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Softly Elastic 6 DOF Input

Martin Sundin[1,2] and Morten Fjeld[2]
[1]Axiglaze AB, Stockholm, Sweden
[2]TableTop Interaction Lab, CSE, Chalmers University of Technology, Gothenburg, Sweden

The aim of this work is to identify the properties that a universal multidimensional input device should have in order to optimally function with 3D applications, including Web browsers, window managers, digital content creation software, and computer games. Such applications have become increasingly effective due to the rapid development of computer graphics. This situation has generated a greater need for multidimensional input devices. It is conjectured that an ideal universal multidimensional input device should allow for 2D pointing as well as precise manipulation and navigation within 3D environments. Accordingly, the device should offer (a) six degrees of freedom, (b) a range of motion adapted to finger manipulation, (c) elastic suspension providing rich sensory feedback, and (d) position and rate control. The input device, SpaceCat, was designed to offer all these properties. Although such devices are known to benefit 3D navigation, this work demonstrates that they also benefit 3D object manipulation.

1. INTRODUCTION

With the appearance of three-dimensional (3D) graphic applications for desktop PCs, a need for efficient and effective interaction with 3D environments for both home and office use has arisen. Some typical professional uses are in the fields of engineering, architecture, medicine, entertainment, and digital content creation.

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Correspondence should be addressed to Morten Fjeld, TableTop Interaction Lab, Computer Science and Engineering, Chalmers University of Technology, Gothenburg, Sweden. E-mail: morten@fjeld.ch

Nonprofessional uses are dominated by computer games, but in the future, 3D Internet and 3D window managers may popularize. Although the conventional computer mouse with its two degrees of freedom (DOF) emerged along with the graphical user interface, a universal manual input device for 3D environments affording three or more DOFs has yet to parallel the emergence of 3D applications. We aim to develop such a universal input device, which handles the tasks of a conventional mouse along with providing input for 3D environments. The aim of the work presented is to identify a number of principles that a universal, multidimensional input device should fulfill to adequately serve 3D applications. Consequently, the following issues motivate our research:

Issue 1: Task categories preferably performed using multidimensional input devices
Issue 2: Universal versus specialized input devices (both in terms of user's and designer's choice)
Issue 3: Design principles facilitating the usability of universal multidimensional input devices

Today, multidimensional desktop input devices are predominantly used for computer-aided design (CAD) in engineering. Typically, such devices are used for 6 DOF viewpoint control with the user's nondominant hand (Hirzinger & Gombert, 1998). These devices are stiffly elastic with a relatively small motion range of a few millimeters designed for rate control. This market is dominated by 3DConnexion with such products as SpaceBall (http://www.3dconnexion.com/; Figure 1).

Although we seek design principles facilitating the usability of universal, multidimensional input devices, we regard the current use of 6 DOF input for CAD systems as too limited for our investigation. Digital content creation tools such as 3D Studio MAX (http://www.discreet.com/) and Maya (http://www.alias.com/) demand a wider range of interaction particularly suitable for multidimensional input devices. Whereas CAD users define geometry with

FIGURE 1 SpaceBall.

FIGURE 2 SpaceCat.

numerical input or by defining geometrical constraints for *physical objects with tolerances required for production*, users of digital content creation tools (DCC) create *virtual objects for images* in, for example, movies, advertisements, arts, and education. The latter user group requires functions such as modeling, motion capture,[1] object positioning, object trajectory definition, camera positioning, camera path definition, light source placement and animations, and part assembly, which all may be efficiently supported with sufficient precision for image generation by a 6 DOF input device. We note that these functions belong to different task categories, such as *manipulation* and *navigation*. Furthermore, they are preferably supported by different interaction metaphors, such as *object-in-hand* and *camera-in-hand*. Given the multitude of functions, task categories, and metaphors, insight into DCC user needs should provide an inroad to the three research issues just pointed out. This should also help us to understand why products currently on the market (e.g. SpaceBall) have not been utilized for digital content creation, even though commercial plug-ins are available.

With the goal of higher user acceptance of multidimensional input devices for 3D applications, we have designed a 6 DOF input device called SpaceCat (http://www.axiglaze.com/; Sundin, 2001; Figure 2) with prototypical plug-ins for 3D Studio MAX and Maya. The device is *softly elastic* with one order of magnitude lower stiffness and one order of magnitude bigger range of motion than the state of the art desktop 6 DOF input devices. Thereby, not only rate control is feasible as in the state-of-the-art input devices, but position control is also made possible. Position control means that moving the handle of a SpaceCat with any translation and/or rotation lets the object on the screen follow the handle movement one to one.[2] We expect SpaceCat's position control to be better than SpaceBall's rate control for positioning tasks such as manipulating body parts of a puppet in digital

[1]Recording the device handle position and coupling it to a virtual object, for instance a body part of a puppet.

[2]The site http://www.axiglaze.com/gallery1.htm shows an early version of SpaceCat, preceding the one used in the experiment.

content creation. With our study we intend to determine if SpaceCat's softly elastic input control is better than SpaceBall's stiffly elastic input control for position control,[3] and if so, whether the difference is great enough to justify investments to bring SpaceCat to market.

The next section addresses previous research in the area, as it relates to the three issues mentioned previously. Also, it defines design principles such as device stiffness, range of device motion, and transfer function between device movement and virtual object movement. Section 3, the body of the article, presents an empirical within group comparative experiment between SpaceBall and SpaceCat for a manipulation task in 3D Studio MAX. Section four concludes the paper by discussing the results and presenting future research issues.

2. LITERATURE ANALYSIS

Literature on input devices can be found in a range of research fields including experimental psychology, human motor control, aviation and aerospace, telemanipulation, and man–machine interaction. More recently, alternative input devices have been studied by researchers of human–computer interaction to achieve efficient user-computer information flow (Jacob, 1996). Indeed, most input device research aims at faster, more natural, and more convenient ways for users to transmit information to increasingly complex software.

This section treats the three research issues defined above, beginning with multidimensional input and task categories. This is followed by research on universal versus specialized input devices and design principles of universal input devices, including stiffness and transfer function between device and virtual movement. Then there is a separate summary of previous results. Finally, this section concludes by setting up the main hypothesis and two subhypotheses.

2.1. Issues of Multidimensional Input

Because there is no established standard for multidimensional devices (3 DOF or higher), significant work has been invested into using the conventional 2 DOF mouse for interaction with 3D environments (Houde, 1992). Many 3D software products today use the mouse buttons or keyboard buttons to connect subsets of multiple DOF in the application with 2 DOF planar movements. There are reasons to expect, however, that a 3 DOF or higher input device would provide more direct input (Shneiderman, 1993) and yield a higher performance than a 2 DOF mouse because:

[3]As seen in Figures 1 and 2, SpaceBall and SpaceCat differ not only in terms of stiffness but also in the posture of the user's hand. For SpaceCat the palm rests on a horizontal support resulting in a considerable pronation of the hand. For SpaceBall, there is neither pronation nor supination. The palm has no support and its design typically leads to some extension of the hand. So none of the devices is ergonomically optimal, but because we are carrying out a short-term study, these ergonomic drawbacks are not expected to influence our results. Furthermore, we note that both devices are similar in the sense that they were designed for finger manipulation.

- Multidimensional input devices can provide a more direct map from the user's intentions to the 3D application. Therefore, interaction with multidimensional devices should be easier to learn, provide less cognitive load, and give more cognitive support for both novice and expert users.
- Multidimensional input devices may draw more fully on human motor and coordination skills in transmitting information in more channels from the user to the computer, thus potentially saving time.

In the literature, we find examples supporting strengths of multidimensional input. For a 3D rotational task, Djajadiningrat, Overbeeke, and Smets (1997) showed that performance for a rotation task depends on DOF in the input device. The best performance was achieved with free rotation of all three rotational DOF. Hinckley, Czerwinski, and Sinclair (1997) compared the use of an arc ball controlled by a conventional mouse and a multidimensional input device. They found that their 3 DOF input device was 36% faster and without any loss in manipulation precision. The improved performance could be advantageous for a range of user tasks such as modeling, motion capture, object positioning, object trajectory definition, camera positioning, camera path definition, light source placement and animations, and part assembly (Foley, Wallace, & Chan, 1984). These tasks belong to different *task categories* as defined below and are preferably supported by different *interaction metaphors* and *transfer functions*.

Task categories for 3D environments. Slater and Davison (1991) suggested five task categories for multidimensional input devices for 3D environments:

- *Navigation* (1): Change of viewpoint position and/or orientation.
- *Global Selection* (2): Selection of an object in the scene.
- *Local Selection* (3): Selection of a part of an object—for example, a set of specific points, polygons, or patches.
- *Rigid Body Transformation* (4): Change of an object's position and/or orientation, whereby its local geometry remains unchanged.
- *Deformation* (5): Change of an object's local geometry, for example, manipulation of control points of polygons or patches.

In this article we only refer to the three task categories – navigation (1), selection (2, 3), and manipulation (4, 5) – for simplification.

Interaction metaphors. In this article we refer to the following two metaphors:

- *Object-in-hand metaphor*: An *exterocentrical* metaphor whereby the scene moves in correspondence with the input device. If the handle of the input device is twisted *clockwise* the scene rotates *clockwise*. If the handle is moved *left* the scene shifts *left*, and so on.
- *Camera-in-hand metaphor*: An *egocentrical* metaphor whereby the user's view is controlled by direct movement of a virtual camera. If the handle is twisted *clockwise* the scene rotates *counter-clockwise*. If the handle is moved *left* the scene shifts *right*, and so on.

Ware and Osborne (1990) performed an experiment investigating these metaphors whereby it was shown that there is no single best metaphor. For manipulation tasks, the object-in-hand metaphor was superior, whereas for navigation tasks the camera-in-hand metaphor was superior. Poupyrev, Weghorst, Billinghurst, and Ichikawa (1998) examined two basic interaction metaphors for egocentric direct manipulation in virtual environments, these being: virtual hand and virtual pointer, in object selection and positioning experiments. Fjeld, Ironmonger, Guttormsen Schär, and Krueger (2003) experimentally compared the camera-in-hand and object-in-hand metaphors in a two-handed, two-device, 3 DOF, brick-based tangible user interface for the navigation of 3D virtual environments.

Clutching. A clutch is necessary for position control when no direct mapping exists between the movements of the controlled object and the input device or when the limits of the controlling human limbs do not allow for convenient virtual movements. If, for instance, the user wants to turn the object 60° but the device's range of motion is limited to 30° and the gain is 1, it is necessary to reclutch at least once. This clutching, also known as indexing, is comparable to lifting the mouse to put it in the middle of the mouse pad.

Fitts' law and finger manipulation. Various parts of the human body are disproportionately represented in the brain relative to their physical size. The fingers especially have a large representation compared to wrists, elbows, and shoulders. Fingers are provided with an outstanding potential for complex manipulations, which will be of great importance in 6 DOF interaction.

To measure the motor capabilities of different parts of the human body, the performance index $1/b$ of Fitts' law (Fitts, 1954) has been used, which is one of few simple relationships available in user interface research and development:

$$T = a + b\log_2(2A/W) \tag{1}$$

This models the time T needed to point to a target of width W at distance A. The factor $\log_2(2A/W)$, called index of difficulty, signifies that humans react logarithmically to a larger A. This is similar to humans' reactions to increased sound volume, light intensity, and temperature as well. The parameters a and b are determined empirically. The performance index $1/b$ is measured in the unit bit/s and is used to determine the information processing rate of the motor system. Research has shown that isotonic as well as isometric input devices follow Fitts' law (Douglas & Mithal, 1997, p. 107).

Langolf, Chaffin, and Foulke (1976) tested the information-processing rate of different parts of the body. They concluded that the rates $1/b$ for the fingers, wrist and arm were 38 bits/sec, 23 bits/sec, and 10 bits/sec, respectively. This investigation has been cited by Card, MacKinley, and Robertson (1991) to predict promising improved alternatives to the conventional mouse, where fingers are utilized to a greater extent. There are even products that have been designed according to Langolf's findings. A pen-shaped device was presented in Ullman (2004), but no comparative studies including this product have been published yet to the authors' knowledge. Another device, the track ball, utilizes finger movements to a greater extent than the conventional mouse. Zöller and Konheisner (1999) compared a track ball with a conventional mouse, the latter of which proved to be significantly faster, contrary to Langolf's prediction.

Zhai (1995) compared a clutchless, isotonic 6 DOF device designed for finger manipulation (the "finger ball") and an isotonic data glove with an integrated clutch controlled by the arm and wrist. In Zhai's experiment, 10% of manipulation time was used for clutching and so one would expect that this would make the interaction 10% slower. It was however noted that when clutching, the participants were not necessarily idle but most likely engaged in mentally preparing their next actions. It is indeed known that mental rotation takes a certain amount of time (Shepard & Metzler, 1971). Hence, the manipulation slowed down less than the 10% clutching time would cause. Furthermore, Zhai showed that manipulation with the finger ball was faster even if the clutching time were subtracted from the times achieved with the data glove. Zhai concluded from this that it is advantageous to design an input device for finger manipulation.

