provide more insights in which feedback modality is most suitable to apply in each hand, considering their different resolutions.

A final remark with regard to the interaction in itself is that the current study was limited to right-handed people. A justifiable choice, considering the development-time restraints and the fact that approximately 90% of the Dutch citizens is right-handed (van Strien, 2001). However, in order to verify the implementation of the KCM within this task, it might be interesting to investigate the effects for left-handed people. Another possible extension might be to exchange the functionalities of both Sensators in the task and thus to exchange the role each hand assumes.

In this study, a coupling between (asymmetric) bimanual interaction and TUIs was made. These aspects are closely connected, but as said, bimanual tasks require careful design. Earlier studies with regard to bimanual interaction in HCI (e.g., Kabbash et al., 1993; Kurtenbach et al., 1997; Hinckley et al., 1998; Cutler et al., 1997) have demonstrated that some traditional input devices are more suitable for the non-dominant hand, whereas others function better in the dominant hand (e.g., a stylus). The current generation of Sensators does neither consider the different roles of the hands, nor the fact that some physical shapes are more suitable than others: They all have a generic, cubical shape. This might have affected the bimanual interaction and in particular the accuracy achieved. Moreover, the coupling as applied between the physical and digital object might have hindered the interaction. Since the image corner was coupled to the approximate center of the Sensator, the image corner was not directly visible during the task. Since the image corners were to be located correctly, the shape of the Sensators might thus have affected the functionality somewhat in a negative way. With regard to possible future research – and eventually the development of applications – we suggest to explore the opportunities of adjusting the shape of the objects in order to make them more task-
specific, to make the interaction more intuitive, and to make the objects more suitable for the specific function of the hand. The current generation of Sensators might benefit from ‘sleeves’ attached to the objects; for instance a circular sleeve to simulate a knob, or an arrow-shaped sleeve for pointing in a certain direction.

Besides the shape of the objects and the implementation of the bimanual interaction, another multi-faceted aspect is at stake; the feedback. We have chosen the applied visual and tactile stimuli carefully, but it might have affected the perception and interpretation nonetheless. We chose the colours of the visual feedback in line with what Trumbo (1981) suggested; a certain ordering in the colours should be present when representing ordinal data. Moreover, the blue tints were chosen since it was assumed these colours would contain relatively little semantic meaning and/or associations. However, adjusting other parameters of colours such as the brightness and the saturation might be more effective means of communication. Similar remarks apply for the tactile feedback. In the current studies, the tactile signal has been varied based on the amplitude. However, as for instance Brewster and Brown (2004a; 2004b) describe, does a vibrotactile signal consist of several parameters that can be adjusted. The adjustment of amplitude might not have been the most suitable manipulation, since people have difficulties with distinguishing between the different levels (van Erp, 2002; Self, van Erp, Eriksson & Elliott, 2008). Moreover, both the visual and tactile stimuli consisted of several distinctive levels, instead of a gradual increase in darkness or intensity. This was done to ensure that each visual stimulus had a tactile counterpart and vice versa. It might be interesting to explore the effects of gradual transitions in the feedback. The choices we made with regard to the feedback were mainly defined by the capabilities and limitations of the Sensators and were partly in line with Meijer’s (2013) earlier research. It may however be worthwhile to explore the effects of the adjustment of other parameters of the several stimuli, in order to provide a more complete set of design guidelines for active TUIs.

Van den Hoven et al. (2007) and for instance Sarter (2006) emphasize the importance of the evaluation of ideas and prototypes with regard to respectively tangible interaction and multimodal feedback. The studies as described in this thesis contribute to both fields, but there are numerous options for further investigation as we have pointed out. It obviously is very important to understand basic principles of the respective research fields before they can be applied in specific tasks and contexts. However, applications are often multi-faceted and effects of feedback can be very task-specific (Prewett et al., 2012). Therefore it is also necessary to develop applications and verify whether the knowledge gained from the several studies actually applies in real-world settings.

Throughout the three studies, we investigated the effects of multimodal feedback. This sorted several effects for which possible explanations have been described. That is, possible underlying theories with regard to multimodal perception have been introduced. However, no adequate verification of these theories could be provided; only suggestions could be made. This is due to the setup of the studies, as well as to the results. Based on results of Study 1 and mainly Study 2 it seems reasonable to assume that the MRT (Wickens, 2002; Wickens, 2008) was at stake. However, in order to provide more consistent evidence, further research is recommended. Since the MRT mainly applies in high cognitive load situations (Wickens, 2008), and because providing information multimodally has proven to be beneficial in data-rich environments (e.g., Sarter, 2006), it might be useful to investigate the effects in high load situations. It would be interesting to study whether – and if so, how – the effects of different combinations of feedback vary over different degrees of task difficulty and thus cognitive load. Besides this, the possible effects of cross-modal links (Sarter, 2006) could not be investigated due to the exploratory setup of the study. Since it is likely that these links are present somehow, it might be worthwhile to investigate them more thoroughly in future research. Insights in this are valuable, especially since cross-modal switching might involve extra switching costs (van Erp, 2006). This is in particular the case in switching to and from the haptic channel (Spence & Driver, 2000).

