Force Feedback in Virtual Assembly Scenarios: A Human Factors Evaluation

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DLR

Content

Motivation:
VE Training for Space Applications

Canadarm 2

Input Devices onboard the ISS

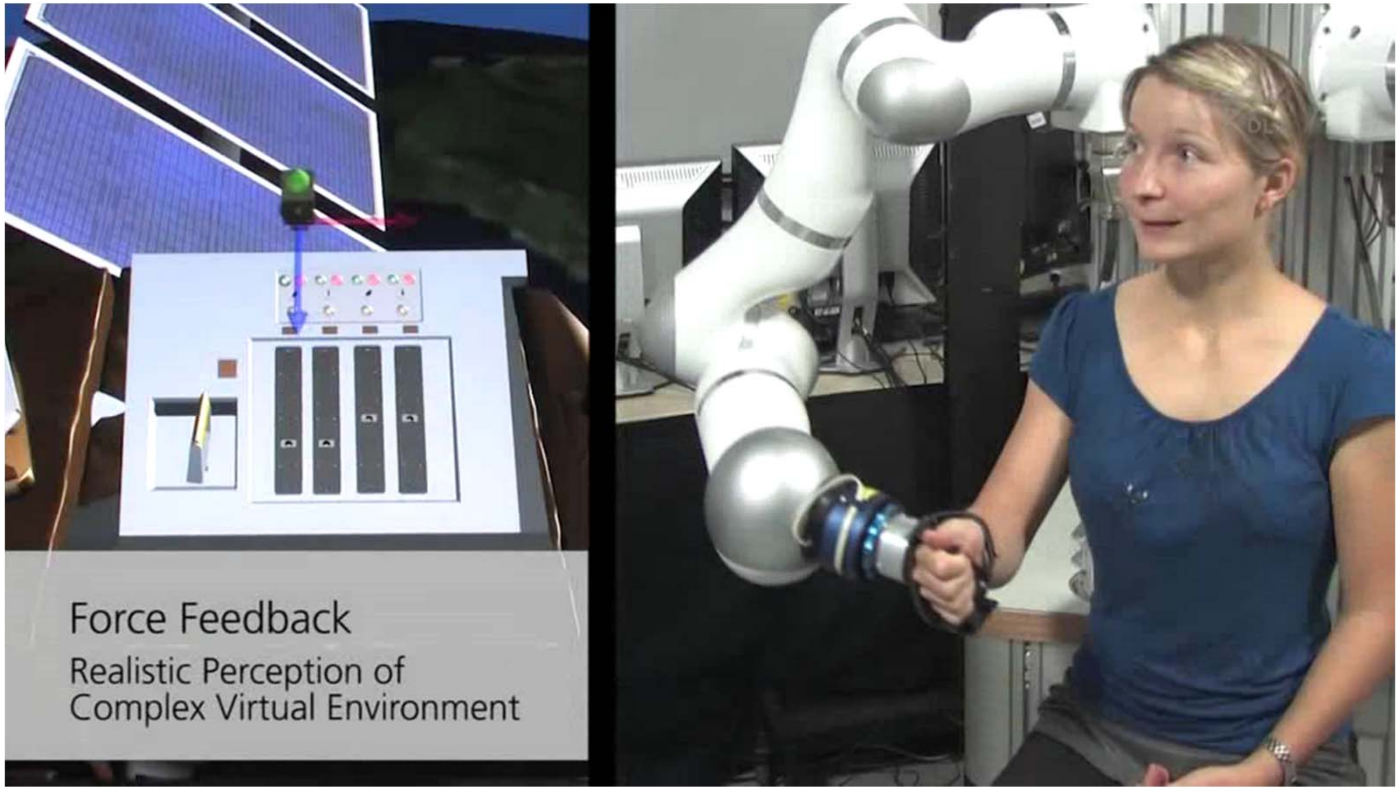
All pictures by courtesy of the Canadian Space Agency, CSA