Balakrishnan and MacKenzie (1997) criticized the method Langolf used to achieve his results and designed a new test to check the results for finger, wrist, and forearm movements. They determined much lower rates for all tested limbs and actually calculated the lowest processing rate to be with finger movements. It is, however, an issue whether their experiment design is adequate. Their measurements incorporated only the forefinger moving in the direction of thumb and middle finger, which is physiologically a different movement from the tapping movements performed in Langolf's experiment. Indeed, it is known that fingers are weaker in the side-to-side movements that Balakrishnan used. Therefore we felt that their results were of limited use to our work and did not consider them any further.

In conclusion, the majority of research supports the idea that a 6 DOF input device should be built for finger manipulation. This would optimize the human processing speed of motor information and minimize the physical workload.

Input device embodiment and usage. Because of the great variety of input devices, taxonomies for input device classification have been suggested. Foley et al. (1984) classified input devices under the graphics subtasks they were capable of performing. Buxton (1987a) classified the input devices according to their physical properties. Card et al. (1991) classified input devices morphologically to detect spaces for new input device designs (see Barber, 1997, for a review on taxonomies).

Some multidimensional devices were developed in an evolutionary process starting from the mouse. Examples with up to five DOFs are found in Slater and Davison (1991); Balakrishnan, Baudel, Kurtenbach, and Fitzmaurice (1997), and Zhai and MacKenzie (1998). Balakrishnan et al. presented a mouse with two translational and two rotational DOF. It was shown that in a 3D positioning task, this device was 30% faster in comparison to a conventional mouse operated by mode switching. Some devices provide 6 DOF with separated rotational and translational input (cf. designs by Froehlich, Hochstrate, Suku, and Huckauf, 2006), and the companies Global Devices (http://www.globaldevices.com) and Dimentor (http://www.dimentor.com). Other input devices map all the 6 DOFs of a solid body (cf. Sundin, 2001; Zhai, 1995; and the commercial products of 3DConnexion [http://www.3dconnexion.com]), or some of the 23 DOFs of the human hand (Sturman, 1991).

A recurring issue is that of two-handed (bimanual) input techniques. Guiard and Ferrand (1996) provided a framework indicating which classes of two-handed interfaces might improve performance without any additional cognitive load. High DOF multidimensional input can be achieved by using both hands with lower DOF input devices. Zhai, Kandogan, Smith, and Selker (1999) used two 2D-joy sticks for a 3D navigation task. Hinckley et al. (1998) use a touch pad combined with a "touch mouse" for a 2D map navigation task, and Kurtenbach, Fitzmaurice, G., Baudel, and Buxton (1997) gives a similar example from the field of graphic artist modeling tools. Gribnau and Hennessey (1998) presented a study in which they compared one-handed, one device versus two-handed, two device 6 DOF input. They conclude that after a learning period, the use of two-handed two device 6 DOF input for an assembly task is preferable. The company DigitalArt-Forms (http://www.digitalartforms.com) has created software to extend the range of use for two-handed two device 6 DOF input to also include modeling and navigation.

An example of a multidimensional input device in combination with the conventional mouse is the use of 6 DOF input devices in CAD (Hirzinger & Gombert, 1998). The 6 DOF input device is used to orient the target object or change the viewpoint with the non-dominant hand, whereas the dominant hand operates the computer mouse for conventional CAD GUI operation. This is a kind of space-multiplexed input (Fitzmaurice & Buxton, 1997) where the 6 DOF input device acts as a graspable user interface that is always connected to the view port. Hirzinger and Gombert pointed out the analogy to work with physical tools and work pieces, in which the right hand typically manipulates the tool and the left hand readily orients the work piece. The manual work with a work piece and a tool has been investigated by Hinckley, Pausch, Proffitt, Patten, & Kassell (1997). When studying the roles of the dominant and the non-dominant hand they found that the specialized roles of the hands only are significant when precision tasks are performed. This confirmed earlier results by Kabbash, MacKenzie, and Buxton (1993). The fact that 6 DOF devices in CAD are used solely with the nondominant hand thus implies that current 6 DOF devices are not as suitable for precision tasks as the conventional mouse. This may be because they are relatively stiff with a small range of motion for rate control only. We note that the currently used combination of a 6 DOF-input device and the conventional mouse in CAD does not provide any means for precise simultaneous 6 DOF manipulation.

Aiming to broaden the use of 6 DOF CAD input, we developed SpaceCat (Sundin, 2001). In a series of experiments, we compared the rate-controlled, stiffly elastic 6 DOF input device SpaceBall with SpaceCat for CAD input (Sundin, Weiss, & Sundin, 2000). One group of the participants performing the tests had at least half a year experience using the CAD system combined with SpaceBall and performed an assembly task with mathematical constraints. The other group's participants had no experience of 6 DOF input devices or CAD systems. For the experienced users, the control order or the kind of input device did not play a major role when solving the CAD task. For them the functionality of an input device working in position control mode did not provide a major advantage as compared with the currently available, commercial state-of-the-art 6 DOF input devices that work in rate control mode. The result from the inexperienced participants was different. They clearly preferred SpaceCat's position control to SpaceBall's rate control. This reaction from novice users was also confirmed in additional qualitative tests.

Specialized versus universal input devices. From a user's perspective there are a number of advantages that favor the use of universal input devices with software systems:

- All users are trained on the same input devices. Such input devices are available for most computer systems and can be used without practice.
- Standard software is compatible with universal input devices. The software is ready to use after download and installation without any need to purchase a physical device.
- Time moving between specialized input devices is avoided.
- Limited desktop real estate is not occupied by a number of specialized input devices.
- A mass-produced universal input device lowers production costs.

For the software designer the arguments are similar. Software companies usually only optimize their software for the generic keyboard and mouse.[4] By using generic interfaces, software compatibility depends only on the operating system. The companies do not have to concern themselves about different versions of different input devices or commit themselves to shipping and service for specialized input devices.

These advantages in favor of universal input devices give today's generic mouse a strong position over alternative input devices both from the user's and the designer's perspective. In the future, however, we expect interaction with 3D environments to become part of standard software. In the previous section we indicated that the use of a 2 DOF pointing device like the mouse is not optimal for interaction with 3D environments. Thus, a new universal input device with extended capabilities is needed. So far, multidimensional input devices have been launched for specialized software such as CAD. However, no multidimensional input device has thus far been suggested as a universal input device because the current solutions are not as good as a conventional mouse for pointing tasks and do not provide precise manipulation, as argued in the previous section. A new standard should allow for 2D pointing as well as precise manipulation and navigation within 3D environments. This view is shared by Rossignac (1998, p. 66):

[4]With a generic mouse we mean any pointing device supporting the generic mouse interface of modern GUI operating systems, such as conventional mice, track balls, track pads, track points, and touch screens.

"The solution should be suitable for inexpensive desk-top systems and for collaborative environments. Furthermore, the same paradigm should be used for controlling the relative position of the geometric features in an assembly as for controlling the view."

We observe that most keyboards are designed for space-multiplexed input and most mice for time-multiplexed input (Fitzmaurice & Buxton, 1997). Restricting each hand to only space- or only time-multiplexed input typically leads to specialized solutions. General solutions mostly favor single-handed mouse input, combined with single- or two-handed keyboard input. This way of working is common practice and has proven efficient in digital content creation tools such as 3D Studio MAX and Maya, which are targets in our research. With such tools, the user's dominant hand operates the mouse while the user's nondominant hand operates shortcuts and modifiers at the keyboard. Our aim is to support this working practice with a universal input device not only supporting 2D pointing but also 3D interaction. This leads us to work for a single-handed input device.

As a candidate for a universal input device, a 6 DOF device is a natural choice since it corresponds to all DOF for a rigid body. Positioning and orientating a virtual object or the task of viewpoint navigation inherently have 6 DOF. In cases where there is a need for less than 6 DOF, the most direct mapping from the input device to action can be chosen, for example, when 3D rotations are needed only the three rotations of the input device are in use. Navigation is an example of a task that is not necessarily solved best with 6 DOF. Zhai et al. (1999) use a two-handed solution with two standard pointing devices (i.e., 4 DOF) in a special navigation task where the horizon was fixed. However, a better solution to the task may be to use a subset of the degrees of freedom in a 6 DOF input device, as the mapping is more direct and solved with only one hand.

An open question is whether there exists a technology suitable for all tasks. Selection, manipulation, and navigation are inherently different and may require different metaphors for efficient interaction. Fitzmaurice and Buxton (1997) argued for multiple specialized input devices, individually adjusted to user preferences.[5] Most probably a "one fits all" technology does not exist. On the other hand the conventional mouse is not the optimal standard input device. As pointed out earlier, our goal is to find a better standard that handles all the tasks the conventional mouse solves today and provides a basic input device for 3D environments. Following the arguments presented we assume that a 6 DOF input device for single-hand use is the best candidate, and we now investigate the physical properties such a device should have to support a variety of 3D functions belonging to different task categories and using different metaphors.

2.2. Issues of Device Stiffness and Transfer Function

Two basic properties pertaining to an input device are its *device stiffness*, that is, the function between the device handle position and the force applied to the handle,

[5]At this point we would also like to point out that there is also a considerable ergonomic advantage using various input devices, giving the user the opportunity of change.

and the *transfer function*, that is, the function between the device handle position and the output on the computer screen.

Device stiffness. If we assume linear compliance K_s and linear viscosity B_s, the physical properties of a device can be modeled as

$$M_s \ddot{u} + B_s \dot{u} + K_s u = F_u \quad (2),$$

where F_u are the forces and torques acting on the device handle, M_s is the mass and inertia matrix, and u is a deflection vector of position and orientation of the device handle.

The compliance K_s has especially attracted much interest among researchers. K_s has also been referred to as device stiffness, which is the terminology used in this article. Zhai (1995) used a model with $M_s \approx B_s \approx 0$ and the following three categories for stiffness:

Isotonic Input: An input device with zero stiffness (K_s = 0), that is, there is no self-centering effect.

Elastic Input: A device with some stiffness ($K_s \neq 0$), that is, the forces on the handle are proportional to the deflections.

Isometric Input: An elastic input device with infinite stiffness ($K_s = \infty$), that is, the device handle does not allow any deflection but records force and torque.

Most researchers support the assertion that isometric devices are required for fast response whereas isotonic devices yield a higher accuracy. This means that isotonic control is advantageous for positioning tasks (which plays a part in target acquisition or docking), whereas isometric control is advantageous in irregular tracking tasks. Other tracking tasks, such as tracking predictable targets or tracking step-changes, are better with isotonic control because they enable high precision combined with quick movement and are closely related to positioning tasks.

Transfer function. The transfer function controls how the device handle actions are transmitted into the controlled system:

$$\Gamma = f(u) \quad (3),$$

where Γ is the position and orientation of the controlled virtual object as defined in Appendix A, and u is defined as in Equation 2.

The three transfer functions of lowest control order are defined as

Position Control (or zero order control): The position and orientation of the controlled object are proportional to the deflection (here: position and orientation, or force and torque for ideally isometric devices) of the device handle, that is, $\Gamma(t) = f_0\, u(t)$ where the gain f_0 is a constant diagonal matrix.

Rate Control (or first order control): The translation and rotation velocity of the controlled object is proportional to the deflection of the device handle, that is, $\Gamma(t) = f_1 \int u(t)\, dt$ where the gain f_1 is a constant diagonal matrix. Rate control is sometimes also referred to as velocity control.

Acceleration Control (or second order control): The translation and rotation acceleration of the controlled object is proportional to the deflection of the device handle, that is, $\Gamma(t) = f_2 \iint u(t)\, dt^2$ where the gain f_2 is a constant diagonal matrix.

These control modes can be summarized into one expression where s is the Laplace variable:

$$\Gamma(s) = f_0 u(s) + f_1 \frac{1}{s} u(s) + f_2 \frac{1}{s^2} u(s) \qquad (4).$$

It is known that acceleration control is difficult to handle (Kim, Tendick, Ellis,& Stark, 1987; Wickens, 1991), and therefore it is not considered here.

There is, in general, a trade-off between maximal virtual motion speed $\partial\Gamma/\partial t$ and the virtual accuracy $\partial\Gamma/\partial u$, i.e. the precision, for any transfer function (Jagacinski, 1989). Kim et al. (1987) investigated optimal gains f_0^{opt} and f_1^{opt} for position and rate control in a linear transfer function, that is, f_0 and f_1 defined as constant diagonal matrices. In both cases, the optimum depended on the task, the input device, and personal preferences. Zhai (1995) concluded that for isometric rate control, any value, $f_{1,}$ in a wide range around the optimum value, f_1^{opt}, gave similar results: The difference in mean completion time in a docking task varied within 10%, given a gain f_1 that varied by a factor of four. This is consistent with other research which demonstrates that the gain is of little importance when using pointing devices for selection in graphical user interfaces (Douglas & Mithal, 1997). Accordingly, because not much can be achieved by optimizing the parameters of a simple linear transfer function, researchers have sought for nonlinear transfer functions. In the following we present nonlinear transfer functions for rate and position control aiming to improve the speed-precision trade-off.