17 At least less than for instance the transition between green and red, which are closely associated with ‘correct’ and ‘incorrect’ respectively.
Closely related to the underlying principles of the perception of simultaneously presented stimuli and paying attention to them, are fixation strategies. These have proven to have a certain effect on bimanual interaction (e.g., Hesse et al., 2010; Srinivasan & Martin, 2010). In the three studies, we neither investigated the fixation strategies, nor did we control these. An analysis of these strategies, for instance by means of eye-tracking, might provide clearer insights in the focus of attention within bimanual interaction with active tangibles. In turn, a more thorough understanding of these attention shifts between dominant and non-dominant hand can provide more insights in the underlying mechanisms. For instance in the influence of different feedback modalities presented to each hand, possible cross-modal switching costs, the amount of parallel hand movement, and the perception mechanisms at stake when multiple feedback channels are presented simultaneously. In other words: the task efficiency and workload – two of the most important aspects of the current project – could be explained in more detail.

6.3 Concluding Remarks

Throughout the three studies, the perception of multimodal feedback was investigated in an applied setting: a motor task. By doing so, we aimed at providing insights in the main research question: “How should feedback in generic active tangible objects be designed to facilitate the user in asymmetric bimanual interaction?” Unfortunately, the results did not concretely answer this question. A tentative conclusion is that with low task loads – of which our experimental conditions may have consisted – it does not really matter which combination of feedback modalities is presented to the user. More elaborate research is required in order to provide more thorough insights; we defined several implications for future research. However, the studies actually did result in knowledge about the undesirability of a specific form of feedback: The simultaneous presentation of tactile signals does clearly deteriorate the performance, as well as the user experience and the workload. This clearly is not desirable.

From the outset, this work has focused on the possible added value of multimodal feedback within (bimanual) tangible interaction. We provided initial implications with regard to the design of future applications, although the implications are very task-dependent and context-related. Besides the implications for design, this research project points out the importance of relating and integrating the several fields of research related to this particular form of HCI, as well as the importance of investigating their effects on users. With this study, we have contributed to the respective fields of research, in the sense that we have developed, described, and justified an experiment aimed at the mentioned integration and evaluation. Hopefully, our work and suggestions will eventually lead to a more thorough understanding of whether and how we can benefit from the myriad objects, tools and toys in our complex world.
7. References


Appendices
A. Table of Appendices

A. Table of Appendices ........................................................................................................ 1
B. Sensators ........................................................................................................................... 2
   1. TNO and the Sensators ............................................................................................... 2
   2. Feedback ..................................................................................................................... 2
   3. System Input ................................................................................................................ 3
   4. Earlier Versions of the Sensators .............................................................................. 4
C. Study 1; Wizard of Oz Seabattle – Instructions ............................................................. 6
D. Study 1, 2 & 3 – Questionnaire after Condition .......................................................... 8
E. Study 1; Wizard of Oz Seabattle – Final Questionnaire ................................................ 9
F. Study 2 & 3; Picture Manipulation – Informed Consent Form ..................................... 10
G. Study 2 & 3; Picture Manipulation – Instructions ......................................................... 11
H. Study 2 & 3; Picture Manipulation – Concluding Questionnaire .................................. 13
I. Study 2; Picture Manipulation – Results ...................................................................... 15
   1. Trial Times .................................................................................................................. 15
   2. Parallelism ................................................................................................................... 15
   3. Workload .................................................................................................................... 16
   4. User Experience ......................................................................................................... 17
J. Study 3; Multimodal Picture Manipulation – Results ...................................................... 18
   1. Trial Times .................................................................................................................. 18
   2. Parallelism ................................................................................................................... 18
   3. Workload .................................................................................................................... 18
   4. User Experience ......................................................................................................... 19
B. Sensators

1. TNO and the Sensators

TNO, Netherlands Organisation for Applied Scientific Research, is an independent research organization aimed at creating meaningful innovations in order to improve the quality of society as a whole. TNO carries out projects for many different organisations in many different disciplines. Besides these demand-driven projects, TNO has got several Enabling Technology Programs (ETPs), which are less demand-driven, but aim at gaining and developing knowledge within a specific domain. Within the ETP ‘Models’, TNO has worked on the project ‘Intuitive User Interaction’ since January 2011 and within this project, different generations of active tangible user interfaces have been developed: ‘Sensators’. The purpose of the Sensators is to explore and evaluate different ideas, theories and concepts with regard to active tangible user interfaces.

Since the Sensators are considered general testing and evaluation tools, and since no specific applications have been developed yet, the current fourth generation of Sensators has a generic cubical shape. The objects have been developed in order to work in combination with a Samsung Surface multitouch screen (SUR40). The Sensators are capable of conveying system feedback within different modalities by means of electronics that are embedded in the 3D-printed housing. Moreover, the Sensators can provide input to the system in several ways. Each Sensator has a length and width of 65mm and a height of 50mm. The shape, which is slightly convex on top and slightly concave at the bottom, makes the Sensators easily stackable.

