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Design of Control Elements in Virtual Reality - Investigation of Factors Influencing Operating Efficiency, User Experience and Presence

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ABSTRACT

Virtual reality (VR) makes it possible to test prototypes of devices in a simulation of the later usage environment. A weak point is the insufficient design of haptic feedback during the interaction with the prototypes. In this study, user tests are conducted to investigate how rotary controls and joysticks in VR must be designed and configured so that positioning tasks can be performed efficiently and generate a high user experience and presence. For this purpose, 25 subjects perform tasks in VR with the controls. According to the method of design of experiments, 14 factors, such as vibration feedback or sensitivity, are systematically varied. The control accuracy, the time on task as well as the user experience, presence and perceived workload are measured. The effect of a factor on the recorded parameters is examined by means of multi-factorial ANOVA (α = .05). Linear regression is used to calculate models between factors and parameters. For the rotary control, 10 factors and 4 interactions were identified that have a significant effect (p $\geq$ .05) on the measured parameters. For the joystick, 12 factors and 8 interactions were determined. With the mathematical models, optimized control device configurations for the VR could be calculated. The results show a high scatter. With a full-factorial test design, the results have to be verified.

Keywords: Human machine, Interface, Design of experiments, VR, UX

INTRODUCTION

In order to discover potential usage problems early in the development process, user tests are conducted on functional prototypes. The production of prototypes is expensive and time-consuming (Zhou et al., 2019). For this reason, companies are increasingly using virtual prototypes (Bullinger and Dangelmaier, 2003). Virtual reality (VR) technologies provide the opportunity to test the usability of virtual prototypes in a simulation of the intended use environment (Salwasser et al., 2019). Components of many prototypes include human-machine interfaces (HMI), such as touchscreens, rotary or rotary-push controls, joysticks, or variations of these. Studies and textbooks exist on the optimal dimensioning of these actuators and their haptic and acoustic feedback to achieve high control accuracy and user experience (UX) (Schmid et al., 2019; Reisinger, 2009; Schmidtke and Jastrzebska-Fraczek, 2013). However, the findings from these studies cannot be applied to virtual prototypes. Parameters such as the detent moment of rotary controls cannot be simulated in VR. Therefore, virtual prototypes are often examined in a mixed reality environment (Bolder et al., 2018). Here, virtual environments are mixed with real controls. Especially in very early development phases, fully virtual prototypes are advantageous. Different HMIs can be tested without needing to produce multiple prototypes. However, due to the reduced feedback, controls in VR cannot be operated as precisely as in reality. This leads to a reduction in control accuracy and control speed, which limits the evaluation of the usability and UX of virtual prototypes (Bruno et al., 2010; Stamer et al., 2020).

A major influence on the results of user tests in VR is the feeling of "being there" (presence) of the users (Busch et al., 2014). A low Presence results in a low UX. The user is aware that it is a simulation, which changes their behavior (Lorenz et al., 2018).

It follows that HMIs in VR must be adapted to the changed modalities, but the interactions must still be realistic enough to generate a high presence. Studies that investigate how HMI controls must be designed in VR in order to enable efficient operation with a high level of user experience and presence are not yet available.

This study investigates how rotary controls and joysticks must be designed in VR so that control tasks can be performed as quickly and precisely as possible. In addition, it will be investigated which control parameters have an effect on the UX, the presence and the perceived workload.

METHODS

Experimental Setup and Procedure

In user tests, subjects (n = 25) test the control of a joystick and a rotary control in VR. The head-mounted display "Valve Index" (Valve Corp., USA) is used to visualize the VR environment. Interaction with the control devices in VR is performed with the Valve Index controllers or with HTC Vive controllers (High Tech Computer Corp., Taiwan). The subjects (f: 10, m: 15, Age: 24 ± 3 years) perform four tasks per control in VR. There, the subjects see two screens. One screen shows a vertical bar graph with a scale from 0 to 100% for the operation of the joystick or a numerical value between 0 and 100% for the examination of the rotary control (see Fig. 1). On the other screen, the subjects see the tasks shown in Table 1.