Nonlinear rate control. Dynamic filters and nonlinear static filters make it possible to achieve both a large range of virtual motion and precision in rate control. Ware and Slipp (1991) used a nonlinear transfer function for isometric rate control. The angular rate was proportional to the square of the applied torque $\dot{\theta} = T^2$. The transitional rate was described by $\dot{x} = F^{2.5}$ where F is the applied force. SpaceBall uses $\dot{\theta} = T^{2.2}$ and $\dot{x} = F^{2.75}$ according to Zhai (1995), that is, Equation 3 becomes $\Gamma = f_1 \int (u_1^{2.2}\, u_2^{2.2}\, u_3^{2.2}\, u_4^{2.75}\, u_5^{2.75}\, u_6^{2.75})^T\, dt$.

Rutledge and Selker (1999) tested other quadratic transfer functions for an isometric finger operated joystick called "track point," which is widely used in laptops, to be used in rate control. The transfer function in the final product (Barrett, Selker, Rutledge, & Olyha, 1995) is described by $\Gamma = f_1 \int u\, dt + f_0\, u$. With this proportional-derivative control of the velocity, a negative inertia of the cursor is simulated.

Nonlinear position control. Filters are also used for position control to achieve both a wide range of virtual motion and precision. In conventional mouse drivers, the gain matrix f_0 typically increases with the input device velocity, that is, a rate-aided position control described as $\dot{\Gamma} = f_0(\dot{u})\,\dot{u}$. This makes it possible to move longer distances without clutching. However, there is no research which confirms that rate-aided position control gives a better performance (Douglas & Mithal, 1997). One argument against rate-aided position control and dynamical transfer functions in general is that it violates the user's experience of manipulating real objects: The faster the input device handle is moved a certain distance, the farther the resulting movement on the computer screen will be. With regard to the open loop character of human motor control (cf. footnote 11), it can be assumed that dynamic transfer functions make the learning of motor programs harder. If transfer functions without dynamics are implemented, the experienced user can use the same movements at a faster pace and achieve the same result. We especially expect that rate-aided control will provide no advantage for controlling rotations since a user only needs a maximum of ±180° to perform any rotation. This can be achieved with a ±30° range of motion and a linear gain of 6.

Alternatives that allow a greater range of virtual motion and avoid the problem of the dynamic transfer function are nonlinear transfer functions with a gain dependent on the position according to $\Gamma = f_0(u)\,u$. Poupyrev, Billinghurst, Weghorst, and Ichikawa (1996) implemented an increasing f_0 for increasing u, which he refers to as "The Go-Go Interaction Technique." Thus, the technique has its strength where the user needs precision within short reach and less precise manipulation far away.

Matching device stiffness and control order for positioning tasks. Having analyzed device stiffness and transfer functions (here: control order), we now discuss feasible combinations of these two. Figure 3 lists experiments (1–6) for feasible combinations of device stiffness and control order in positioning tasks. The positioning tasks include 2 DOF pointing and 6 DOF positioning.

Because the elastic devices studied differ by one order of magnitude in stiffness we find it useful to employ the device categories *softly elastic* and *stiffly*

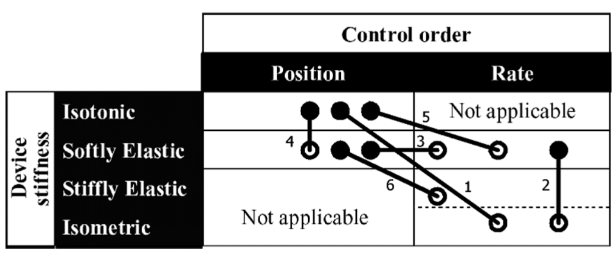

FIGURE 3 The "double ball bars" refer to positioning experiments comparing different kinds of interaction. *Note.* Experiments 1, 2, 3, 4, and 5 are cited and discussed in this section. Experiment 6 comprises the body of this work as presented in the next section. More efficient kinds of interaction are marked with a solid circle.

elastic.[6] Because of their small range of motion and high stiffness, we furthermore assume stiffly elastic input devices to have the same use characteristics as isometric input devices; hence the dashed line between the two bottom rows of Figure 3. Thus, in the following, we consider three categories of input devices, these being isotonic, softly elastic, and third englobing category comprised of stiffly elastic and isometric devices. It has been shown that isotonic rate control and isometric position control are not feasible (Zhai, 1995). Hence, stiffly elastic position control is also assumed not being feasible.

Experiment 1 (Figure 3): Isotonic Position Control Versus Isometric Rate Control

In a 6 DOF positioning task experiment, Zhai (1995) compared (a) isotonic position control using a magnetic tracker with (b) isometric rate control using a SpaceBall 2003. With isotonic position control, both the learning time and the completion time of the task were shorter. However, the device is somewhat fatiguing because it must be manipulated freely in the air. So a benefit of the isometric device is less fatigue because the arm can rest on the desktop during usage.

Experiment 2 (Figure 3): Softly Elastic Rate Control Versus Isometric Rate Control

In a 6 DOF positioning task experiment, Zhai (1995) compared (a) elastic rate control using the "elastic general-purpose grip" with (b) isometric rate control using a SpaceBall 2003. In terms of completion time there were no significant differences between the devices. Elastic rate control, however, was shown to have a shorter learning time. Zhai points to greater proprioception[7] in elastic devices as a reason for this. The later generations of SpaceBall (SpaceBall 3003 FLX and

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[6]SpaceBall 4000 FLX has a maximum deflection of approximately 3 mm at a maximum force of approximately 10N, that is, a stiffness of approximately 33N/cm. Space Mouse has a maximu deflection of 1.5 mm at a maximum force of 4.4N (Magellan/Space Mouse User's Manual Version 1.3), that is, a stiffness of approximately 30N/cm. On the contrary SpaceCat has a maximum translational deflection of approximately 15 mm and maximum rotational deflection of approximately 30° at a maximum force less than 2N, that is, a stiffness of approximately 1.3N/cm. The "elastic general-purpose grip" has a stiffness of 120g/cm, that is, approximately 1.2N/cm. Furthermore, SpaceCat and the "elastic general-purpose grip" were designed to allow for finger manipulation, that is, allowing for at least 1 cm of deflection combined with the spring forces for optimal kinesthetic feedback. Because of the different design principals and a stiffness ratio of almost 30 SpaceBall 4000 FLX and Space Mouse are called *stiffly elastic* devices in contrast to the *softly elastic* devices SpaceCat and the "elastic general-purpose grip."

[7]Proprioception is internal, bodily feedback on muscle and joint positions. It is generally recognized to be a crucial factor in input technology, but the literature has not been consistent on whether isotonic or isometric devices provide more proprioceptive cues. Although proprioception has been central in the debate, its actual importance is not clear. In psychomotor literature there has been an ongoing debate between centralists and peripheralists. Centralists support open-loop behavior of the human motor system, whereas peripheralists emphasise the role of proprioception in a closed-loop control system; see Singer (1975) for an overview. More recent research shows that both systems synergetically cooperate in motor control. This suggests that proprioception's greatest role is in the learning of new motor programmes and in the control of slow and precise movements (Weiss, 1998).

SpaceBall 4000 FLX, both stiffly elastic) were designed for less stiffness than the earlier generations (SpaceBall 2003 and SpaceBall 3003, both isometric). Therefore, according to this experiment, SpaceBall 4000 FLX should be better in terms of learning compared to SpaceBall 2003. This experiment was also performed for a 6 DOF tracking task experiment with the same results as for the 6 DOF positioning task experiment.

Experiment 3 (Figure 3): Softly Elastic Position Control vs. and Softly Elastic Rate Control

In a pointing task experiment, Li (2001) compared (a) softly elastic position control with (b) softly elastic rate control, in both conditions using a quCat.[8] The experiment was aimed at finding the optimal control mode for pointing with a universal input device using 6 DOF softly elastic input. Eight men between 24 and 35 years old each performed 96 tasks in one session for both position and velocity control. The independent variables in the usability test were the subject, the transfer function, the set, the subset, the moving distance, the target size, and the moving direction. The experiment design was balanced, having the same structure as experiment 6 presented below. Position control performed better than velocity control in terms of completion time in most tasks while the difference in completion time was smaller for long distance tasks, mean completion time for position control was 17% faster than for velocity control.

Experiment 4 (Figure 3): Isotonic Position Control Versus Softly Elastic Position Control

In a pointing task experiment, Li (2001) compared (a) isotonic position control using a conventional mouse with (b) softly elastic position control using a quCat. Experiment 4 was designed to find out whether it is possible to reach the goal of a universal input device which is applicable to 3D tasks as well as 2D pointing, that is, to assess whether softly elastic input is good enough for pointing. Li let the participants perform the same tasks as performed with softly elastic rate control in Experiment 3, but with a conventional (isotonic) mouse using standard Microsoft Windows 2000 settings. She compared this data with the data already collected in Experiment 3 with softly elastic position control. With the mouse, the tasks were completed an average of 28% quicker than with the SpaceCat. The difference in completion time was larger with higher precision and longer movements. However, it should be noted that because Experiment 3 was performed in one session, the participants had no opportunity to learn to efficiently interact with SpaceCat's softly elastic position control, all being experienced mouse users. Thus, it is difficult to draw any conclusion on SpaceCat's performance in a real working environment. We note that by using a universal input device for 2D and 3D time spent in switching between devices is avoided, for example, when switching between selection in a context related pop up menu and 3D manipulation.

[8]QuCat is a newer product prototype than SpaceCat based on the same technology but with stiffer springs and smaller range of motion.

Hence, there is a motivation for 2D pointing with SpaceCat even if it is not as fast as the conventional mouse.

Experiment 5 (Figure 3): Isotonic Position Control Versus Softly Elastic Rate Control

Because Experiment 4 showed that isotonic position control is better than softly elastic position control and Experiment 3 showed that softly elastic position control is better than softly elastic rate control, both in pointing task experiments using the same experimental set-up, we assume that isotonic position control is better than softly elastic rate control for pointing tasks. Therefore Experiment 5 is omitted.

6 DOF softly elastic position control vs. 6 DOF stiffly elastic rate control. Experiment 6 (Figure 3) comprises the body of this article. Because we consider softly elastic position control to be a crucial feature of a universal input device, this is the main issue of our research. We carried out a within-group 6 DOF positioning task experiment comparing (a) softly elastic position control using a SpaceCat with (b) stiffly elastic rate control using a SpaceBall 4000 FLX. From Figure 3 it is evident that for a universal input device to handle both rate control and position control it needs to be a softly elastic input device, because stiffly elastic (and isometric) position control and isotonic rate control are not applicable. Furthermore, according to Experiment 2, the softly elastic SpaceCat will be better for rate control than state-of-the-art, stiffly elastic devices. It remains an open question, however, whether 6 DOF positioning tasks are better solved by softly elastic input in position control mode than stiffly elastic input in rate control mode. Answering this question is the objective of experiment 6 presented in the experimental section.

Other experiments. Figure 3 presents positioning experiments and is only concerned with input devices where all DOFs have the same device stiffness. A more complete taxonomy could include experiments with input devices where the DOFs have different stiffness. Such experiments were performed with two 6 DOF desktop input devices combining isotonic rotational input with elastic translational input (Froehlich et al., 2006). Both devices exhibit performance advantages of more than 20% over the stiffly elastic 6 DOF input device, Space Mouse, in a 3D docking task.

2.3. Summary of Previous Results

Those parts of the previous results we find most relevant to our work are now summarized and presented in the following.

Physiological implications on handling and learning. The sensorial capabilities and motor skills of the human hand have consequences for input device design. First, because of greater proprioceptive feedback, the handling of softly elastic input devices is easier to learn than that of isometric or stiffly elastic ones. Second, the greater proprioceptive feedback makes slow, precise movements easier to control. Furthermore, a softly elastic input device designed for finger manipulation allows for dexterous manipulation and fast learning because of the human hand's extraordinary motor control capabilities.

Trade-off between virtual motion and precision. A range of device motion adapted to the human hand implies limitations on the precision and range of virtual motion in the target system. For position control there is a trade off between range of virtual motion and precision whereas in rate control there is a trade-off between velocity at maximum device deflection and precision. The problems this poses might be improved by nonlinear transfer functions allowing both accuracy and a wide range in virtual position and velocity respectively.

Control task, control order, and metaphors. We conjecture that in control tasks, the control mode of the input device should correspond to the controlled variable. That is to say, for instance, *positioning tasks* are best solved with position control. Thus, manipulation and docking tasks, which typically require the control of a position and an orientation, are best solved with position control. In many cases the required range of virtual motion can be achieved with sufficient accuracy using position control and a range of device motion adapted to finger manipulation. This renders the trade off between range of virtual motion and accuracy unproblematic. It also mirrors the human tendency to think about manipulation as something best done with the fingers, and thus, an exterocentrical metaphor, that is, an object-in-hand metaphor, should be used. *Navigation tasks*, on the other hand, typically requires controlling the velocity of observers covering long distances and is thus best solved with rate control. When navigating in virtual worlds the user is embedded in a virtual environment. Hence, an egocentrical metaphor, that is, a camera in hand metaphor, should be used. Finally, *tracking tasks* may involve tracking positions as well as velocities. Hence, the control order should be adapted correspondingly.

With respect to the discussed control tasks, control orders, and metaphors we hence conjecture that there are two main types of preferred usage:

1. Positioning, manipulation, and docking using position control and the object-in-hand metaphor.
2. Navigation using rate control and the camera-in-hand metaphor.

The hypothesis and the following usability test below only concern the first type of usage.