![Figure B-1: Sensators.](image)

2. Feedback

The current fourth generation of Sensators can provide visual (changing colours), auditory (pre-recorded samples), and vibrotactile feedback. A RGB-LED is integrated in the top center of the Sensator, just underneath the 3D-printed housing. Due to the translucent material the complete top part of the Sensator assumes the colour that is emitted by the RGB-LED. An embedded mp3 audio processing shield enables the Sensators to process mp3 audio output signals. An SD-card containing several mp3 files is integrated in the hardware. Each Sensator contains two vibrating motors; one with a higher frequency and one with a lower frequency. Each of these vibrating motors can produce nine different levels of intensity; setting 1 being the lowest intensity (very close to the detection threshold) and setting 9 being the highest. Different vibrotactile patterns can be presented by the Sensators, making use of either one or both vibrating motors at a time.
A feedback demonstration application (see Figure B-2) has been developed for use on an Android tablet computer. This application contains 20 buttons which can be configured in order to let one or more Sensators at a time display predefined feedback patterns. The feedback modality and patterns can differ per Sensator. The demonstration application has been used in Study 1, the Wizard of Oz Pilot study.

![Screenshot of the Feedback Demonstration Application.](image)

**Figure B-2: Screenshot of the Feedback Demonstration Application.**

3. **System Input**

The Sensators have been developed to be used and tested on a Samsung Surface (SUR40) computer. When located on the screen, the Surface can identify the Sensators by means of their so-called fiducial markers. Each Sensator has got a unique fiducial marker on the bottom side (see Figure B-3). With this marker, the identity of the Sensator can be recognized (since the marker is unique). Moreover, the location as well as the orientation of the Sensator can be derived from the detection of the fiducial marker. Both the location and orientation can serve as means of system input.

![A Fiducial Marker underneath the Sensator.](image)

**Figure B-3: A Fiducial Marker underneath the Sensator.**

Besides providing input by means of location and orientation, a Sensator can also sense whether it is being touched or not. This is done by means of the four silver conductive touch fields on either side of the Sensator, as can be seen in Figure B-4. Despite the option to provide different forms of system input, only the locations (and movements) of the Sensators have been used throughout the three studies.

![Image of Sensator with touch fields.](image)
The Sensator hardware consists of a custom Arduino TUI Printer Circuit Board. This circuit board consists of an open hardware design for the Arduino board containing an Atmel AVR processor and on-board input/output support. The software consists of a standard programming language compiler and a boot loader that runs on the Arduino board. A Bluetooth communication shield was added to facilitate two-way communication with both the SUR 40 Surface table and the Android tablet pc. The internal 12V battery is rechargeable via mini-USB connection.

4. Earlier Versions of the Sensators

As said, the Sensators used throughout the project are part of the fourth generation. A short description of the earlier versions as well as the most relevant improvements will follow here. The first generation of Sensators can be considered more of a ‘proof-of-concept’ (see Figure B-6). A large egg-shaped plastic object served as the main part of this generation. This shape contained the RGB-LED. On the outside of the main shape, the remaining hardware was installed. With the second generation Sensators, a large leap forward was made. Custom-made 3D-printed housing was developed in which all hardware was embedded. Moreover, this generation of the Sensators was capable of moving autonomously (see Figure B-7), making it a combination of active TUIs presenting multimodal feedback and active self-rearranging objects (Poupyrev et al., 2007).
Figure B-6: The very first Sensators.

Figure B-7: An impression of the Second Generation of Sensators.

The main disadvantage of the second generation Sensators was its size; the Sensators were too clumsy and therefore nearly unworkable. To overcome this issue, the self-rearranging aspect of the Sensators was dropped. That is, the third generation Sensators could not move autonomously anymore. A result of this was that the third generation was much smaller. The shape was slightly cubical and at each side of the cube, a vibrating motor was installed. This internal vibrating motor was connected to a small pin sticking out of the Sensator. The purpose of these small pins was to provide both input (i.e., is the Sensator touched at that specific side?). and output (i.e., the vibrations are transferred to the hand via the small pin). The aim of this side-specific vibrotactile feedback was to explore the opportunities of conveying specific feedback messages to different fingers. Once evaluated, it turned out that the vibrating motors and their pins did not work as intended. When feedback aimed at one finger was presented, resonance of the tactile signal occurred. This resulted in vibrations in the entire object, making it impossible to identify the location and thus meaning of the presented stimulus. I guess we can say that TNO should have hired me in an earlier stadium, since I already encountered this problem before (Van den Hoven, Willemse & Buil, 2009).
In deze studie gaan we een vorm van ‘Zeeslag’ spelen. Op de Surface tafel verschijnt een grid, waarop je de locatie van een schip moet vinden. Het schip is niet zichtbaar, maar de locatie moet gevonden worden met behulp van twee Sensators tegelijk; in elke hand één. De Sensator in je linkerhand is om te zoeken naar de voorkant van het schip, die in je rechterhand is voor de achterkant. Elke Sensator geeft feedback naarmate hij dichter bij zijn specifieke doel komt.