Each subject tests both controls in randomized order. The time for processing the tasks (time on task) is measured. In addition, the position accuracy is determined by counting and summing up positioning errors. If, for example, the test person turns the rotary control in task 1 and reaches a value of 14 instead of 12, then turns back to 11 and then to the required value of 12, 3 errors are noted.

After completing the tasks, the subjects evaluate the control device and the user test in terms of perceived presence with the Slater-Usoh-Steed-Questionnaire (SUSQ) in a German adapted version (Wall et al. 2018). In addition, the user experience is surveyed with the User-Experience

Figure 1: Experimental setups in the VR. **Left**: VR environment crane cabin, joystick, visualization of hand, visual feedback. **Right**: VR environment table, rotary control with knob, inclination 45°.

Table 1. Tasks of the user tests.

Task	Rotary control	Joystick
1	*"Set the value from 0 to 12".*	*"Set the value from 0 to 42".*
2	*"Set the value from 12 to 11".*	*"Set the value from 42 to 41".*
3	*"Set the value from 11 to 31".*	*"Set the value from 41 to 8".*
4	*"Set the value of 31 to 10, then to 15, then to 8".*	*"Set the value of 8 to 98, then to 40, then to 50".*

Questionnaire (UEQ) (Laugwitz et al., 2008) and the perceived workload with the NASA RAW-TLX in the German short version (Hart, 1986).

Design of Experiments

In the method of design of experiments, several factors are varied simultaneously. The factors are varied according to a defined system (experimental design), so that the effect of a single factor can be statistically calculated. The factors and the examined levels are shown in Table 2. The maximum (+) and minimum (−) values are selected to have the largest possible difference within a realistic range.

The **inclination of the rotary control** describes the angle between the control device and the table (see Fig. 1. Right: inclination 45°). The **angular resolution** describes the sensitivity of the rotary control. With an angular resolution of 10 °/value, the rotary control must be turned by 10° so that the value displayed on the screen changes by one.

For the examination of the joystick, the **maximum deflection angle** is varied. I.e. the joystick can be deflected from the zero position (perpendicular to the table) e.g. by a maximum of 30° (level 0) to the front and to the back. The factor **max. positioning speed** describes the maximum possible rate of change in the respective maximum deflection. The factor **angular resolution** describes the relationship between the deflection angle and the change in the percentage value of the bar graph. In case of a linear (+) angular resolution, the change of the positioning value is proportional to the deflection angle. With a 3-stage (−) angular resolution, three angular ranges are defined

Table 2. Factors of the experimental design. After each experiment run, the levels (−, 0, +) of the factors are systematically varied.

	Factor	−	0	+
Rotary control	Angular resolution	10 °/Value	—	45 °/Value
	Diameter	40 mm	80 mm	110 mm
	Inclination control device	0 °	45 °	90 °
	Shape	Knurling	Knob	Cylinder
Joystick	Max. Angle of deflection	15 °	30 °	45 °
	Max. positioning speed	2,5 %/s	5 %/s	10 %/s
	Size (vertical / horizontal)	15 / 7 cm	24 / 11 cm	32 / 15 cm
	Angular resolution	3-Stage	5-stage	linear
	Visual feedback	Yes	—	No
	Shape	horizontal	—	vertical
Rotary control and joystick	Haptic feedback	Yes	—	No
	Acoustic feedback	Yes	—	No
	Hand visualization	Yes	—	No
	Position of the subject	Sitting	—	Standing
	VR environment	Table	—	Crane
	Input device used	HTC Vive	—	Valve Index

in which the change in positioning value is the same. A joystick with **vertical handle** (cf. Fig. 1. left) and a joystick with **horizontal handle**, similar to a thrust lever of airplanes, are tested. Either the test persons see only the bar graph (+) or an additional bar graph is displayed as **visual feedback** (−) of the current rate of change (cf. Fig. 1. left). For both control devices it is investigated whether **haptic** or **acoustic feedback** as well as the **visualization of the hand** have an effect on the evaluation parameters. If the subject activates for example the joystick, a hand grasping the joystick is visualized in VR. If there is no visualization, the subject only sees the joystick and its deflection. If a value is changed, the subject hears a click and/or feels a vibration of the controller.