Control task, control order, and device stiffness. A softly elastic input device is suited for both position and rate control. However, different spring constants are appropriate for different tasks. *Low stiffness* is better for manipulation and other tasks demanding precision. *High stiffness* is better for navigation and tasks demanding fast reactions.

2.4. Formulation of Hypotheses

Because of the different characteristics of 6 DOF interaction tasks that might occur within the same application, a universal input device should allow for both position control and rate control. To achieve this, it is necessary to provide a larger range of device motion than current products do. According to previous research on finger manipulation, Fitts' law, and submovements, as presented above, a proper range of device motion should be adapted to finger manipulations. Drawing on information from previous results about the control task, control order, metaphors, device stiffness, range of device motion, and the physiological implications of handling and learning, we formulated the following hypothesis and subhypotheses:

Hypothesis: For positioning tasks, softly elastic input with position control is better than stiffly elastic input with rate control.
Subhypothesis 1: For tasks requiring precise positioning the advantage of softly elastic input with position control over stiffly elastic input with rate control is expected to be bigger than for tasks requiring less precise positioning;
Subhypothesis 2: For tasks requiring short distance positioning the advantage of softly elastic input with position control over stiffly elastic input with rate control is expected to be bigger than for tasks requiring long distance positioning.

To test this, we designed and performed an experiment comparing two devices, one featuring position control and the other featuring rate control. The following section reports on the experiment and its results. This is followed by a final section presenting future research.

3. EXPERIMENT

The input devices, SpaceCat and SpaceBall, were compared in a 3D docking task. SpaceCat is a softly elastic input device that was used in position control mode whereas SpaceBall is a stiffly elastic input device used in rate control mode. SpaceCat was especially conceived to fulfil requirements from previous research and was developed in an interdisciplinary project at the Centre for Integrated Production Systems at the ETH in Zürich, Switzerland (Sundin, 1999).

It was assumed that the hypothesis and subhypotheses previously formulated are correct. Our hypothesis was tested by comparing trial completion times for SpaceCat and SpaceBall. Eight participants each completed 12 trials for each of the two input devices after having been trained to use them. In each trial the task was to move a cursor to a target. Both the cursor and the target had specified sizes and were at a specified distance from each other at the beginning of each trial. We used two distances (short and long) and two target sizes (small and big). Thus we have a Subject (8) × Device (2), Distance (2), and Target Size (2) factorial design. The participants performed three repetitions of each cell, a cell having same values of Subject, Device, Distance, and Target Size. That is, each participant performs *three trials for each of the four combinations of Distance and Target Size* (i.e., three trials each of small target/short distance, small target/long distance, big target/short distance, big target/long distance) using each of the two devices. All of the independent variables are repeated measurements, thus following a within-subjects design.

The gathered data were used not only to compare SpaceCat and SpaceBall completion times but also to examine whether SpaceCat and SpaceBall comply with Fitts' law. For this purpose we summarized the independent variables, Distance and Target Size, in a new combined independent variable termed Index of Difficulty (cf. Equation 1).

Furthermore, it is relevant to not only measure the completion time for docking the six degrees of freedom of the cursor with the target but also consider whether some of the degrees of freedom are more difficult to control than others. Therefore, the *dependent* variable, Half-Way Time, was introduced to measure the time it takes to get half way from the start position to the end position in each degree of freedom separately in the trials. Thus, the *independent* variable, Degree of Freedom, had to be introduced into our experimental design.

We also have the independent variable Musician and the confounding variables Geometrical Setup and Permutation of level of difficulty. In the experiment presented next, we were not interested in studying the effect of these three variables. It is shown in Appendix B that each of them did not affect the validity of our experiment. Finally, we have the dependent variable Learning, which is examined in the following section.

3.1. Experimental Design and Procedure

For economic reasons a balanced experiment design with 8 participants was performed on a standard desktop PC.

Participants. Eight men ages 24, 25, 27, 27, 27, 29, 32, and 44 successfully took part in the experiment.[9] All had at least 10 years of computer mouse experience and operated it with their right hand. One subject had one year of SpaceBall experience but the others were new to both SpaceBall and SpaceCat. The subjects included three mechanical engineers, two architects, two physicists, and one chemist. The reason for choosing only men at a technical university was to minimize the number of influencing factors, considering that typical users of 6 DOF

[9]We actually started with 10 participants; however, 2 participants had to be dismissed, which left us with 8 participants for the experiment. One participant was dismissed because he had no 3D perception at all and the second because he had a learning disability. After 1 hr the first participant had solved only one trial and the second just four, corresponding to a small fraction (some 4%) of trials performed by all the other participants within the same time. The 2 participants were equally unable to solve tasks with both SpaceCat and SpaceBall.

desktop input devices are men with a technical education. Four of the eight subjects happened to be amateur musicians, two of whom played the violin, another, the viola, and the last, the cello (by coincidence the instrumentation of a string quartet).

The reason for choosing 8 participants only can be understood from the purpose of our study. We wanted to find out if SpaceCat's softly elastic input control is better than SpaceBall's stiffly elastic input control for positioning tasks, and if so, whether the difference is sufficient to motivate investment in further development of SpaceCat. For this purpose there need to be clearly measurable benefits, which should be apparent also with a small number of participants. Thus, we carried out a cost-effective experiment while still assuring the results needed for an empirically grounded no-go decision. No attention was paid to the time of the day when the experiment was performed. It was carried out at roughly all times of day but most participants participated during lunch or in the evening.

Apparatus. The docking task was performed in 3D Studio MAX v3.0 with two different input devices. The stiffly elastic input device, SpaceBall 4000 FLX (cf. Figure 1), was used in rate control mode and the softly elastic input device, SpaceCat (cf. Figure 2), was used in position control mode.

SpaceBall used the SpaceWare driver 9.2 for Windows and the SpaceWare AniMotion software plug-in for 3D Studio MAX v3.x. For SpaceCat, a new driver and 3D Studio plug-in was developed (Willburger, 2000). Another plug-in was developed to handle the experimental data, that is, monitor the motion paths and completion time.

The experiment ran on a desktop Compaq PC (Intel Pentium Pro 200 MHz, Windows NT 4.0, 64 MB RAM, Matrox Millenium Graphics Card 8 MB, monitor 17 in. at resolution 1024 × 768 pixel). The system reaction time was tested with a SpeedCam + LITE camera with a time resolution of one frame per millisecond. The screen ran with a screen build-up frequency of 85 Hz. The 3D Studio MAX view was updated every third screen build-up yielding approximately 28 frames/sec, which gives an impression of smooth movement. The system reaction time for both SpaceCat and SpaceBall was approximately 0.10 sec. This time lag was short enough not to be noticed by the participants.

Factorial design. In accordance with Appendix A, the observed paths are denoted with the following tensor:

$$\Gamma_{nmkijhg} \qquad (5),$$

where the variables are

Γ position and orientation of the controlled virtual object, cf. Appendix A
$n \in [1, N = 8]$ participant identification number
$m \in [1, M = 2]$ device id, where C≡1≡ SpaceCat and B≡2≡ SpaceBall
$i \in [1, I = 2]$ target size, where b≡1≡big target and s≡ 2≡small target
$j \in [1, J = 2]$ distance, where S≡1≡short distance and L≡2≡ long distance

$h \in [1, H = 6]$ degree of freedom index (according to Equation A4 in appendix A)
$g \in [1, G_{nmlkij}]$ docking path sample index
$k \in [1, K = 3]$ subset index, each subset including $IJ = 4$ docking trials

The trajectory of each degree of freedom in each trial was sampled at times, t_{nmkijg}, giving a time discrete path function, Γ_g. Each docking trial path contains G_{nmkij} samples. The trial *completion time* is denoted by $\hat{T}_{nmkij} = t_{nmkijGnmkij}$. Because no real-time operating system was used, there was no accurate sampling rate. A sample time interval, t_{g+1}-t_g, had a mean value of 0.077 sec. Three percent of the time intervals were longer than 125 msec, and six sample intervals (i.e., 0.0038%) were longer than 250 msec. No sample interval was longer than 500 msec.

To address our hypothesis and subhypotheses, we tested the completion times of SpaceCat and SpaceBall in a $N(= 8) \times M(= 2) \times I(= 2) \times J(= 2)$ within-subjects factorial design with $K = 3$ repetitions of each cell with the same values for *n, m, i,* and *j*. In the repetitions, the geometrical setup and permutation of level of difficulty was changed as described below. Thus, the variance caused by different geometrical setups in the trials is contained in variable Subset *k*. Modeling *k* in a $N \times M \times K \times I \times J$ factorial design allows us to control the effects of Subset and thereby the effects of the confounding variables Geometrical Setup and Permutation and if possible omit Subset from the model. Similarly, the influence of the independent variable, Musician, must be controlled and omitted if possible.

Another factor that demands consideration is learning, as pointed out and investigated in Sundin (2001). The participants were instructed to learn using the devices before collecting the experimental data presented in this work. There were two instruction phases, Ph1 aided and Ph2 unaided, followed by Ph3, in which Γ_{nmkij} as defined in Equation 5 was collected. In Ph3, 24 trials, 12 with each input device, were presented, these having the same geometrical setup and permutation as in Ph2. It should be noted that we do not use any data from the Ph2 in the presented work to avoid influence of short-term learning effects. Learning, however, as investigated in Sundin (2001), was based on data collected in Ph2 and Ph3. In Ph1, participants were instructed to perform 24 trials, 12 with each input device, to understand its functionality and how the experiment works. In Ph2, 24 trials, 12 with each input device, were repeatedly presented to each subject. Hence, we have two box designs; one box design for assessing the influence of Geometrical Setup and Permutations embedded in a second box design for assessing learning. The 4 first participants performed a total of four learning assessment repetitions in Ph2 (3 repetitions) and Ph3 (1 repetition), as exemplified by Figure 4. To save time, the remaining 4 participants performed only two repetitions in Ph2. In Sundin (2001), an evaluation of the learning effect showed that, for SpaceCat, the average completion time decreased by 14.0% between two consecutive sets of 24 trials, whereas for SpaceBall, the average completion time decreased by 6.7%.