Deze feedback is visueel (de Sensator verandert van kleur), of tactiel (de Sensator trilt). Hieronder staat een afbeelding van hoe de feedback wordt gegeven:

<table>
<thead>
<tr>
<th>Afstand t.o.v. Doel</th>
<th>Visueel</th>
<th>Tactiel</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;2 hokjes</td>
<td>Grijs-blauw</td>
<td>Zachte trilling</td>
</tr>
<tr>
<td>2 hokjes</td>
<td>Lichtblauw</td>
<td>Middelharde trilling</td>
</tr>
<tr>
<td>1 hokje</td>
<td>Donkerblauw</td>
<td>Harde trilling</td>
</tr>
<tr>
<td>Sensator op Doel</td>
<td>Geen kleur</td>
<td>Geen trilling</td>
</tr>
</tbody>
</table>

Denk er aan dat je met twee handen tegelijk werkt en per hand feedback krijgt voor een ander doel.

In elke trial moet één schip gevonden worden. Dit schip kan een lengte hebben van 2, 3 of 4 hokjes en is altijd óf horizontaal óf verticaal georiënteerd.

Het is de bedoeling dat je elke trial zo snel en nauwkeurig mogelijk uitvoert en dat je beide Sensators zoveel mogelijk tegelijk gebruikt.
Een trial begint door beide start-knoppen onderin het scherm in te drukken. Vervolgens kun je zoeken naar het schip. Wanneer je het gevoel hebt dat de Sensators op de locatie van de voorzijde respectievelijk de achterzijde van het schip staan, druk je op de finish-knop. Na het indrukken van de finish-knop wacht je even op het teken van de experiment-leider voordat je door kunt gaan.

Er zijn 4 condities met in elke conditie 9 trials:
- Linker-Sensator: Tactiele feedback, Rechter-Sensator: Tactiele feedback
- Linker-Sensator: Tactiele feedback, Rechter-Sensator: Visuele feedback
- Linker-Sensator: Visuele feedback, Rechter-Sensator: Tactiele feedback
- Linker-Sensator: Tactiele feedback, Rechter-Sensator: Tactiele feedback; beide Sensators fysiek verbonden.

Na elke conditie is er een korte vragenlijst die gaat over de trials in de conditie die je zojuist ervaren hebt. Tijdens de trials worden je handen met de Sensators gefilmd voor analyse. Verder zul je tijdens de trials een hoofdtelefoon dragen met geluid om het geluid dat de Sensators maken tijdens het trillen te maskeren.
D. Study 1, 2 & 3 – Questionnaire after Condition

Sessie 1
Conditie: VV

Mentale Belasting
Hoe was het niveau van de mentale belasting in de taak?
Erg laag | Erg hoog

Fysieke Belasting
Hoe was het niveau van de fysieke belasting in de taak?
Erg laag | Erg hoog

Tijdsdruk
Hoe ervoer u het niveau van de tijdsdruk?
Erg laag | Erg hoog

Prestatie
Hoe succesvol was u in het uitvoeren van de taak? (Zo snel en nauwkeurig mogelijk)
Perfect | Mislukking

Inspanning
Hoeveel moeite moest u doen om dit prestatie-niveau te halen?
Erg weinig | Erg veel

Frustratie
Hoe was uw frustratie-niveau?
Erg laag | Erg hoog

Wat is uw algemene reactie m.b.t. de feedback-combinatie in de taak?

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verschrikkelijk</td>
<td>Prachtig</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moeilijk</td>
<td>Makkelijk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frustrerend</td>
<td>Bevredigend</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In welke mate heeft u uw handen gelijktijdig gebruikt?
Totaal niet gelijktijdig O O O O O O O Volledig gelijktijdig

Hoe zou je je zoek-strategie omschrijven?

---

18 Consisted of 5-point scale instead of 9-point during the Wizard of Oz Pilot study.
19 Only applicable in the Wizard of Oz Pilot study.
### E. Study 1; Wizard of Oz Seabattle – Final Questionnaire

<table>
<thead>
<tr>
<th>Naam:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leeftijd:</td>
</tr>
<tr>
<td>Links/Rechts-handig:</td>
</tr>
</tbody>
</table>

#### Welke conditie was:

*(rangschik d.m.v. de cijfers 1 (beste), 2, 3 en 4 (slechtste) achter de feedbackcombinatie te zetten)*

<table>
<thead>
<tr>
<th></th>
<th>Links</th>
<th>Rechts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Het beste voor mijn algemene prestatie</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Tril</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visueel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fysiek verbonden:</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Het prettigst</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Tril</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visueel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fysiek verbonden:</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Het minst mentaal belastend</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Tril</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visueel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fysiek verbonden:</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Het duidelijkst</td>
<td>Tril</td>
<td>Tril</td>
</tr>
<tr>
<td>Tril</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visueel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fysiek verbonden:</td>
<td>Tril</td>
<td>Tril</td>
</tr>
</tbody>
</table>
F. Study 2 & 3; Picture Manipulation – Informed Consent Form

Bijlage

Ondergetekende,

Naam ....................

Geb. Datum.....................

verklaart op volkomen vrijwillige basis deel te nemen aan het experiment

“The effects of feedback in bimanual tangible interaction”

bij TNO-TM te Soesterberg.