The **Valve Index Controllers** (+) have integrated sensors to detect the hand and finger positions. This makes it possible to "grasp" the control devices similar to reality. For the **HTC Vive controllers** (−), interaction is done by bringing the controller close to the control device and pressing the "trigger button" on the back of the controller.

In order to determine the effect of a single factor on the evaluation parameters (time on task, positioning error, UX, presence, perceived workload), a response surface screening experimental design with 25 runs is created. The experimental design is created and randomized using Design Expert 13 software (Stat-Ease, Minneapolis, USA). The effect of a level change on the evaluation parameters is examined using multifactorial ANOVA ($\alpha = .05$). Linear regression is used to calculate a mathematical relationship between factor and evaluation parameter. These equations are presented in coded form. Thus, the numerical factor values are not used in the equations, but -1 for the lower level and +1 for the upper level. With this equations, the relative influence of a factor can be determined by comparing the factor coefficients. Equation 1 shows an example of a coded equation. The factor x_1 is calculated by subtracting the mean value of the evaluation parameter (Y) of all runs with the level (+) from the mean value of runs with the level (−) and then dividing by 2 (Siebertz et al., 2017). In this example, the factor x1 has a positive effect and x_2 a negative effect on the evaluation parameter Y.

$$Y = 10 + 2x_1 - 1.7x_2 \tag{1}$$

To verify the accuracy of the mathematical models, Cook's distance is used. Cook's distance indicates the change in the regression function when the values of an experimental run are not included. Large differences between Cook‘s distances are an indication of outliers. Cook‘s distances above a value of one are considered critical and can bias the model (Siebertz et al., 2017).

Subsequently, numerical optimization calculations are carried out with the mathematical models. Using the Design Expert software, it is calculated for each control device which factor values can be used to achieve a high level of control accuracy, UX and presence with a low level of time expenditure and perceived workload.

RESULTS

Rotary Control

At least one factor has a significant influence on the evaluation parameters *Time on Task* (ToT), *Accuracy (*Acc.), *Presence (*SUSQ) and on the dimensions *Perspicuity (*UEQ_P), *Efficiency* (UEQ_E) and *Novelty* (UEQ_N) of the User Experience Questionnaire. Four interactions of factors have a significant influence on the evaluation parameters.

Table 3 shows the comparison of the factors and evaluation parameters, including the significance values calculated using variance analysis. If no significance value is entered, this factor has no significant effect ($p \geq .05$) on the respective evaluation parameter.

Table 4 shows the mathematical models for the calculation of the evaluation parameters. In addition, the adjusted coefficient of determination ($R^2{}_{Adj}$) and the signal-to-noise ratio (SNR) are shown. Factors shown in italics have no significant influence on the respective evaluation parameter. They are in the model because an interaction with this factor has a significant influence on the evaluation parameter.

For the parameter UEQ_P, the critical Cook's distance is exceeded in one test run. All other calculated Cook's distances are below 0.5.

The calculated optimized design of the factors for the lowest possible positioning time and perceived workload, with high control accuracy, UX and presence is a rotary control with vibration feedback, without acoustic feedback, with visualization of a knurling, an angular resolution of 10-12 °/value, a 40 mm diameter and no inclination. Visualization of the hand should be omitted. The rotary control should be operated using the Vive controller.

Table 3. Factors with significant effect on the evaluation parameters in the study of the rotary control.

Factor	ToT	Acc	SUSQ	UEQ_P	UEQ_E	UEQ_N
A	<.001	.005	—	—	<.001	—
B	—	—	.035	.042	.043	—
C	<.001	—	—	<.001	—	—
D	—	—	—	—	—	—
E	—	—	—	—	—	.018
F	.001	—	—	—	—	—
G	<.001	—	.032	—	—	—
H	<.001	—	—	.043	—	—
J	.001	.049	—	—	—	—
K	—	—	—	.013	—	—
AB	—	.049	—	—	—	—
AK	.002	—	—	—	—	—
CH	—	—	—	—	—	.009
FJ	—	—	.008	.002	—	—

A: angular resolution; B: diameter; C: inclination; D: Haptic feedback E: Acoustic feedback; F: Visualization hand; G: Shape; H: Position subject; J: Input device; K: VR environment

Table 4. Mathematical models of the rotary control with coded factors.