VR Canadarm Training Simulator

Motivation:
VE Training for Space Applications

VR simulator for Extra-Vehicular Activities (EVAs)

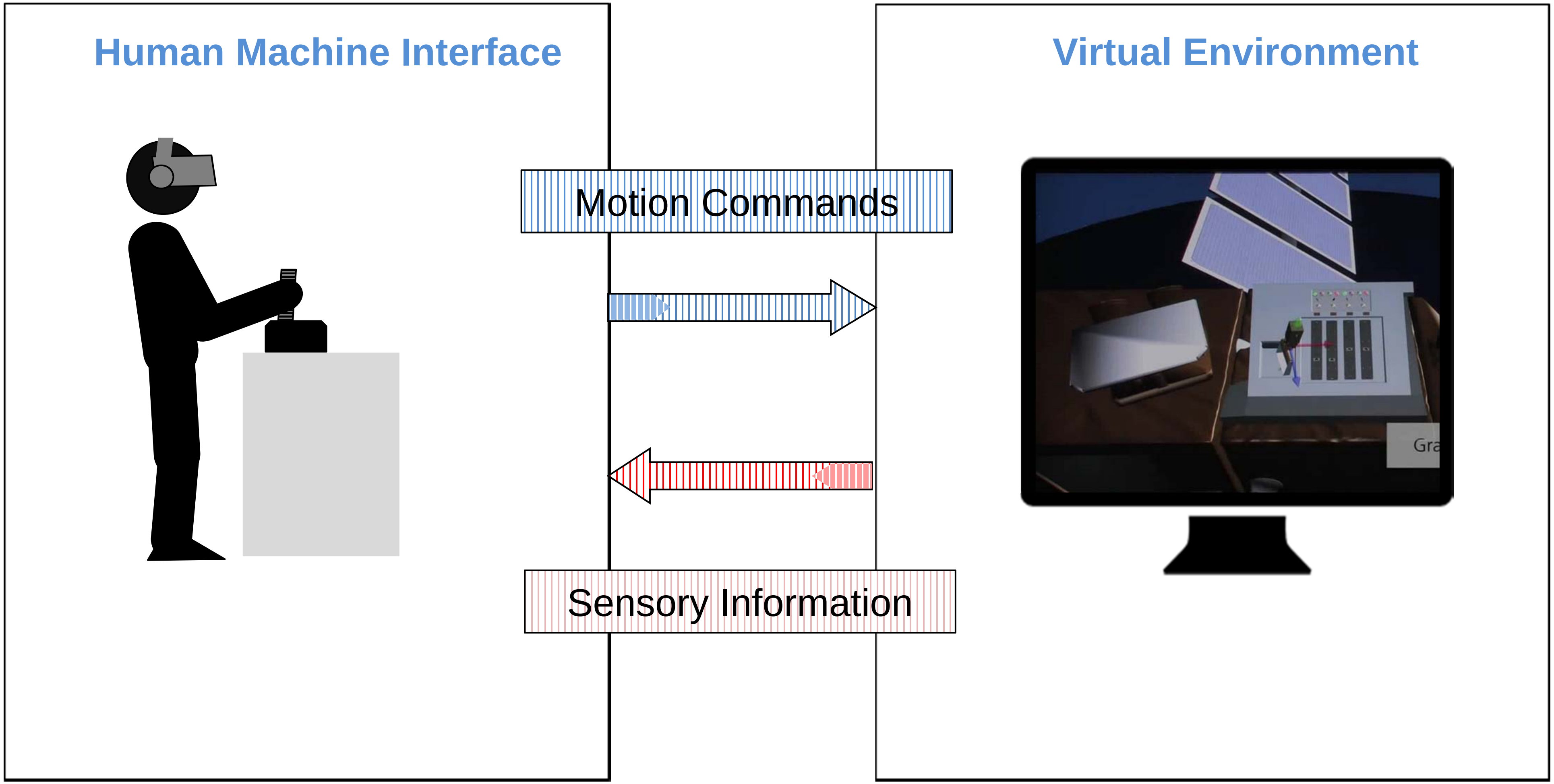
Motivation:
VE Training for Space Applications