The order in which the docking trials were collected for each participant is described by the index ξ, that is, ξ starts with $\xi = 0$ for the first trial and is then incremented after each trial. The collected data can thus be described alternatively by $\Gamma_{n\xi hg}$. Target Size *i*, Distance *j*, Subset *k* and Device *m* are functions of the index ξ (cf. Figure 4):

```
Ph:222222222222222222222222222222222222222222222222222222222222222222222222333333333333333333333333
ξ+1:1  4   8  12  16  20  24  28  32  36  40  44  48  52  56  60  64  68  72  76  80  84  88  92  96
m :CCCCCCCCCCCCBBBBBBBBBBBBCCCCCCCCCCCCBBBBBBBBBBBBCCCCCCCCCCCCBBBBBBBBBBBBCCCCCCCCCCCCBBBBBBBBBBBB
i :LSSLLLSSSLSLLSSLLLSSSLSLLSSLLLSSSLSLLSSLLLSSSLSLLSSLLLSSSLSLLSSLLLSSSLSLLSSLLLSSSLSLLSSLLLSSSLSL
j :bsbsbsbsbssbbsbsbsbsbssbbsbsbsbsbssbbsbsbsbsbssbbsbsbsbsbssbbsbsbsbsbssbbsbsbsbsbssbbsbsbsbsbssb
ID:231424131432231424131432231424131432231424131432231424131432231424131432231424131432231424131432
k :111122223333111122223333111122223333111122223333111122223333111122223333111122223333111122223333
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FIGURE 4 Experimental design for the first participant (n = 1). *Note.* In Ph1, the participant learned how to use the input devices and how the experiment would work without any data collection (not shown in the figure). In Ph2, data were collected to assess learning (cf. Sundin, 2001). The data presented in this work are taken from Ph3, with 12 trials for each input device. In total, the participant performed 96 registered trials as seen from the trial index, ξ. The device ($m = C$ for SpaceCat and $m = B$ for SpaceBall) was changed after each set of 12 trials. Distance ($i = S$ for short distance and $i = L$ for long distance), Target Size ($j = s$ for small target and $j = b$ for big target), and the corresponding index of difficulty, $ID = 2(i - 1) + (j - 1)$, are systematically varied as a function of ξ. Each Subset box, k, contains all 4 indexes of difficulty. To facilitate comprehension of the figure, the first subset of each set of 12 trials has been marked gray.

$$i = i(n, \xi \bmod IJK) \quad (5.1)$$

$$j = j(n, \xi \bmod IJK) \quad (5.2),$$

that is, the Distance and Target Size are functions of participant and trial. The combination of i and j is repeated after each set of IJK = 12 trials.

$$m = 1 + (\xi \text{ div } IJK + (n-1) \bmod M) \bmod M \quad (5.3),$$

that is, the input device is changed after each combination of Distance and Target Size have been repeated K = 3 times, that is, after IJK = 12 trials. Every second participant starts with SpaceCat, and the rest start with SpaceBall for a counter balanced design to avoid systematic influence caused by learning or fatigue.

$$k = 1 + (\xi \text{ div } IJ) \bmod K \quad (5.4),$$

that is, each subset consists of four trials, each with a different combination of Distance and Target Size. Accordingly, the subsets are systematically varied blocks of 4 trials including all IJ = 4 indexes of difficulty. With 8 participants, each permutation of Distance and Target Size occurs exactly once in a balanced experiment design since $(IJ)! = NK = 24$, that is, there were 24 different subsets of which each of the 8 participants used three in the three repetitions.

The different target sizes and distances make possible a simple test of Fitts' Law with the four corresponding indexes of difficulty ID. The four levels of task difficulty are (a) short distance combined with big target, (b) long distance combined with big target, (c) short distance combined with small target, and (d) long distance combined with small target.

Target and cursor. The target and cursor were each displayed as three rigidly connected boxes arranged in an L-form with the relative positions $(0\ 0\ 0)^T$, $(8.5d\ 0\ 0)^T$, and $(0\ 4d\ 7.5d)^T$, where d is the length unit in 3D Studio MAX. The last box was colored differently to make recognition of the structure easier (cf. Figure 5). The target and cursor boxes had the diagonals $(s_i\ 2s_i\ 2s_i)^T$and $(2s_i\ s_i\ s_i)^T$, respectively, in the same coordinate system as used for the relative box positions. The goal of the docking is to symmetrically attach every cursor box to the respective target box. The task was completed as soon as each cursor box was completely contained in a box with the diagonal $(3s_i\ 2s_i\ 2s_i)^T$, positioned symmetrically around each target box, i.e. the end deviation translation was less than $\frac{s_i}{2}$. s_i took one of the values $s_{i=b} = \frac{d}{2}$ for a big target or $s_{i=s} = \frac{d}{4}$ for a small target.

Camera. The camera through which the participants observed the scene had a 45° angle of view, was positioned at $(0d\ {-240d}\ 65d)^T$and was directed toward the origin. Three point light sources were positioned at $(250d\ {-250d}\ 0d)^T$, $(-250d\ {-250d}\ 0d)^T$, and $(0d\ {-250d}\ 100d)^T$with the light strength set to 0.5 in 3D Studio MAX units.

Geometrical setup of the trials. Similar to Target Size i and Distance j the start and target positions were dependent on the participant and the trial number. This meant that the whole geometrical setup of $i, j, \breve{S}, \breve{Q}, \hat{S}$, and $\hat{Q}$ was repeated after each set of IJK = 12 trials, thereby allowing the assessment of learning under

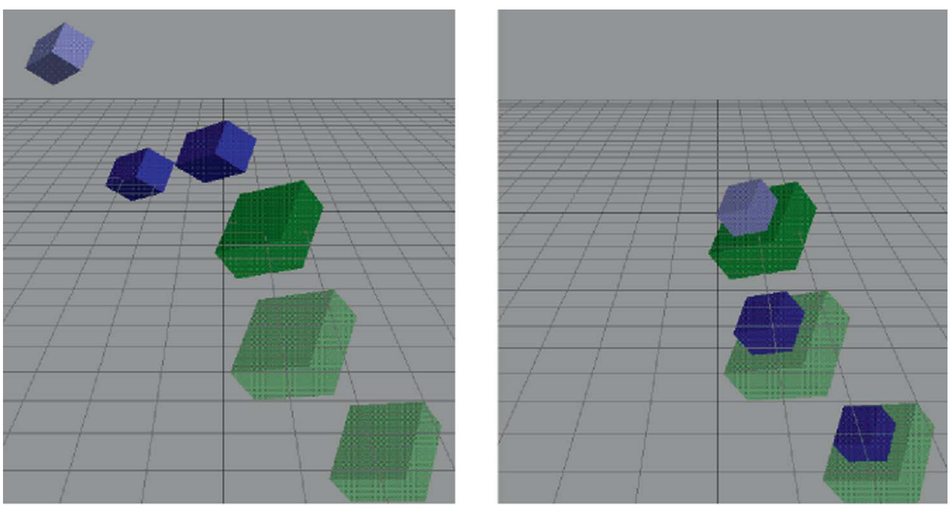


FIGURE 5 In the picture on the left, the cursor (upper-left) and the target (lower-right) have their initial positions for one specific trial: start in upper-left back position and end in lower-right front position. In the right picture the cursor has been moved into the target. The cursor and target each consist of three rigidly connected boxes arranged in an L-shape.

identical conditions. To simplify the expressions below, the dependence of the participant has been omitted, and the variable $\eta = \xi \bmod 12$ has been introduced.

The relative difference between the start and target position and orientations was given for translations by $\Delta\breve{S}_\eta$ and for rotations by

$$\Delta\breve{Q}_\eta = (\cos\Delta\breve{\theta}_\eta/2 \quad \breve{e}_\eta^{\mathrm{T}} \sin\Delta\breve{\theta}_\eta/2)^{\mathrm{T}} \qquad (6),$$

where $\breve{e}$ takes one of the eight possible values $\breve{e}_\eta = \frac{1}{\sqrt{3}}(\pm 1 \ \pm 1 \ \pm 1)^{\mathrm{T}}$.

The start position and orientation were $\breve{S}_\eta = -\Delta\breve{S}_\eta/2$ and $\breve{Q}_\eta = 1/\sqrt{\Delta\breve{Q}_\eta}$, that is, start and target are symmetrically positioned around the origin. Short distance is given by $\Delta\breve{S}_{j=S} = 2.5d$ and $\Delta\breve{\theta}_{j=S} = \frac{\pi}{4}$. Long distance is given by $\Delta\breve{S}_{j=L} = 5d$ and $\Delta\breve{\theta}_{j=L} = \frac{\pi}{2}$. For the rotations, $\Delta\breve{\theta}_\eta$ takes one of the two values of $\Delta\breve{\theta}_j$. For the translations, all possible distances are described by

$$\Delta\breve{S}_\eta = (\pm\Delta\breve{S}_j \pm \Delta\breve{S}_j \pm \Delta\breve{S}_j)^{\mathrm{T}} \qquad (7),$$

that is, for short and long distance, respectively, eight positions are possible.

With the start and end positions and orientations either positively or negatively located symmetrically around the origin, there is a set of $2^H = 2^6 = 64$ combinations. The question was how to select the combinations to be used in the trials.

Because we were not interested in measuring the influence of the start and end positions, one could have argued that only 1 of the 64 possible combinations should have been used. However, if a participant had performed the same movement over and over again we would have measured the participant's ability to learn to solve the particular task and train one particular movement. Our goal was to measure how participants are able to solve different positioning tasks like they would in a production environment with a digital content creation tool. Moreover, performing about 100 trials with the same start and end position would be very tedious for the participant. Furthermore we wanted to avoid having any particularly difficult geometrical setups disproportionately affect the experiment. Therefore we chose to randomly select setups from the possible combinations. It turned out that with some of the $2^{HJ} = 128$ combinations of distance and end position, the docking was difficult because of occlusion. Hence, 24 combinations that were problematic for short distance and 20 for long distance were excluded from the experiment.

A computer program was written to provide a balanced distribution of all possible combinations among the subjects. No start position was reused until all other start positions had been used once. Furthermore, similar start positions were not allowed to follow after each other to avoid that a participant would get used to one specific movement. The randomly generated geometrical setups were combined with the permutations of Distance and Target Size in a counterbalanced design, where each permutation occurred only once in a subset because $(IJ)! = NK = 24$. Thus, the variance of the geometrical setups is contained in the subset variable, k. It is noted that although the geometrical setups have been randomly generated, subset k is not a random factor in a statistical model, because most (i.e. 84 of 96) geometrical setups occur only once in Ph3 (over all participants).

Procedure. The 8 participants were asked to move the cursor as quickly as possible from the start to the target position. The completion time was measured and presented to the participant together with the best time achieved under the currently used trial parameters, m and η, to encourage improved performance with trials having the same conditions. To assure that all test participants had the same level of knowledge before the experiment, they received the following written information:

- Twelve docking tasks are repeated over and over again by using alternatively SpaceBall or SpaceCat.
- Your task is to dock the cursor with the target as quickly as possible in an effort to achieve new records with every trial.
- No attention should be paid to the fact the SpaceCat is an ETH-development created by your test leader.

Before each trial started, the participants were allowed to look at the scene and plan the movement. It is known that assessing the orientation of virtual objects projected on a computer screen poses a certain difficulty (Shepard & Metzler, 1971). To help the participants understand the movement to be performed, an animation of the cursor moving to the target was shown before every trial. The cursor path of the animation was given by

$$\begin{aligned} S_\eta(t) &= \breve{S}_\eta + t\Delta S \\ Q_\eta(t) &= \Delta Q^t \breve{Q}_\eta \end{aligned} \qquad (8),$$

where $t \in [0, 1]$ is approximately the time in seconds.

The trial was started by the participant touching the input device. No time limit was imposed on the participants for the start. The hit of the target (i.e., the end of each trial) was marked with a sound. A different sound was used to indicate when a new record had been achieved. As we saw in the earlier discussion of transfer functions, we did not expect the performance to depend significantly on the gains used. Therefore the gains were kept fixed. The small significance of the gains was confirmed by the qualitative results.

3.2. Quantitative Results

From the movement path trajectories Γ the dependent variables *completion time*, *Fitts' Law parameters* and *half-way time* were calculated as follows from the following analysis. As we are interested in completion time as a function of combinations of Distance and Target Size, we combined Distance and Target Size into the new factor Task Difficulty having four levels. To get an overview of the experimental data we plotted completion times $\widehat{T}_{nk}$ for SpaceCat and SpaceBall versus task difficulty in a box plot, i.e. $\widehat{T}_{nkSb}$, $\widehat{T}_{nkLb}$, $\widehat{T}_{nkSs}$, and $\widehat{T}_{nkLs}$ (Figure 6). Thus, each box represents NK = 24 samples, that is, including all 8 participants and all three subsets for a combination of Device and Task Difficulty.