Equation	R^2_{Adj}	SNR
$ToT = 7.7 + 3.6A + 1.7C - 1F + 2.1G_1 + 0.1G_2 - 1.4H + 1.1J + 0.4K + 1.2AK$	0.96	17.0
$Acc = 0.4 - 0.2A + 0.1B - 0.01D + 0.02E + 0.3F - 0.2AB + 0.3AD - 0.2EF$	0.49	6.1
$SUSQ = 4.3 - 0.7B + 0.4F - 0.5J - 0.7K - 0.9FJ$	0.47	5.7
$UEQ_P = 2.6 - 0.4B - 0.8C + 0.03F - 0.3H - 0.1J - 0.4K - 0.7FJ$	0.54	9.5
$UEQ_E = 1.2 - 0.6A - 0.3B$	0.47	8.2
$UEQ_N = 0.9 - 0.2C + 0.7E + 0.2H + 1.0CH$	0.25	6.9

A: angular resolution; **B**: diameter; **C**: inclination; **D**: Haptic feedback **E**: Acoustic feedback; **F**: Visualization hand; **G**: Shape; **H**: Position subject; **J**: Input device; **K**: VR environment

Joystick

Table 5 shows the comparison of the factors and evaluation parameters, including the significance values calculated using analysis of variance for the joystick tests. At least one factor has a significant influence on the evaluation parameters *Time on Task* (ToT), *Accuracy (*Acc.), *Presence (*SUSQ), *Perceived workload (*NASA Raw TLX) and on the dimensions *Attractiveness (*UEQ_A), *Perspicuity* (UEQ_P), *Efficiency (*UEQ_E*), Dependability* (UEQ_D), *Stimulation* (UEQ_S) and *Novelty* (UEQ_N) of the User Experience Questionnaire.

Table 5. Factors with significant effect on the evaluation parameters in the study of the joystick.

F	ToT	Acc	SUSQ	NASA TLX	UEQ A	UEQ P	UEQ E	UEQ D	UEQ S	UEQ N
A	<.001	.002	—	—	—	—	.037	—	—	—
B	—	.018	—	—	—	—	—	—	—	—
C	.003	.012	—	—	—	—	—	—	—	—
D	.008	—	—	—	.002	—	—	.009	.006	—
E	—	—	—	.018	—	.023	—	.002	—	—
F	.035	—	—	—	—	—	—	—	—	—
G	—	—	—	—	—	—	—	—	—	.002
H	—	—	—	—	.012	—	—	—	—	—
J	—	—	—	—	—	.029	—	—	—	—
K	—	—	—	.031	—	—	—	—	.007	.002
L	—	—	—	—	—	—	—	—	—	.002
M	—	—	—	—	.001	—	—	—	.007	—
DF	.019	—	—	—	—	—	—	—	—	—
DL	—	.037	—	—	—	—	—	—	—	—
JM	—	—	.007	—	—	—	—	—	—	—
HL	—	—	—	.001	—	—	—	—	—	—
AE	—	—	—	—	.001	—	—	—	—	—
AH	—	—	—	—	.003	—	—	—	—	—
BC	—	—	—	—	—	—	—	.016	—	—
AM	—	—	—	—	—	—	—	—	—	.03

A: Positioning speed; B: Deflection angle; C: Size; D: Position subject; E: Shape; F: VR environment; G: Angular resolution; H: Input device; J: Haptic feedback; K: Acoustic feedback; L: Visual feedback; M: Visualization hand.

Table 6 shows the mathematical models for the calculation of the evaluation parameters including the adjusted coefficient of determination (R^2Adj) and the signal-to-noise ratio (SNR) for the examination of the joystick.

The critical Cook's distance is not exceeded for any run. The calculated optimized factors for the joystick are haptic and acoustic feedback, no visual feedback, vertical grip with a height of 20-24 cm, a five-step angular resolution, a maximum deflection angle of ± 15°, a maximum positioning speed of 8 %/sec, and visualization of the hand.