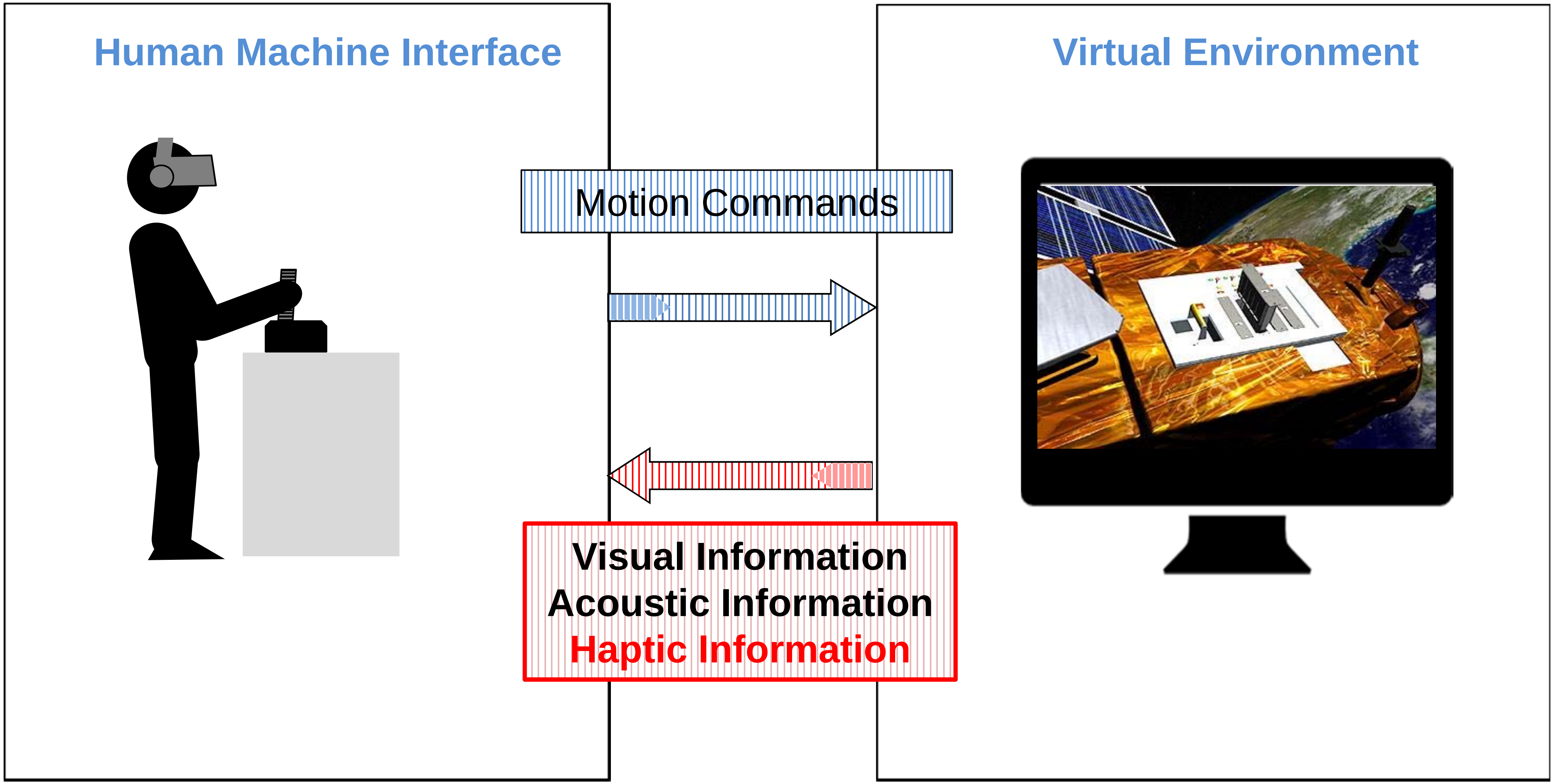
Sagardia et al. 2013

DLR‘s VE Training Simulator for On-Orbit Servicing (e.g. Repair, Maintenance)
Force Feedback is provided by DLR‘s „HUG“ Interface