- De bedoelingen van het experiment en de daarbij gevolgde aanpak zijn tot mijn tevrede nheid uitgelegd, ik heb de schriftelijke informatie over de proef gelezen en mijn vragen zijn door de proefleider bevredigend beantwoord.
- Ik zal me houden aan de veiligheidsregels en aan de instructies van de proefleider.
- Ik kan op elk moment zonder opgaaf van redenen mijn deelname aan het experiment beëindigen
- Evenzo kan de proefleider mijn deelname aan het experiment beëindigen als hij dat nodig vindt.
- Voorts verklaar ik geen mij bekende belemmeringen te hebben om aan de proef deel te nemen.

Soesterberg, datum ..............

Handtekening proefpersoon:………..

TOELATING

Naam proefleider: Christian Willemse

- Ik heb mij ervan overtuigd dat deze proefpersoon voldoet aan de selectiecriteria om aan bovengenoemd experiment deel te mogen nemen.

Soesterberg, datum ..............

Handtekening proefleider: ……….
G. Study 2 & 3; Picture Manipulation – Instructions
Instructie

In de hoofd-studie van dit experiment is het de bedoeling dat u met behulp van de Sensators foto’s die op de tafel zichtbaar zijn gaat bewerken. Hiervoor houdt u in beide handen één Sensator. Elke Sensator heeft zijn eigen specifieke functie. Wanneer u de Sensators over de tafel heen schuift zal de foto van vorm veranderen.

U krijgt zo meteen als eerste onderstaand scherm te zien. Dit bestaat uit twee start-knoppen, een Werkveld en het Voorbeeldveld. Het Voorbeeldveld is een verkleinde weergave van het Werkveld; hierin is een voorbeeldfoto zichtbaar. De cijfers en letters in het zwarte vak zijn niet van belang.


In deze taak is het de bedoeling dat u de locatie en de grootte van de foto in het Werkveld aanpast, zodat deze overeenkomt met de verhoudingen van de foto in het Voorbeeldveld.

Begin van de taak (linkerfoto) en einde van de taak (Rechterfoto)

---

20 In the instructions of study 3, the displayed images were adjusted to the improved experiment setup (i.e., the miniature screen in the top center of the screen).
De taak kunt u volbrengen door beide Sensators te gebruiken. Zoals gezegd heeft elke Sensator zijn eigen specifieke functie.

- De Sensator in uw linkerhand is altijd verbonden met de linksonder-hoek van de foto. Met deze Sensator wordt de locatie van de foto bepaald.
- De Sensator in uw rechterhand is altijd verbonden met de rechtsboven-hoek van de foto. Met deze Sensator wordt het formaat van de foto bepaald.

**Feedback**

Tijdens het uitvoeren van de taken zult u van elke Sensator feedback krijgen; dit bestaat uit kleurveranderingen of trillingen in de Sensators. De feedback is altijd bedoeld om informatie te geven over de specifieke rol van de Sensator.

- De Sensator in de Linkerhand, die bedoeld is voor het verplaatsen van de foto, geeft feedback over hoe dicht u in de buurt zit van de gewenste eind-locatie.
- De Sensator in de Rechterhand geeft feedback over in hoeverre het formaat van de foto in het Werkveld overeenkomt met het gewenste eind-formaat.

**LET OP:** De feedback in beide Sensators staan dus los van elkaar. Dat kan dus bijvoorbeeld betekenen dat de grootte van de foto in het Werkveld perfect is, maar dat de locatie fout is.

In dit experiment zal er gevarieerd worden met de soort feedback die elke Sensator geeft, er zijn drie types feedback:

- Trillfeedback: De Sensator gaat harder trillen naar mate hij dichter bij de gewenste eind-locatie (of eind-formaat) in de buurt komt. Wanneer het gewenste punt bereikt is zal de Sensator stoppen met trillen.
- Visuele feedback: De kleur van de Sensator zal steeds donkerder worden (oplopend van grijsblauw naar donkerpaars) naar mate hij dichter in de buurt komt van het gewenste punt. Als het gewenste eind-punt bereikt is zal hij stoppen met lichtgeven.
- Geen feedback: De Sensator geeft geen extra informatie over hoe dicht u in de buurt bent van de gewenste eind-locatie of eind-grootte. U moet puur op basis van het Voorbeeldveld bepalen of de foto goed staat.
- Multimodale feedback: De Sensator zal zowel van kleur veranderen als gaan trillen. Een combinatie van de twee andere feedback-vormen dus.

Het experiment is verdeeld in 9 (6) blokken, waarin steeds een andere combinatie van feedback wordt getest. In elk blok zult u in totaal 12 (18) foto’s bewerken; 2 oefenopgaves om te wennen aan de combinatie van feedback en daarna 10 (16) ‘echte’ opgaves. Na elk blok krijgt u een korte vragenlijst over dat specifieke blok; denk bij deze vragen niet te lang na en kuis uw eerste ingeving aan. Aan het einde van de 9 (6) blokken volgt nog een korte afsluitende vragenlijst.

U begint zo als eerste met een aantal oefenopgaven om aan de taak te wennen. Stel gerust vragen als er dingen nog niet helemaal duidelijk zijn!

**Samenvatting:**

- Start-knoppen indrukken → Foto verplaatsen en schalen → Finishknop indrukken.
- Zo snel en nauwkeurig mogelijk.
- 9 (6) blokken met steeds andere feedback.
- Vragenlijsten: niet te lang nadenken.