Analysis of variance (ANOVA) of completion time. To test our hypothesis and subhypotheses we set up a mixed model with up to the second order of interaction including Device, Task Difficulty, and Subject (random factor; cf. ANOVA Model 3 in Appendix B. The model has been collapsed over the Musician and Geometrical Setup factors, which is allowable as shown in Appendix B with ANOVA Models 1 and 2. For Device, $F(1, 7) = 38.4$, MSE = 12.6, $p < .0005$; Task Difficulty, $F(3, 21) = 25.3$, MSE = 4.08, $p < .001$; and the interaction between them, $F(3, 149) = 7.28$, MSE = 0.88, $p < .0005$, all effects were highly significant. Thus, considering the effect sizes from our four ANOVA analyses, we can conclude that the factors, Device and Task Difficulty, accounted for the main part of the variance in our experiment, whereas Musician and Subset did not account for any major effects.

To verify the validity of ANOVA Model 3 with a residual analysis (cf. Figure 7) we set up a new version of the ANOVA model identical to ANOVA Model 3 but with the error term omitted. Based on this version, Figure 7 shows that the F test provides a proper basis for the evaluation.

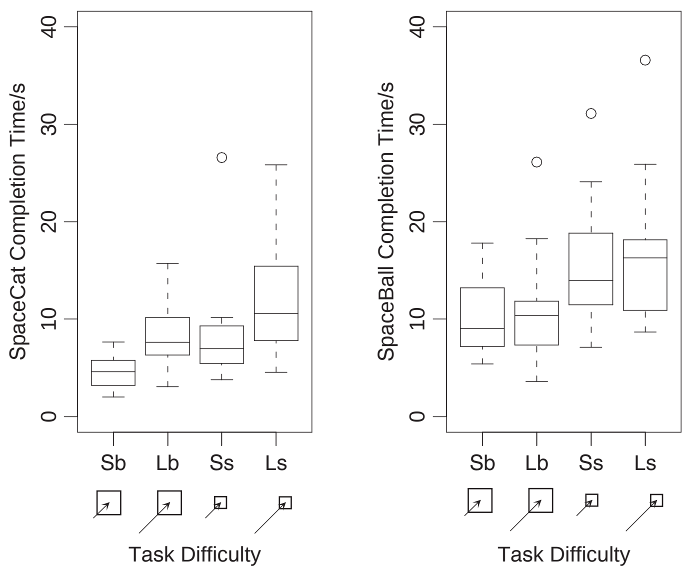


FIGURE 6 Box plots of SpaceCat (left) and SpaceBall (right) of completion time vs. task difficulty. *Note.* The four levels of task difficulty are (a) short distance combined with big target (*Sb*), (b) long distance combined with big target (*Lb*), (c) short distance combined with small target (*Ss*), and (d) long distance combined with small target (*Ls*).

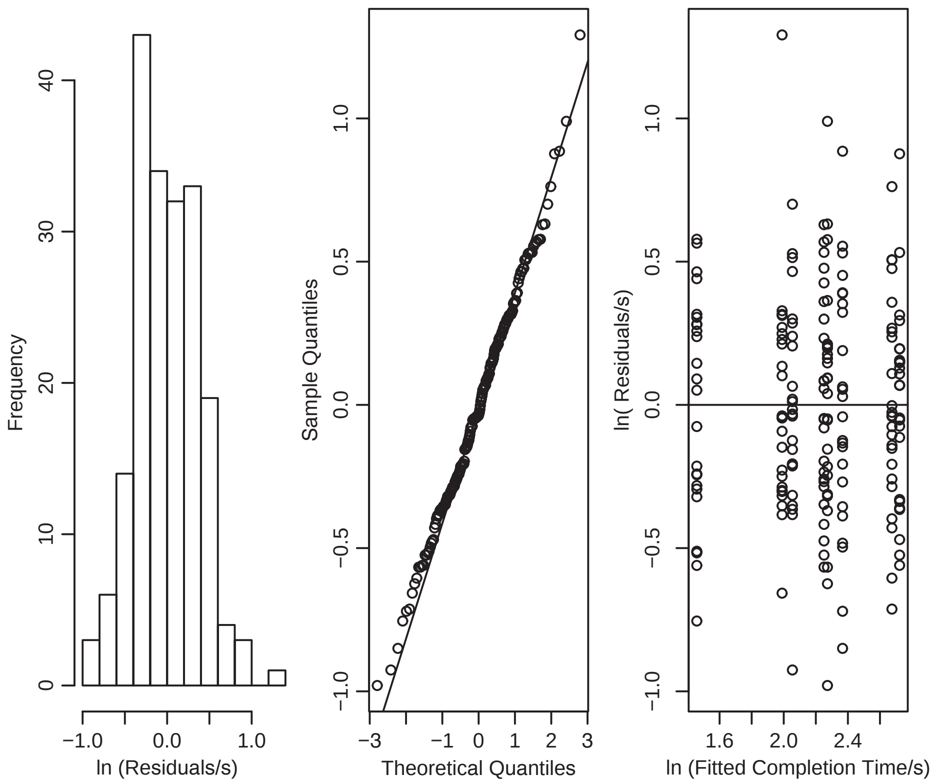


FIGURE 7 ANOVA model verification.

The interactions between Device and Task Difficulty can be explained from Figure 6. We note that for SpaceCat, completion time seems to depend on both distance and target size, as predicted by Fitts' Law (Figure 6, left). This is not the case for SpaceBall, where completion time depends more on target size than distance (Figure 6, right). Having one device that complies with Fitts' Law and one that does not explains the observed interaction between device and task difficulty.

The interaction between Device and Task Difficulty means that there is a lack of additivity for these factors. Hence, our linear model (i.e., ANOVA model) is not applicable for comparing task completion times. Thus, we have to slice our model and compare cell means for each level of Task Difficulty. If the main effects of Device and Task Difficulty were not masked by the interaction we could have continued with post-ANOVA procedures, comparing marginal means in pairs in a single ANOVA model. The disadvantage of comparing cell means from a split model instead of marginal means from a single model is that we operate with less information in each separate analysis. In our case, each analysis contributes only one quarter of the total information since we have four levels of Task Difficulty. To take the split into account, all p values in Figure 8 have been adjusted by a Bonferroni factor of four. Splitting the analysis into four parts and then comparing the differences in completion times is possible, because both participant and

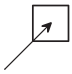
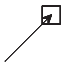
	Task Difficulty *ij*	λ_{ij}	$t(\hat{T}_{nmkij}, \hat{T}_{nmkij})$ $df = 23$	$V(\hat{T}_{nmkij}, \hat{T}_{nmkij})$
	short distance with big target completion time (*Sb*)	0.51	$t(\hat{T}_{nCkSb}, \hat{T}_{nBkSb}) = -6.4$ ($p < 0.001$)	$V(\hat{T}_{nCkSb}, \hat{T}_{nBkSb}) = 1$ ($p < 0.001$)
	long distance with big target completion time (*Lb*)	0.89	$t(\hat{T}_{nCkLb}, \hat{T}_{nBkLb}) = -2.4$ ($p = 0.012$)	$V(\hat{T}_{nCkLb}, \hat{T}_{nBkLb}) = 70$ ($p = 0.011$)
	short distance with small target completion time (*Ss*)	0.57	$t(\hat{T}_{nCkSs}, \hat{T}_{nBkSs}) = -5.3$ ($p < 0.001$)	$V(\hat{T}_{nCkSs}, \hat{T}_{nBkSs}) = 13$ ($p < 0.001$)
	long distance with small target completion time (*Ls*)	0.78	$t(\hat{T}_{nCkLs}, \hat{T}_{nBkLs}) = -2.9$ ($p = 0.0044$)	$V(\hat{T}_{nCkLs}, \hat{T}_{nBkLs}) = 48$ ($p = 0.0013$)

FIGURE 8 Task difficulty *ij* average *quotient* between SpaceCat and SpaceBall λ_{ij}, paired one-tailed *t* test $t(\hat{T}_{nmkij}, \hat{T}_{nmkij})$, and paired one-tailed Wilcoxon signed rank test $V(\hat{T}_{nmkij}, \hat{T}_{nmkij})$. *Note.* Both tests are based on the *difference* in completion time between the devices. All *p* values were adjusted by a Bonferroni correction of a factor of four because of the four tests performed.

differences between SpaceBall and SpaceCat completion times are independent variables. Thus, we obtain four paired tests with SpaceCat and SpaceBall at each level of task difficulty. An advantage, thereby, is that we can use Wilcoxon tests, for which we need not assume that completion time differences are normally distributed.

SpaceCat vs. SpaceBall completion time. Because of the interaction in the ANOVA model we had to split the model into four simplified models, one for each task difficulty, to compare SpaceCat and SpaceBall completion times. Because each participant performed the same $IJK = 12$ trials with each device there is a one-to-one correspondence between the completion times of the two input devices. Thus we can use paired tests with each $NK = 24$ samples for comparing corresponding trials of SpaceCat and SpaceBall. The *t* test can be used when assuming normal distribution of the completion time. Wilcoxon signed rank test can be used when assuming a symmetric distribution of the completion time. As seen in Figure 9 at least the condition of symmetry is given for all levels of difficulty, except for Short Distance combined with Big Target. Because we hypothesized that the softly elastic SpaceCat with position control yields a shorter completion time than the stiffly elastic SpaceBall with rate control we can use one tailed tests. The average *quotients* λ_{ij}, paired one-tailed *t* tests, and paired one-tailed Wilcoxon singed rank tests are presented in Figure 8. The average quotient between SpaceCat and SpaceBall completion times is

$$\lambda_{ji} = \frac{1}{NK} \sum_{nk} \frac{\hat{T}_{nCkji}}{\hat{T}_{nBkji}} \qquad (9).$$

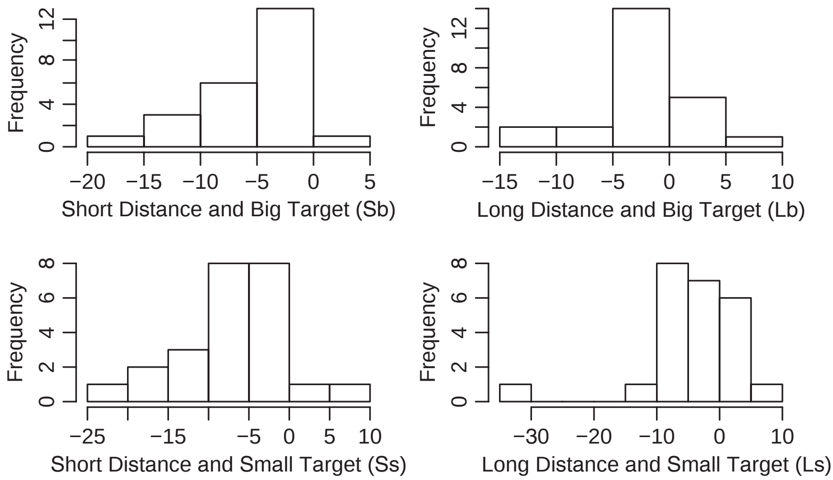


FIGURE 9 Histograms for the four levels of difficulty. (SpaceCat Completion Time - SpaceBall Completion Time)/s is on the x-axis of each histogram.

According to Figure 8 all completion time differences between SpaceCat and SpaceBall are significant, whereby SpaceCat has its greatest advantage over SpaceBall when dealing with short distances or small targets. Difficulty levels involving short distances are highly significant and completion times for SpaceCat are on average less than 60% of SpaceBall completion times. This difference between the input devices is in accordance with our hypothesis. For short distances, the range of device motion of SpaceCat corresponds to the range of desired virtual motion for the task, which allows for a fast completion time because no clutching is necessary. This is also true for the two categories involving small targets where there is a greater need for precise manipulation. The smallest difference between the devices and lowest significance with the Wilcoxon test (p_B = 0.011) was obtained for the combination long distance with big target. Therefore, both subhypotheses have been confirmed.

The small size of our study was enough to achieve significant results. This is also true when considering that we had to slice our model and compare cell means for each level of Task Difficulty, thereby losing factor of four because of the Bonferroni correction. We conclude that the effects we hypothesized are large, and that they can be reliably studied with a small number of participants.

3D Fitts' Law Parameters. The usability test was designed to make a Fitts' law verification for the input devices possible to give a deeper theoretical understanding of the experiment. It is plainly seen in Figure 6 that SpaceBall could not be a Fitts' Law compliant input device in the performed task. The categories, Long Distance with Big Target (Lb) and Short Distance with Small Target (Ss), have the same difficulty index according to Fitts' law, but have very different

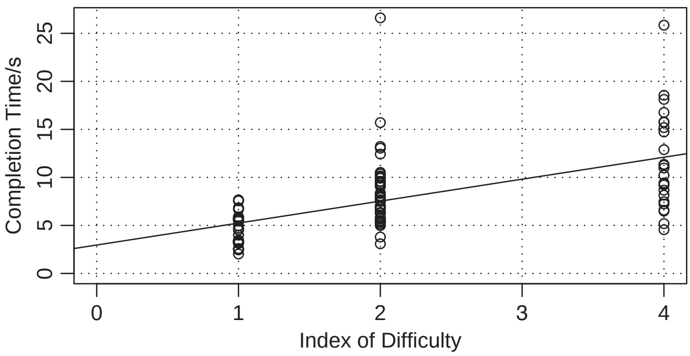


FIGURE 10 SpaceCat performance index.

completion times for SpaceBall.[10] Therefore, further analysis using Fitts' Law was carried out only for SpaceCat.

In Figure 10, all completion times with SpaceCat are fitted to Fitts' Law. The performance index is $1/b = 0.43$. This index is determined mainly by the performance of the participants to target the right depth, which was by far the most difficult DOF. The difficulty to target the depth is also the reason for the large variance in completion time as seen in Figure 10 at each index of difficulty. To gain a deeper understanding of the performance in each separate DOF, an analysis of the half-way time was performed.

Half-way time. The completion time does not reveal in which order the different degrees of freedom approach the target. To get knowledge on how specific degrees of freedom relate to the completion time, $\widehat{T}$, a new performance measure for each degree of freedom called *half-way time* b_h ($h \in [1, 6]$) was introduced:

$$\min_{b_h} \int_{\breve{T}}^{\widehat{T}} (\Gamma_h(t) - \breve{\Gamma}_h(t))^2 \, dt \qquad (10),$$

where

$$\breve{\Gamma}_h(t) = \Gamma(\breve{T})_h \, e^{-\ln 2t/b_h} \qquad (11),$$

that is, the actual paths Γ_h are compared with the path $\breve{\Gamma}_h$, which would have occurred if humans would embody a first order control system according to the control law:

[10]The difference is significant ($p < .001$) according to a unpaired two-sided Wilcoxon test $W(\widehat{T}_{nBkLb}, \widehat{T}_{nBkSs}) = 127$. This is not the case for SpaceCat with $W(\widehat{T}_{nCkLb}, \widehat{T}_{nCkSs}) = 335$ ($p = .34$).

$$\frac{d}{dt}\breve{\Gamma}_h(t) = -\frac{\ln 2}{b_h}\breve{\Gamma}_h(t) \qquad (12),$$

b_h is the same regression parameter as the performance index b in Fitts' law (cf. Equation 1) when neglecting the time lag, a. This is easily seen when reformulating Fitts' law as

$$\frac{W}{2} = Ae^{-\frac{\ln 2(T-a)}{b}} \qquad (13).$$

When setting $a = 0$, according to an idealized Fitts' law without any time lag, Equations 11 and 13 become identical and the half-way time corresponds to the inverse of the Fitts' performance index. This similarity between Equations 11 and 13 indicates that the human control performance is similar to the performance of a first order control system (cf. Langolf et al., 1976).

To compare half-way times for any index of difficulty, they were normalized to the completion time according to

$$\beta_{nmkjih} = b_{nmkjih} / \widehat{T}_{nmkjih} \qquad (14).$$

In Figure 11, each box corresponds to β_{nkij} for the different degrees of freedom and the different input devices. As expected, the depth (i.e., movements along the y-axis or the direction perpendicular to the surface of the computer screen) is much more difficult to control than the other degrees of freedom for both SpaceCat and SpaceBall. This means that the calculated Fitts' Law 6 DOF performance index is, to a great extent, a performance index on controlling depth. Note the similarities between SpaceCat and SpaceBall in Figure 11.

Examples of trajectories. To gain further understanding of how specific degrees of freedom perform, we examine two sample trajectories from participant number 5 from the same task given for SpaceCat and SpaceBall in the last set of trials (Figures 12 and 13). The four graphs correspond to translations (left two graphs) and rotations, (right two graphs) as well as positions (upper two graphs) and velocities (lower two graphs). Generally, the collected trajectories have little in common with those of a first order control system (cf. Equation 11). Rather, the trajectories appear to be characterized by submovements as defined by Jagacinski (1989).[11] A good example of this is given in Figure 12 for the translation and in Figure 13 for the rotation. These trajectories consist of two submovements. The first fast movement is a typical open-loop movement followed by a second regulated,