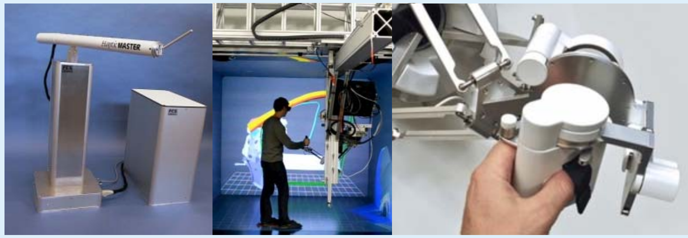
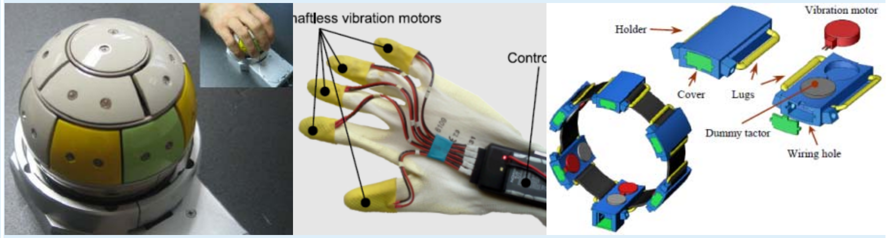
Human Performance in VE



Human Performance in VE: Haptic Feedback

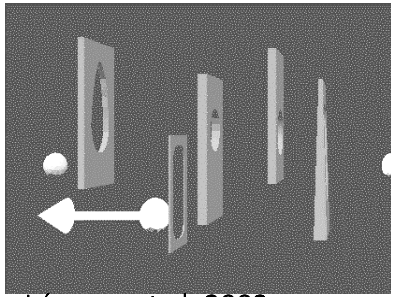


Force Feedback in Virtual Environments
Haptic Feedback

Force Feedback Systems	Vibrotactile Systems
	
Pros: - Multidimensional, kinesthetic feedback	Pros: - Low-cost alternative - Small, light-weight, larger workspaces
Cons: - Costly - Often bulky, heavy, restricted workspaces	Cons: - Substitution of kinesthetic with tactile information - Information density and complexity

Force Feedback in Virtual Environments
Visual Feedback

- Color changes (e.g. Cheng et al. 1996)
- Symbolic Arrows or bar graphs (e.g. Lécuyer et al. 2002)
- „Ghost“ Objects (e.g. Zachmann et al. 1999)



Lécuyer et al. 2002

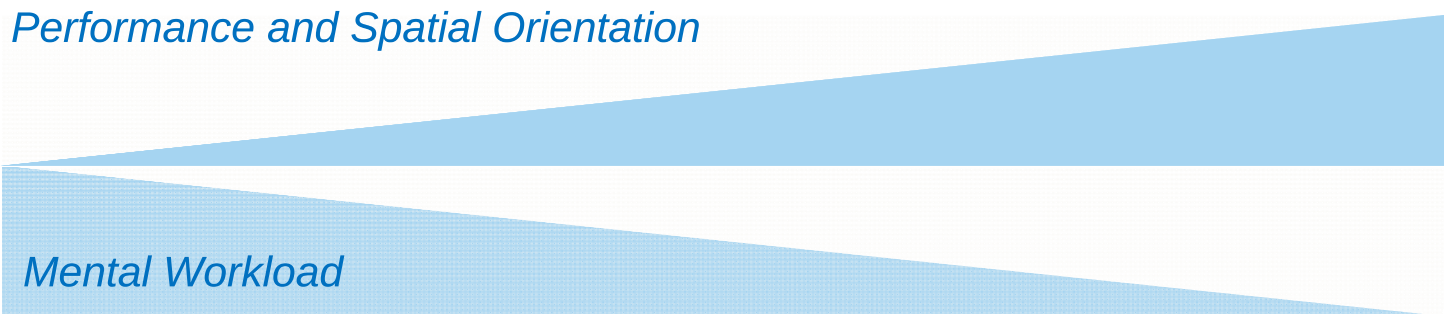
Pros:
- Low-cost alternative
- Unambiguous, directional information