---

21 Only applicable in Study 2.
22 Only applicable in Study 3.
23 Numbers between parentheses refer to study 3.
H. Study 2 & 3; Picture Manipulation – Concluding Questionnaire

Vragenlijst na Afloop

Leeftijd: 

Geslacht: 

Ik ben: 
  O Rechtshandig 
  O Linkshandig

Welke vorm van feedback werkte voor u:

Het beste voor de hele prestatie (Zo snel en nauwkeurig mogelijk)

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Visueel</th>
<th>Trillen</th>
<th>Geen Feedback (Multi-modaal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foto verplaatsen (Links)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto verplaatsen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto schalen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Het snelst

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Visueel</th>
<th>Trillen</th>
<th>Geen Feedback (Multi-modaal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foto verplaatsen (Links)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto verplaatsen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto schalen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Het nauwkeurigst

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Visueel</th>
<th>Trillen</th>
<th>Geen Feedback (Multi-modaal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foto verplaatsen (Links)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto verplaatsen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto schalen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Het prettigst

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Visueel</th>
<th>Trillen</th>
<th>Geen Feedback (Multi-modaal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foto verplaatsen (Links)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto verplaatsen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto schalen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Het duidelijkst

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Visueel</th>
<th>Trillen</th>
<th>Geen Feedback (Multi-modaal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foto verplaatsen (Links)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto verplaatsen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto schalen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Het minst mentaal belastend

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Visueel</th>
<th>Trillen</th>
<th>Geen Feedback (Multi-modaal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foto verplaatsen (Links)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto verplaatsen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Foto schalen (Rechts)</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Kunt u een rapportcijfer geven aan de verschillende combinaties van Feedback die u ervaren heeft? Het gaat hier om een rapportcijfer dat alles samenvat (snelheid, precisie, gebruiksgemak en duidelijkheid).

<table>
<thead>
<tr>
<th>Linkerhand (locatie)</th>
<th>Rechterhand (Format)</th>
<th>Cijfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visueel</td>
<td>Visueel</td>
<td></td>
</tr>
<tr>
<td>Visueel</td>
<td>Trillen</td>
<td></td>
</tr>
<tr>
<td>Visueel</td>
<td>Multimodaal</td>
<td></td>
</tr>
<tr>
<td>Trillen</td>
<td>Visueel</td>
<td></td>
</tr>
<tr>
<td>Trillen</td>
<td>Trillen</td>
<td></td>
</tr>
<tr>
<td>Multimodaal</td>
<td>Visueel</td>
<td></td>
</tr>
</tbody>
</table>

24 ‘Geen Feedback’ only applied in Study 2, ‘Multi-modaal’ was only applicable in Study 3.
25 This question was only applicable in Study 3.
U heeft na elk blok een vragenlijst ingevuld over de werklast. Deze werklast bestaat uit 6 verschillende onderdelen: Mentale belasting, Fysieke belasting, Tijdsdruk, Prestatieniveau (hoe succesvol heeft u de taak uitgevoerd), Moeite (om het prestatieniveau te halen) en Frustratie.

Hieronder staan steeds twee van die onderdelen naast elkaar. Geef voor elk paar aan welke van de twee onderdelen het meeste invloed had op de door u ervaren totale werklast; omcirkel dit antwoord.

<table>
<thead>
<tr>
<th>Moeite</th>
<th>Prestatieniveau</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frustratie</td>
<td>Prestatieniveau</td>
</tr>
<tr>
<td>Tijdsdruk</td>
<td>Frustratie</td>
</tr>
<tr>
<td>Frustratie</td>
<td>Moeite</td>
</tr>
<tr>
<td>Prestatieniveau</td>
<td>Frustratie</td>
</tr>
<tr>
<td>Fysieke Belasting</td>
<td>Tijdsdruk</td>
</tr>
<tr>
<td>Fysieke Belasting</td>
<td>Prestatieniveau</td>
</tr>
<tr>
<td>Tijdsdruk</td>
<td>Mentale Belasting</td>
</tr>
<tr>
<td>Frustratie</td>
<td>Moeite</td>
</tr>
<tr>
<td>Prestatieniveau</td>
<td>Mentale Belasting</td>
</tr>
<tr>
<td>Prestatieniveau</td>
<td>Tijdsdruk</td>
</tr>
<tr>
<td>Mentale Belasting</td>
<td>Moeite</td>
</tr>
<tr>
<td>Mentale Belasting</td>
<td>Fysieke Belasting</td>
</tr>
<tr>
<td>Moeite</td>
<td>Fysieke Belasting</td>
</tr>
<tr>
<td>Frustratie</td>
<td>Mentale Belasting</td>
</tr>
</tbody>
</table>
# Study 2: Picture Manipulation – Results