[11]According to Jagacinski (1989), movement towards a target in a positioning task consists of an initial, open-loop movement followed by closed-loop movements. This movement microstructure is not deterministic, but rather, consists of a series of sub-movements, i.e. irregular periods of acceleration and deceleration. Jagacinski showed that in most cases for both position and rate control, only 2 sub-movements are needed to reach the target, even if Fitts' index of difficulty is large. However, in some cases as many as five sub-movements were observed.

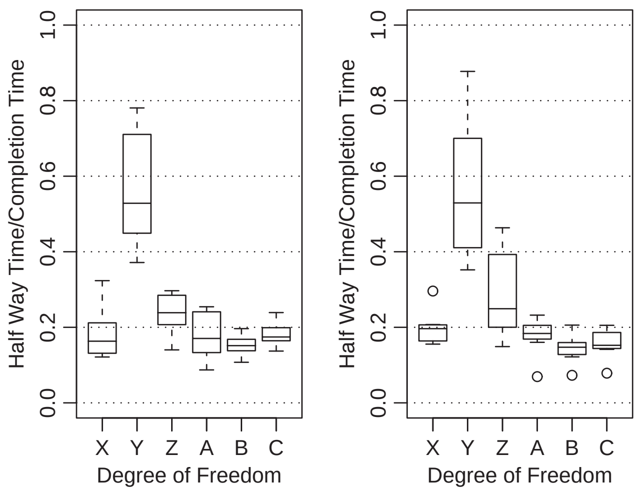


FIGURE 11 Half-way Time for SpaceCat (left) and SpaceBall (right). *Note*. Translations along the x, y, and z-axes are denoted with X, Y, and Z. Rotations around the x, y, and z-axes are denoted with A, B, and C.

closed-loop submovement for the fine positioning. The SpaceCat submovements are separated by a clutching time of 0.25 sec, whereas the SpaceBall submovements are more difficult to identify. The maximum velocity for translations is much higher for the SpaceCat open-loop submovement. This supports the idea that it is possible to develop a faster work pace with a position control device rather than a rate control device because of fast, open-loop movements.

In Figure 13, we see one example demonstrating the difficulty to control the depth. The participant begins with a movement in the wrong direction. In this case, the half-way time is obviously much worse for the ΔS_y trajectory than for the other trajectories.

3.3. Qualitative Results

Following is the qualitative analysis aimed at surveying subjective statements on the gains, spring forces, clutching, and fatigue in the tests.

Sensitivity. In general, the participants accepted the preinstalled parameters, although we noticed a desire for a higher gain on SpaceCat and a lower gain on SpaceBall.

- For SpaceCat orientation, 6 participants desired higher control gain. For translation, 3 wanted higher gain and 1 wanted lower gain.
- For SpaceBall, 3 participants wanted lower gain, whereas only 1 wanted higher gain.

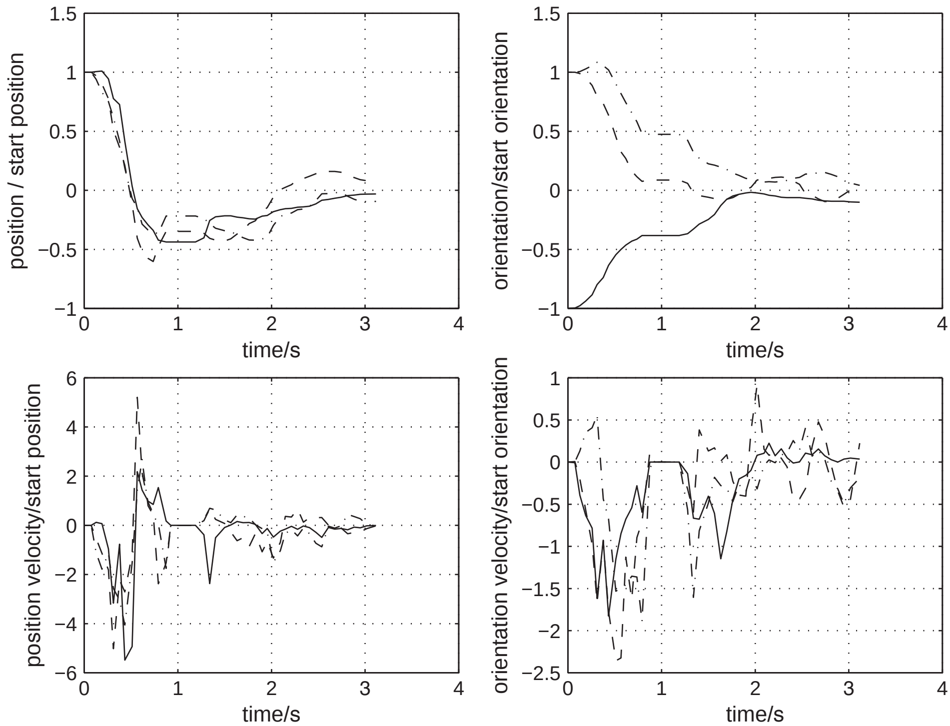


FIGURE 12 Sample SpaceCat trajectory. *Note.* ΔS_x and ΔQ_x is marked with a solid line, whereas the y and z movements are respectively marked with dashes and dash-dots. These trajectories clearly consist of two sub-movements (cf. footnote 11). The first sub-movement ends with a clutch action after approximately 1 sec and is considerably faster than the second one, indicating open-loop behavior. The second sub-movement is a typical, slow precision movement assumed to be controlled in a closed-loop.

Judging from the desired gain changes, it seems most likely that the preinstalled gain settings for both SpaceCat and SpaceBall were near the flat gain optimum according to the section on Transfer Function.

Qualitative Subject Statements. Five of the participants preferred SpaceCat and 1 preferred SpaceBall for this specific docking task. One preferred SpaceCat for translations and SpaceBall for rotations and 1 was undecided. The participants preferring SpaceCat especially valued better precision and better feedback. Some participants remarked that their preference was only valid for the specific task because the need for position and rate control depends on the task. Five of the participants recognized the clutching as SpaceCat's major weakness. It led to unwanted manipulations and was cumbersome when performing long-distance translations and rotations. Indeed, the long-distance moves required three times as much clutching as the short-distance moves, despite the fact that

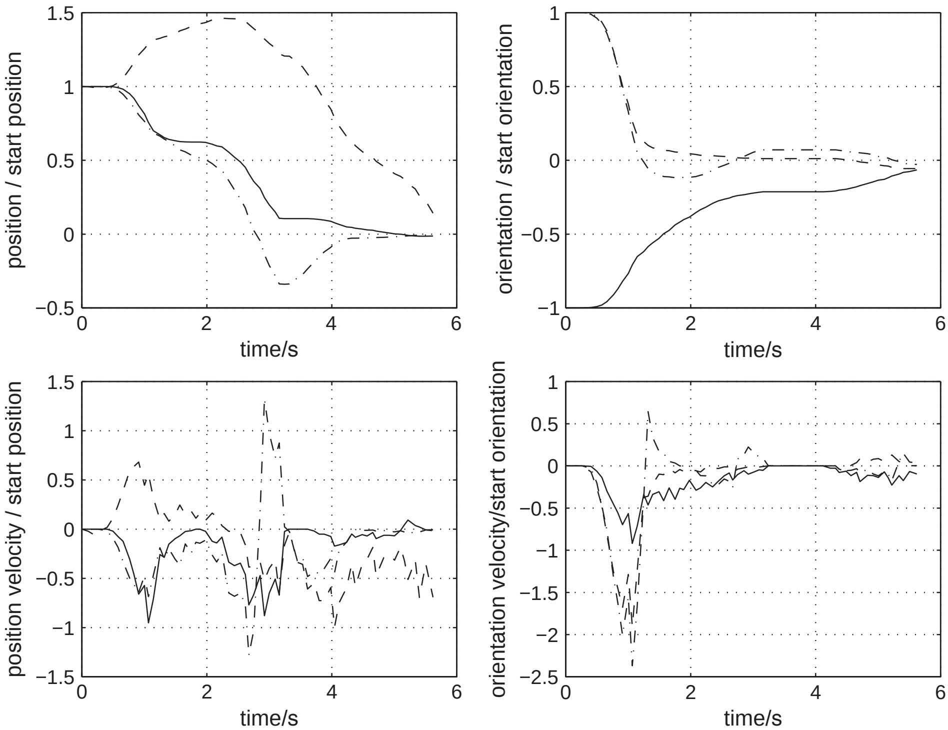


FIGURE 13 Sample SpaceBall trajectory. *Note.* ΔS_x and ΔQ_x are marked with solid lines whereas the y and z movements are respectively marked with dashes and dash-dots. As in Figure 12, this trajectory clearly consists of two submovements. The second submovement starting after approximately 2 sec corrects a move in the wrong direction along the y-axis. This difficulty in the y-axis, that is, the direction perpendicular to the screen surface is typical and reflects the results from section 3.2.

the distance was only doubled. Such unwanted manipulations can also be seen in the trajectories. Possible solutions are better filters and transfer functions as well as the possibility to switch between position and rate control. There were no complaints of muscular fatigue, probably because of the experiment's short duration and the frequent changes between the two input devices. Two of the participants gripped the base of the input device with their nondominant hand. This was true for both SpaceCat and SpaceBall. Two participants stated that the spring forces of SpaceCat were too weak and 2 participants found them just right.

3.4. Summary of Experimental Results

To test our hypothesis, a docking experiment requiring precise manipulation was performed. According to the results, softly elastic position control is better than stiffly elastic rate control in terms of completion time. The devices have greater differences in the completion times for high docking precision and short movements.

Thus, the usability test supports both sub-hypotheses. Furthermore, for the solved tasks SpaceCat complied with Fitts' Law whereas SpaceBall did not. For SpaceBall, completion time depends more on target size than distance, implying that it is better for long distances and worse for precise targeting. We believe that the results justify further research and development of 6 DOF softly elastic input devices.

The main obstacle when performing long distance movements in position control with SpaceCat are the clutch actions. This was confirmed by the measurements of the clutching actions from the study of trajectories and by interviews with test participants. As expected, the most difficult parameter to control was the depth translation, that is, the translation in the viewing direction. The performance pattern in the different degrees of freedom was very similar for both kinds of input devices.

Because position and rate control have their respective advantages an optimal 6 DOF input device should be able to utilize both. SpaceCat's softly elastic suspension creates an advantage for achieving this compared to SpaceBall's stiffly elastic suspension. We expect SpaceCat to work well in both position and rate control due to its greater range of device motion and softer suspension.

4. DISCUSSION AND FUTURE RESEARCH

This section discusses possible improvements to the experiment design. A key issue in this respect has turned out to be the lack of depth cues in the current design. Furthermore, ideas for future experiments are presented. In particular we present cases of usage for digital content creation tools, which are especially believed to benefit from a softly elastic 6 DOF input device. Verifying the usability within these cases will have the highest priority in our upcoming research.

4.1. Potential Improvements of the Performed Experiment

The experimental setup generally worked as intended. In the quantitative test, 1 participant subject had one trial that required a movement to a certain end position and orientation that was more difficult than the others and therefore should have been removed from the list of acceptable end positions. However, the geometrical setup with different end positions and orientations did not account for any significant impact of the experiment.

One question arising from the test is whether it is appropriate to perform a 6 DOF docking task using only a two-dimensional projection of the virtual scene. Other experiments have used stereoscopic glasses to enhance depth perception. However, there is research which has shown that stereoscopic projection only improves 3D perception marginally (Geisler, 1994). A better improvement could be expected by using a viewpoint dependent display to create viewpoint parallax shifts. Further improvements could incorporate shadow parallax or semitransparent objects.

A pragmatic solution would be to simply freeze the depth and allow for only 5 DOF manipulations if there were not enough depth cues present. It would then be necessary to change the viewpoint once to adjust all 6 DOF. Similarly, it has turned out to be useful to freeze one DOF for navigation tasks. When navigating in architectural models, for instance, it might be of advantage to always have the horizon viewed horizontally allowing only five degrees of freedom (cf. Zhai et al., 1999).

So far we only noticed the similarities between the devices in Figure 11. In a further step, a null hypothesis could be formulated and tested.

4.2. Future Basic Experiments

With the presented work we are able to supplement Figure 3 with the previously missing Experiment 6 (Figure 3). In its present form Figure 3 only includes positioning tasks. In future experiments, it could be of interest to extend Figure 3 from two to three dimensions by including also other task categories in a third table dimension. Thereby we consider navigation as the most interesting task, which could be tested in path following or pursuit tracking experiments. Also for other tasks than positioning, we assume that the feasible combinations of device stiffness and control order will be the same. With this assumption we can extend our types of preferred usage to include also device stiffness. Accordingly we conjecture the following two amended types of preferred usage:

- Positioning, manipulation, and docking using isotonic or softly elastic position control and the object-in-hand metaphor.
- Navigation using softly or stiffly elastic rate control and the camera-in-hand metaphor.

The presented experiment only concerned positioning. In a future experiment it would be interesting to compare softly and stiffly elastic rate control for navigation. Such an experiment would give further clues on the usability of a universal softly elastic multidimensional input device versus specialized input devices for positioning and navigation respectively. Further experiments on softly elastic input need to address the question which spring stiffness should be chosen to optimally support both positioning and navigation. Further issues to address in future research include learning and simultaneity of the involved DOF for different device stiffness and tasks.

4.3. Controlling 2D Applications with 6 DOF Input Devices

Using a multidimensional input device for interaction with 2D applications allows for the potential to use the extra degrees of freedom to speed up interaction. For example, translations could be used to move the cursor, whereas rotations could be used for scrolling through a document in two directions. Furthermore, a zoom function could be connected with one degree of freedom.

The clutch could be used for activation, that is, the role of the left mouse button. This could be implemented in a similar way to what is now used with track pads. A quick touch corresponds to a mouse click and a quick touch followed by a movement of the cursor corresponds to a drag and drop.

The use of an elastic 6 DOF input device for 2D selection introduces two main problems to the transfer function. First, it must be possible to accurately achieve all positions on a large high-resolution screen without clutching. Second, the freely suspended handle does not dampen any tremors. The conventional mouse has a very efficient mechanical tremor filter by means of friction between table and mouse while the arm and hand rest on the table surface. Possible solutions to these problems include nonlinear transfer functions, rate-aided position control, and force feedback simulating friction.

The physical design of the input device is also extremely important. With better support for the hand and fingers than in the tested version of SpaceCat, tremors could be significantly reduced. Possible improvements also involve the tuning of spring constants and range of device motion.

4.4. SpaceCat for Digital Content Creation Tools

From this experiment, it can be assumed that SpaceCat is beneficial to both position and rate control in up to 6 DOF. Next, we present some cases of usage where these properties may benefit interaction in digital content creation tools.