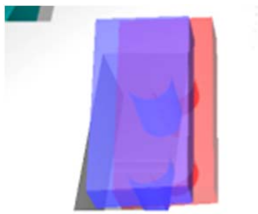
Cons:
- Sensory substitution
- Visual clutter
- Increased workload

Zachmann et al., 1999

A Virtual Assembly User Study

To what extent are **task performance, mental workload and spatial orientation** negatively affected when **substituting force feedback** with **vibrotactile** or **visual** feedback of collisions?

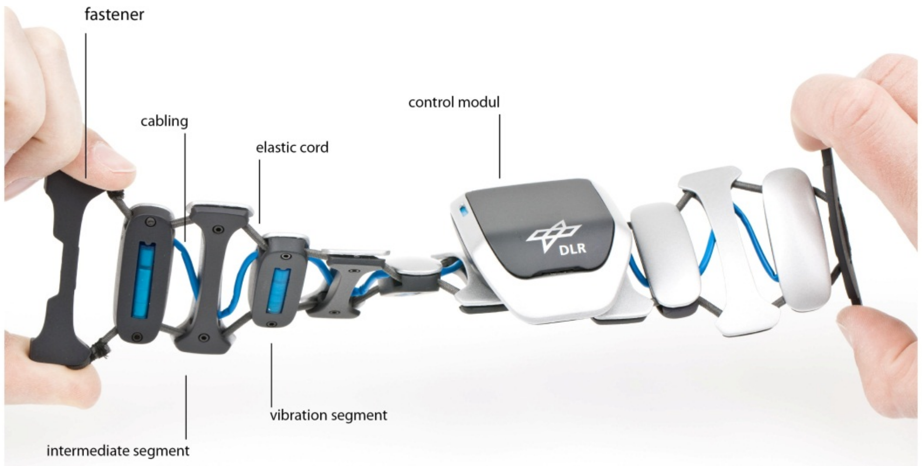




Apparatus: „HUG“

Specifications	
Dynamic mass	2 x 14 kg
Peak force	2 x 150N
Number of DoF	2 x 7 revolute joints
Sensors in each joint	two position sensors one torque sensor
Additional Sensors	2 x 6DoF FT-Sensor
Sampling rates	40 kHz current control 3 kHz joint internal 1 kHz Cartesian

Apparatus: VibroTac



DLR Innovationspreis 2012

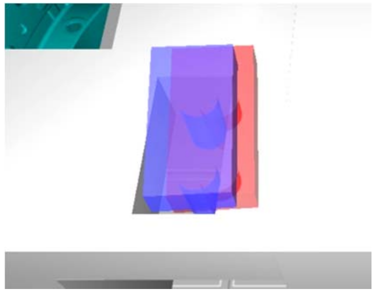
2012 INNOVATION WORLD CUP FINALIST
SENSODRIVE

M2M CHALLENGE 12/13
M2M Challenge Winner in the category Healthcare

Specifications	
Vibration Segments	6 DC vibration motors
Wireless Communication	XBee Interface
Vibration Frequency	up to 180 Hz

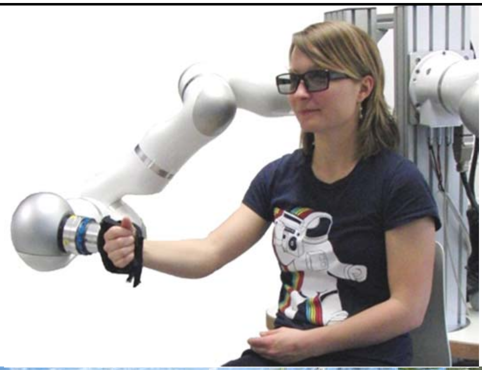
Experimental Conditions

1. Visual Feedback

2. Vibrotactile Feedback

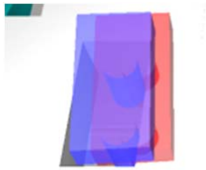
3. Force Feedback



Sample, Experimental Design, Procedure

Sample: N = 42 subjects (M_{Age} = 30.3 yrs.)