## 1. Trial Times

Table I-1: Descriptive Statistics of the Trial Times in MilliSeconds.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
<th>Mean before Outlier Removal</th>
<th>Difference before and after Outlier Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>18</td>
<td>14447,5000</td>
<td>39268,5714</td>
<td>23274,524096</td>
<td>7191,6712152</td>
<td>19698,190</td>
<td>26850,8582</td>
<td>32724,524096</td>
<td>3208,915895</td>
</tr>
<tr>
<td>VT</td>
<td>18</td>
<td>15020,6900</td>
<td>31466,0000</td>
<td>21981,168100</td>
<td>5031,4937002</td>
<td>19479,065</td>
<td>24483,2721</td>
<td>21981,168100</td>
<td>3070,705974</td>
</tr>
<tr>
<td>VN</td>
<td>18</td>
<td>11101,7000</td>
<td>26171,0000</td>
<td>18729,487963</td>
<td>3515,294087</td>
<td>16981,373</td>
<td>20477,603</td>
<td>18729,487963</td>
<td>1563,489815</td>
</tr>
<tr>
<td>TV</td>
<td>18</td>
<td>16193,6667</td>
<td>40247,2500</td>
<td>25073,443056</td>
<td>7661,874421</td>
<td>21262,288</td>
<td>28884,5982</td>
<td>25073,443056</td>
<td>5581,769643</td>
</tr>
<tr>
<td>TT</td>
<td>18</td>
<td>14939,3333</td>
<td>64238,0000</td>
<td>33521,724074</td>
<td>14160,2056974</td>
<td>26480,019</td>
<td>40653,429</td>
<td>33521,724074</td>
<td>4962,159524</td>
</tr>
<tr>
<td>TN</td>
<td>18</td>
<td>11115,7143</td>
<td>34776,6250</td>
<td>22022,332429</td>
<td>5924,4903705</td>
<td>19076,153</td>
<td>24968,512</td>
<td>22022,332429</td>
<td>4145,241276</td>
</tr>
<tr>
<td>NV</td>
<td>18</td>
<td>12689,8750</td>
<td>23594,3750</td>
<td>17594,481790</td>
<td>3085,1761709</td>
<td>16060,264</td>
<td>19128,699</td>
<td>17594,481790</td>
<td>1561,669296</td>
</tr>
<tr>
<td>NT</td>
<td>18</td>
<td>13496,8889</td>
<td>29718,9000</td>
<td>19875,953549</td>
<td>4654,2370316</td>
<td>17561,456</td>
<td>22190,451</td>
<td>19875,953549</td>
<td>788,190741</td>
</tr>
<tr>
<td>NN</td>
<td>18</td>
<td>9453,7778</td>
<td>34295,0000</td>
<td>16720,362191</td>
<td>6262,7270436</td>
<td>13605,981</td>
<td>19834,743</td>
<td>16720,362191</td>
<td>1035,521142</td>
</tr>
<tr>
<td>Valid N (listwise)</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## 2. Parallelism

Table I-2: Descriptive Statistics of the Objective Parallelism Data in Percentages.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>18</td>
<td>10,42</td>
<td>44,08</td>
<td>25,4203</td>
<td>10,48917</td>
<td>20,204</td>
<td>30,636</td>
</tr>
<tr>
<td>VT</td>
<td>18</td>
<td>5,86</td>
<td>43,49</td>
<td>27,2925</td>
<td>10,73270</td>
<td>21,955</td>
<td>32,630</td>
</tr>
<tr>
<td>VN</td>
<td>18</td>
<td>4,28</td>
<td>46,75</td>
<td>22,3490</td>
<td>11,58458</td>
<td>16,588</td>
<td>28,110</td>
</tr>
<tr>
<td>TV</td>
<td>18</td>
<td>12,12</td>
<td>53,12</td>
<td>27,7569</td>
<td>11,72454</td>
<td>21,926</td>
<td>33,587</td>
</tr>
<tr>
<td>TT</td>
<td>18</td>
<td>4,13</td>
<td>49,72</td>
<td>24,2626</td>
<td>13,16233</td>
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<td>7,62701</td>
<td>17,896</td>
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<tr>
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<td>7,94321</td>
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Table I-3: Descriptive Statistics of the Subjective Parallelism Data (After recoding to Percentages).

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<th>Mean</th>
<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
</tr>
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<td>44,472</td>
<td>69,417</td>
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<td>19,29359</td>
<td>67,489</td>
<td>86,678</td>
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</tbody>
</table>
### 3. Workload

#### Table I-4: Descriptive Statistics of the Weiged Workload Scores (1-20 Range).

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<th>Mean</th>
<th>Std. Deviation</th>
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<th>95% CI Upper Bound</th>
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</thead>
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<td>4,451</td>
<td>8,949</td>
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<td>6,707407</td>
<td>3,3592824</td>
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<td>16,0667</td>
<td>8,000000</td>
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<td>7,662963</td>
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<td>9,814</td>
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<td>4,1786885</td>
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<td>9,234</td>
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#### Table I-5: Descriptive Statistics of the Mental Demand Scores (1-20 Range).

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<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
</tr>
</thead>
<tbody>
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<td>4,702</td>
<td>3,773</td>
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<td>8,920</td>
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<td>3,399</td>
<td>3,754</td>
<td>7,135</td>
</tr>
<tr>
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<td>17</td>
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<td>5,062</td>
<td>5,205</td>
<td>10,240</td>
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<tr>
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<td>6,492</td>
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#### Table I-6: Descriptive Statistics of the Frustration Scores (1-20 Range).