Position control with the dominant hand: for tasks requiring precise control within a small range of virtual motion.

Motion capture: for example, animation of a puppet's body part. The suitable degrees of freedom depend on the body part. For example, the head requires three rotations whereas the hands or feet need interaction in five or six degrees of freedom. The hips can probably be connected to all 6 DOF since the body parts connected to hips give sufficient depth cues.

Fine positioning of objects or light sources: which can take place in 5 or 6 DOFs depending on whether sufficient depth cues are present.

Modeling: manipulation of a control mesh for NURBS or surface splines, e.g. extruding faces in 5 or 6 DOFs, or 3D manipulation of vertices or edges.

Rate control with the dominant hand: for motion capture of camera paths and light animations.

Rate control with the nondominant hand: for low precision navigation: This is how 6 DOF input devices are used in CAD today. For animation software, it could be used similarly, i.e. navigating the scene.

Position control with the nondominant hand: for adjusting the view port while an object is being manipulated. This might allow for faster work than rate control with the nondominant hand, as used in CAD today. The actual manipulation could be done with the mouse like in today's CAD or even with a second SpaceCat.

In some cases a combination of position and rate control for different degrees of freedom could be advantageous:

Rate control for translations and position control for rotations: in architecture or gaming applications. It would give a "flying helicopter metaphor" using rate control to regulate the speed of the helicopter but turning the viewpoint (the head of the pilot) with position control. For the translations, rate control would be needed for movements over long distances. For rotations, there is basically never a need for a large range of virtual motion since any rotation can be achieved with 180° or less.

Rate control for controlling the depth or "forwards direction" and position control for all other DOF: for a first-person shooting game like Forsaken or an endoscope simulator. In Forsaken, the player follow narrow passages and needs to control his speed along the passage but at the same time wants to target enemies through quick and precisely controlled sideways translations, or rotations.

When using different transfer function for different DOFs, such as in these two cases, one could also consider adapting the physical properties (cf. Equation 2) according to the transfer function. Hence, in line with our theory, one would use stiffer device properties for the DOFs using rate control than those using position control. It is noted that the use of force feedback could enable any combination of physical properties with any DOF and block unused DOFs. Adapted to different cases of usage this may be a future research strand.

A universal input device poses the problem of making it transparent to the user which mode the device is in, e.g. position or rate control. Additional complexity is added because different applications provide different sets of functionality. Support may be offered through haptic (e.g., simple mechanical switches or advanced switches with force feedback) or visual means (e.g., LEDs or displays) on the device itself. A potential improvement on simply providing visual support on the device would be to visualize mode information on the computer screen, which could be accomplished by altering the mouse cursor. The keyboard could be used to switch between the modes or to decide which virtual object to connect to the input device.

Finally, we note that direct input is common in all tasks discussed thus far. However, there are applications where no such direct metaphor exists and moreover, may not be desired (cf. Bowers, 1998). For example, multidimensional input can be used to control sounds or colors. In a digital content creation tool, the 6 DOF of the input device could be connected to virtual sliders, which could be coupled to any object parameter, more or less in the fashion of direct manipulation. The less direct control, the more randomness is introduced into the movements.

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APPENDIX A MATHEMATICAL BACKGROUND OF PATH DESCRIPTION

A Euclidian motion from p to q can be written in matrix vector notation as:

$$\begin{aligned} &E : R^3 \to R^3 \\ &p \mapsto q \\ &p = Rq + S \end{aligned} \quad \text{(A1)},$$

where R is a 3×3 rotation matrix and $S = (S_x \ S_y \ S_z)^{\mathrm{T}}$ is the translation vector (Hoschek and Lasser, 1992). Instead of a rotation matrix, the orientation can be described by a normalized Hamiltonian quaternion (Pletinck, 1989):

$$Q = (Q_t \quad Q_x \quad Q_y \quad Q_z)^{\mathrm{T}} = (\cos\theta / 2 \quad \overline{e}^{\mathrm{T}} \sin\theta / 2)^{\mathrm{T}} \quad \text{(A2)},$$

where $\overline{e}$ is the normalized rotation vector and θ is the rotation angle.

Let $S(t)$ and $Q(t)$ denote the position and orientation of the controlled object at time t and $\breve{T}$ denote start time. The position and orientation of the docking task are defined as $\breve{S}$ and $\breve{Q}(\breve{e},\breve{\theta})$ at the start $\widehat{S}$ and $\breve{Q}(\breve{e},\breve{\theta})$ at the target (or end), which is reached from the start position and orientation within a certain tolerance at time $\breve{T}$. The difference between the current position and orientation and the target at time t is thus:

$$\begin{aligned} &\Delta S(t) = S(t) - \widehat{S} \\ &\Delta Q(t) = Q(t)\widehat{Q}^{-1} \\ &\Delta \overline{e}(t) = \overline{e}(t) - \widehat{e} \\ &\Delta\theta(t) = \theta(t) - \widehat{\theta} \end{aligned} \quad \text{(A3)}.$$

The difference in the target position and orientation at the start position and orientation is accordingly denoted by $\Delta\breve{S} = \Delta S(\breve{T}), \Delta\breve{Q} = \Delta Q(\breve{T}), \Delta\breve{e} = \Delta\overline{e}(\breve{T})$, and $\Delta\breve{\theta} = \Delta\theta(\breve{T})$. If we make the restriction, $\Delta\breve{\theta} \in [-\pi/2 \quad \pi/2]$, we can define a simple, numerically stable, and unambiguous measure for the distance to the target in position and orientation of the controlled object as follows:

$$\Gamma = (|\Delta S_x| \quad |\Delta S_y| \quad |\Delta S_z| \quad |\Delta Q_x| \quad |\Delta Q_y| \quad |\Delta Q_z|)^T \qquad \text{(A4).}$$

To measure the over-all performance of the docking task, the completion time, $\hat{T} - \breve{T}$, is used. To simplify the notation the start time is set to zero, $\breve{T} \equiv 0$, and the completion time becomes equal to $\hat{T}$.

APPENDIX B COLLAPSING ANOVA MODEL FACTORS

B.1 Collapsing the ANOVA Model Across the Musician Factor

To collapse the ANOVA Model across the Musician factor we have to find out if there is any difference in completion time between musicians and nonmusicians, whereby we can confirm or reject our assumption that there is no effect and there are no interactions. So, having both fixed and random factors, we set up a mixed model where ln(Completion Time / s) is a function of the fixed factors: Device, Subset, Task Difficulty, Musician, and the random factor, Subject (cf. ANOVA Model 1). Our approach with Device as a fixed factor allows us not only to compare SpaceCat and SpaceBall completion times, but also to check whether SpaceCat and SpaceBall respectively comply with Fitts' Law for the given task. Musician is a control variable taking the value, 1, for participants 2, 3, 5 and 8, corresponding to those subjects who play a string instrument, and the value, 0, for the others. ANOVA Model 1 included interactions up to the second order.

Performing an ANOVA analysis with this model on the $\hat{T}_{nmkij}$ data set, showed that Device, Task Difficulty, and the interaction between them were all highly significant. Musician, $F(1, 6) = 0.0018$, MSE = 0.0011, $p = .97$, and subset index, $F(2,12) = 0.99$, MSE = 0.20, $p = .40$, were not significant. Hence, we conclude that the coincidence of four participants being amateur musicians did not create any net effect or interactions with any significant influence on the experiment. Thus, we were able to collapse our model across that factor.

ANOVA Model 1: log(Time) ~ (device+task_difficulty+subset+musician)^2 +
Error(subj+subj:device+subj:task_difficulty+subj:subset+subj:musician)

Error: subj

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
musician	1	0.0011	0.0011	0.0018	0.9676
Residuals	6	3.8224	0.6371		

Error: subj:device

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
device	1	12.6540	12.6540	36.5062	0.0009298 ***
device:musician	1	0.2293	0.2293	0.6615	0.4470985
Residuals	6	2.0797	0.3466		

Error: subj:task_difficulty

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
task_difficulty	3	12.2367	4.0789	21.7654	3.25e–06 ***
task_difficulty:musician	3	0.0099	0.0033	0.0177	0.9967
Residuals	18	3.3733	0.1874		

Error: subj:subset

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
subset	2	0.39483	0.19741	0.9876	0.4008
subset:musician	2	0.20913	0.10457	0.5231	0.6056
Residuals	12	2.39881	0.19990		

Error: Within

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
device:task_difficulty	3	2.6327	0.8776	7.5395	0.0001119 ***
device:subset	2	0.0390	0.0195	0.1675	0.8459625
task_difficulty:subset	6	0.3613	0.0602	0.5173	0.7943484
Residuals	125	14.5497	0.1164		

Signif. codes: ‘ *** ’ 0.001 ‘ ** ’ 0.01 ‘ * ’ 0.05 ‘ . ’ 0.1 ‘ ’ 1

B.2 Collapsing the ANOVA Model Across the Factor Geometrical Setup

To collapse the ANOVA Model across the Geometrical Setup factor we have to find out if there is any difference in completion time between the different geometrical setups. Since the geometrical setup varied in the repetitions, we can assume that the variance caused by the geometrical setup is contained in the subset factor. Thus, we assume that the subset factor does not yield any net effect or significant interactions. In order to test this, a second model was set up without the Musician factor (cf. ANOVA Model 2). Device, Task Difficulty, and the interaction between them were all highly significant. Because Subset, $F(2, 14) = 1.06$, MSE = 0.20, $p = .37$, did not yield any main effect or significant interactions, we concluded that the geometrical setup did not, as expected, have any significant influence on the experiment. Accordingly, we collapsed our model over the Subset factor. Thus we arrive at ANOVA Model

3 with the factors that we are actually interested in for testing our hypothesis and subhypotheses.

ANOVA Model 2: log(Time) ~ (device+task_difficulty+subset)^2 + Error(subj+subj:device+subj:task_difficulty+subj:subset)

Error: subj

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Residuals	7	3.8235	0.5462		

Error: subj:device

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
device	1	12.6540	12.6540	38.361	0.000448 ***
Residuals	7	2.3090	0.3299		

Error: subj:task_difficulty

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
task_difficulty	3	12.2367	4.0789	25.318	3.585e-07 ***
Residuals	21	3.3832	0.1611		

Error: subj:subset

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
subset	2	0.39483	0.19741	1.0598	0.3728
Residuals	14	2.60795	0.18628		

Error: Within

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
device:task_difficulty	3	2.6327	0.8776	7.5395	0.0001119 ***
device:subset	2	0.0390	0.0195	0.1675	0.8459625
task_difficulty:subset	6	0.3613	0.0602	0.5173	0.7943484
Residuals	125	14.5497	0.1164		

ANOVA Model 3: log(Time) ~ (device+task_difficulty)ˆ2+ Error(subj+subj:device+subj:task_difficulty)

Error: subj

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Residuals	7	3.8235	0.5462		

Error: subj:device

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
device	1	12.6540	12.6540	38.361	0.000448 ***
Residuals	7	2.3090	0.3299		

Error: subj:task_difficulty

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
task_difficulty	3	12.2367	4.0789	25.318	3.585e–07 ***
Residuals	21	3.3832	0.1611		

Error: Within

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
device:task_difficulty	3	2.6327	0.8776	7.2836	0.0001365 ***
Residuals	149	17.9527	0.1205		

Signif. codes: ‘ *** ’ 0.001 ‘ ** ’ 0.01 ‘ * ’ 0.05 ‘ . ’ 0.1 ‘ ’ 1