Within-subject design (random condition order):

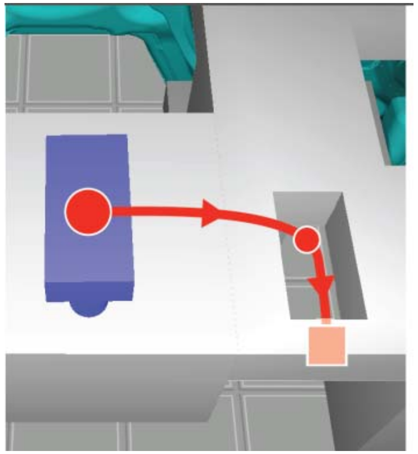


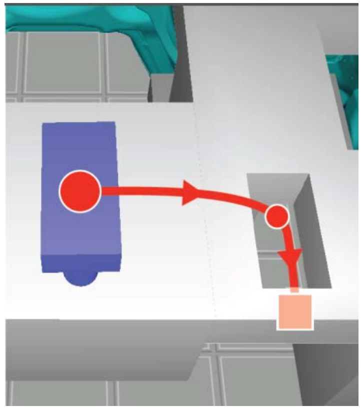
vs.

vs.

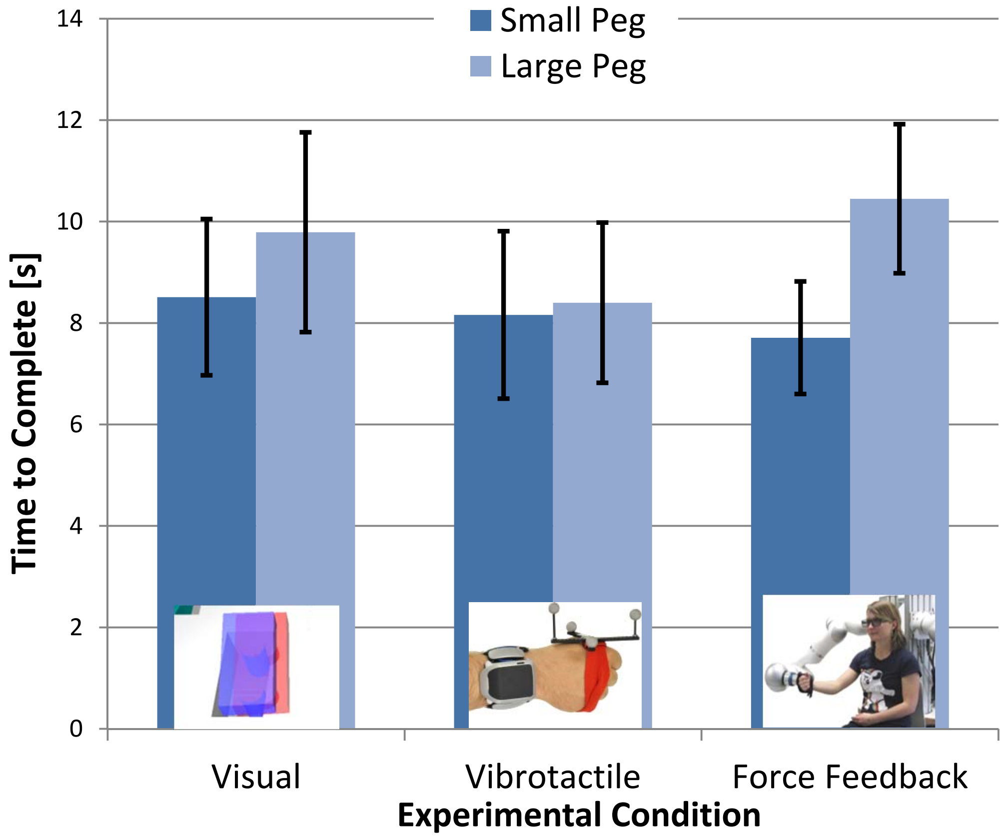
Procedure

- Instruction
- 3 Feedback Conditions
- Peg-in-hole: Small vs. large peg





Completion Time - Peg-in-hole



ANOVA

Feedback main effect:
$F\,(2, 39) = 1.0$; *ns.*

Difficulty main effect:
$F\,(1, 40) = 27.8$; $\boldsymbol{p < .001}$

Feedback x Difficulty interaction
$F\,(2, 39) = 8.5$; $\boldsymbol{p = .001}$

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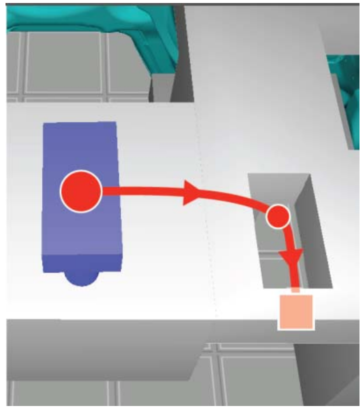
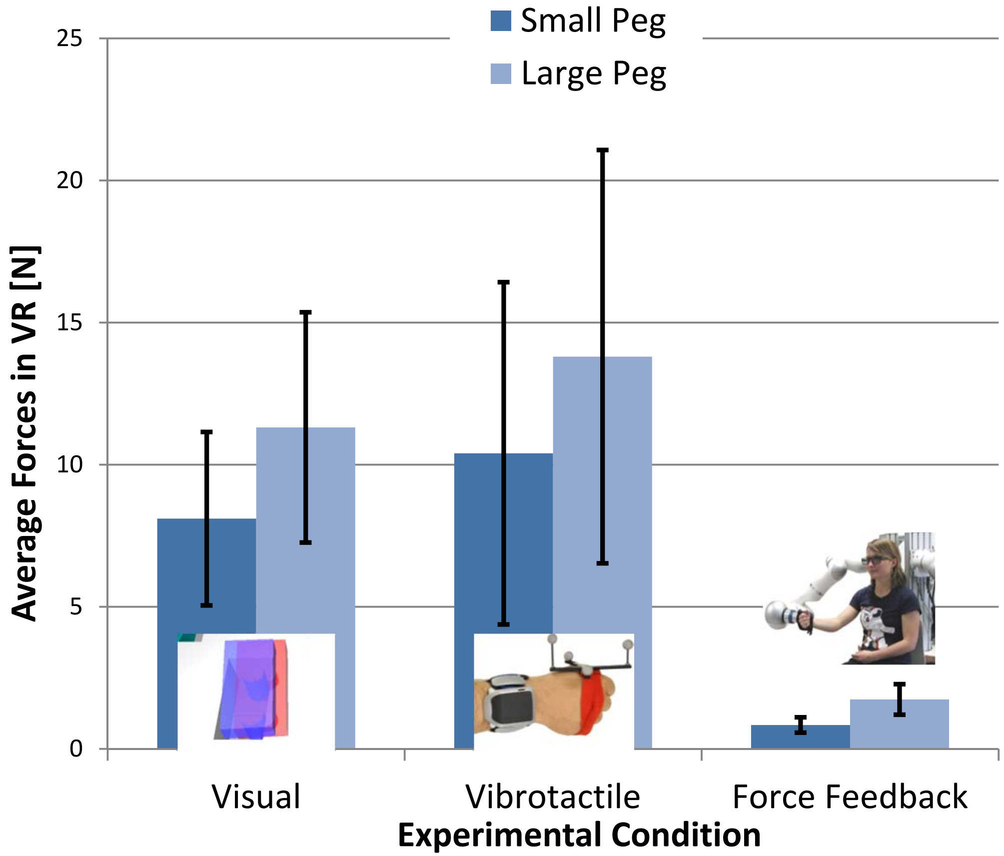
Collision Forces - Peg-in-hole