DISCUSSION

Using the Design of Experiments method, it was possible to identify factors that have a significant influence on the control accuracy, time, presence, UX and perceived workload when operating control devices in VR. With the help of the optimization calculations, factor values were calculated with which a high positioning accuracy, presence, UX and a low positioning time and perceived workload can be achieved. However, the results show high scatter in some cases. These are mainly due to the different previous experiences of the test persons with VR systems.

Table 6. Mathematical models of the joystick with coded factors.

Equation	R^2_{Adj}	SNR
ToT = 12.3 − 4.8A + 1.0C1 − 2.4C2 + 1.1D − 1.0F − 1.0DF	0.87	17.2
Acc = 1.8 + 1.1A − 0.9B + 1.3C1 + 1.2C2 + *0. 6D* + *0. 4L* + 0.8DL	0.54	7.4
SUSQ = 4.1 − *0.1J* − 0.6K + *0.1M* + 0.7JM	0.27	5.9
NASA = 5.0 + 1.2E + 0.8F + *0.2H* − 1.0K + *0.8L* − 1.9HL	0.46	7.6
UEQ_A = 1.2 +*0.01A* − 0.4D + *0.07E* + 0.3H − 0.4M − 0.5AE + 0.4AH	0.62	9.4
UEQ_P = 2.2 − 0.5E + 0.5J	0.24	5.7
UEQ_E = 1.35 + 0.35A	0.14	3.4
UEQ_D= 1.6 +*0.2B* +*0.1C1* + *0.3C2* + 0.5D − 0.5E + $0.8BC_1$ − $0.8BC_2$	0.47	8.4
UEQ_S = 0.9 − 0.4D − 0.4K − 0.4M	0.50	9.2
UEQ_N= 1.1 − *0.1A* + 0.01G1 − 0.7G2 − 0.4K + 0.5L − *0.05M* + 0.3AM	0.58	9.5

A: Positioning speed; **B**: Deflection angle; **C**: Size; **D**: Position subject; **E**: Shape; **F**: VR environment; **G**: Angular resolution; **H**: Input device; **J**: Haptic feedback; **K**: Acoustic feedback; **L**: Visual feedback; **M**: Visualization hand.

A prerequisite for the application of Design of Experiments is that the factor levels can be changed independently of each other. For example, this makes it impossible to include optical hand tracking systems in the experimental design, since these do not allow haptic feedback. Changing the haptic feedback factor would therefore require the use of a different controller. A change in the level independent of other factors would not be possible.

The optimization calculation for the rotary control shows that a suitable angular resolution is 10-12 °/value. This value corresponds approximately to the lower level. 10 °/value was defined as the lower level because at a higher angular resolution, the acoustic and haptic feedbacks were no longer sufficiently perceptible when the rotary control was turned quickly. According to the optimization calculation, however, acoustic feedback can be dispensed with. In a subsequent experimental design, only the haptic feedback should be considered. Optimized modulation of the haptic feedback could change the lower level of angular resolution to 5 °/value. This will investigate whether an optimal angular resolution is actually 10-12 °/value.

Subjects took about 2 seconds longer to complete the tasks with the Index controller compared to the Vive controller (see Table 4: 1.1J *2). This is mainly due to re-gripping of the control device. With the Index controller, the hand must be opened and then the forearm rotated. With the Vive controller, only the index finger has to be released from the trigger button.

The factor max. positioning speed (A) has a negative effect on the positioning time and a positive effect on the positioning accuracy of the joystick. This means that an increase in the max. positioning speed leads to a reduction in the positioning time and to an increase in the number of positioning errors.

The 8 %/sec calculated by the optimization calculation is thus a compromise between positioning speed and positioning accuracy.

The factors acoustic feedback (K), haptic feedback (J) and visualization of the hand (M) have an effect on presence and UX. Overall, the subjects rated the joystick better when it had acoustic and haptic feedback and a hand enclosing the joystick was visualized.

A screening experimental design was used in this study. Screening experimental designs are used to identify factors that have a significant influence on the evaluation parameters. Thus, the mathematical models created and optimization calculations performed in this study provide only a rough orientation. In a follow-up study, detailed investigations will be carried out with the significant factors using a full factorial experimental design. The factors will be tested on several levels and with a significantly increased number of experiments in order to further increase the accuracy of the mathematical models.

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