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<th>Maximum</th>
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<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
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### 4. User Experience

#### Table I-7: Descriptive Statistics for the Terrible - Wonderful QUIS Item (0-9 Range).

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<td>5.742</td>
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<td>5.981</td>
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#### Table I-8: Descriptive Statistics for the Difficult - Easy QUIS Item (0-9 Range).

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#### Table I-9: Descriptive Statistics for the Frustrating - Satisfying QUIS Item (0-9 Range).

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<td>5.981</td>
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<td>4.899</td>
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<td>2.579</td>
<td>2.939</td>
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<td>2</td>
<td>8</td>
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<td>1.833</td>
<td>4.866</td>
</tr>
<tr>
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<td>4</td>
<td>8</td>
<td>6.72</td>
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<td>6.023</td>
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<td>8</td>
<td>5.67</td>
<td>1.910</td>
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</table>
J. Study 3; Multimodal Picture Manipulation – Results

1. Trial Times

Table J-1: Descriptive Statistics of the Trial Times in MilliSeconds.

<table>
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<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
</tr>
</thead>
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<td>31985,06</td>
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<td>567,58</td>
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<td>23975,41</td>
<td>8169,23</td>
<td>20037,978</td>
<td>27912,858</td>
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<tr>
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<td>5465,76</td>
<td>15376,396</td>
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</tbody>
</table>

2. Parallelism

Table J-2: Descriptive Statistics of the Objective Parallelism Data in Percentages.

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<th>Mean</th>
<th>Std. Deviation</th>
<th>95% CI Lower Bound</th>
<th>95% CI Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>19</td>
<td>5,89</td>
<td>24,46</td>
<td>16,854</td>
<td>5,58</td>
<td>14,16</td>
<td>19,54</td>
</tr>
<tr>
<td>VT</td>
<td>19</td>
<td>2,24</td>
<td>32,88</td>
<td>16,752</td>
<td>7,78</td>
<td>13,00</td>
<td>20,50</td>
</tr>
<tr>
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<td>23,96</td>
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<td>14,35</td>
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<tr>
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Table J-3: Descriptive Statistics of the Subjective Parallelism Data (After recoding to Percentages).

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<th>Minimum</th>
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<th>Std. Deviation</th>
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<td>12,5</td>
<td>87,5</td>
<td>46,053</td>
<td>28,28</td>
<td>32,42</td>
<td>59,69</td>
</tr>
<tr>
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<td>12,5</td>
<td>87,5</td>
<td>47,368</td>
<td>23,04</td>
<td>36,26</td>
<td>58,47</td>
</tr>
<tr>
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<td>87,5</td>
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<td>20,01</td>
<td>31,89</td>
<td>58,99</td>
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<td>12,5</td>
<td>87,5</td>
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<td>25,96</td>
<td>34,19</td>
<td>59,23</td>
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<tr>
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<td>31,89</td>
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</table>

3. Workload

Table J-4: Descriptive Statistics of the Weiged Workload Scores (1-20 Range).

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<th>Minimum</th>
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<th>Std. Deviation</th>
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<th>95% CI Upper Bound</th>
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</thead>
<tbody>
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<td>2,951179</td>
<td>5,792</td>
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<tr>
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<td>19</td>
<td>2,6667</td>
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<td>8,680702</td>
<td>3,6174987</td>
<td>6,927</td>
<td>10,434</td>
</tr>
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<td>19</td>
<td>3,2667</td>
<td>16,200</td>
<td>8,150877</td>
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<td>14,2667</td>
<td>8,659649</td>
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</table>

Valid (listwise)
Table J-5: Descriptive Statistics of the Mental Demand Scores (1-20 Range).

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<td>3.827</td>
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<td>7.490</td>
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</table>

Table J-6: Descriptive Statistics of the Frustration Scores (1-20 Range).

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<th>Minimum</th>
<th>Maximum</th>
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</thead>
<tbody>
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<td>VV</td>
<td>19</td>
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<td>4.669</td>
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<td>9.264</td>
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</table>

4. User Experience

Table J-7: Descriptive Statistics for the Terrible - Wonderful QUIS Item (0-9 Range).

<table>
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<th>Minimum</th>
<th>Maximum</th>
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<tbody>
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<td>8</td>
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<tr>
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<td>3</td>
<td>8</td>
<td>5.89</td>
<td>1.370</td>
<td>5.234</td>
<td>6.555</td>
</tr>
<tr>
<td>VM</td>
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<td>8</td>
<td>6.11</td>
<td>0.809</td>
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<tr>
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</table>

Table J-8: Descriptive Statistics for the Difficult - Easy QUIS Item (0-9 Range).

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<th>Minimum</th>
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</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>19</td>
<td>2</td>
<td>8</td>
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<td>8</td>
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<td>5.923</td>
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<td>4.873</td>
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<tr>
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<td>3.89</td>
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<td>3.234</td>
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</table>
### Table J-9: Descriptive Statistics for the Frustrating - Satisfying QUIS Item (0-9 Range).

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<tr>
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### Table J-10: Descriptive Statistics of the Grades (1-10 Scale).

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