<u>ANOVA</u>

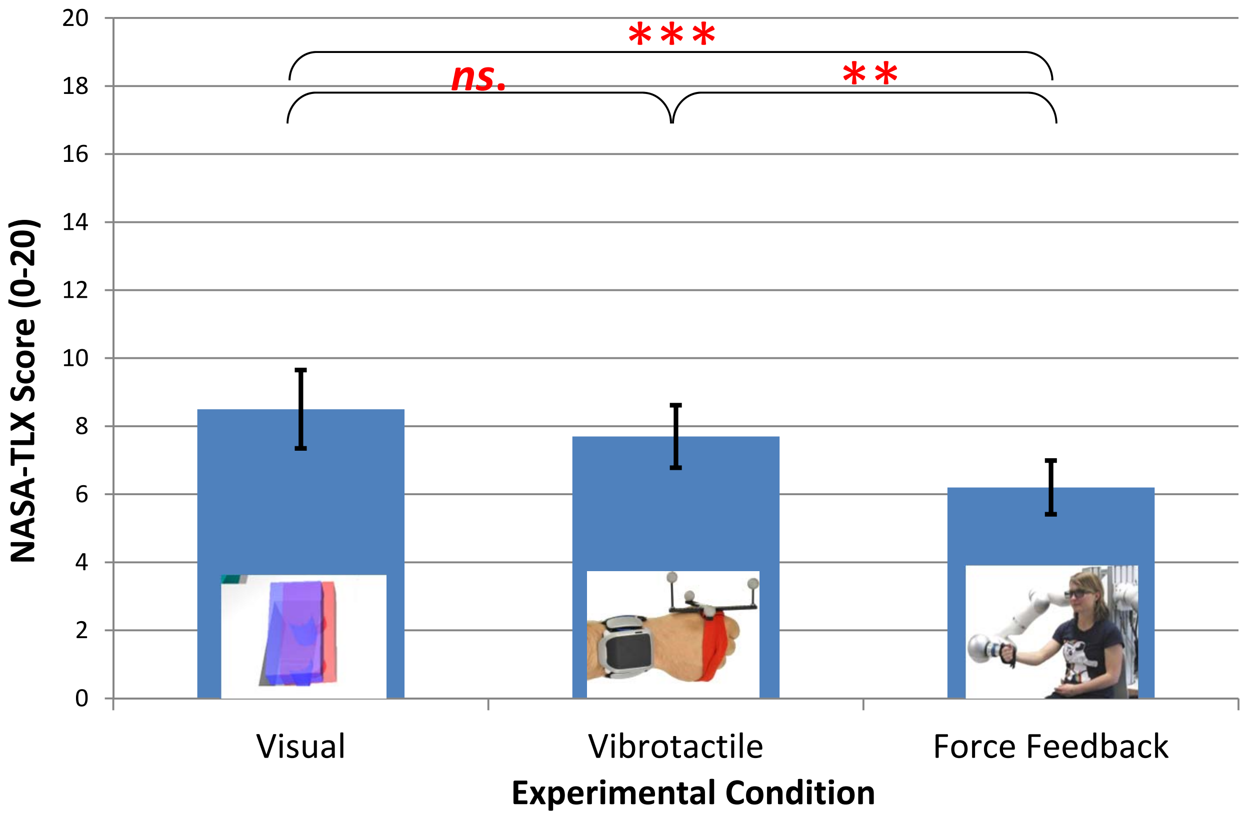
Feedback main effect:
F (2, 39) = 23.6; ***p < .001***

Difficulty main effect:
F (1, 40) = 7.8; ***p < .001***

Feedback x Difficulty interaction
F (2, 39) = 2.5; ***p < .10***

Mental Workload

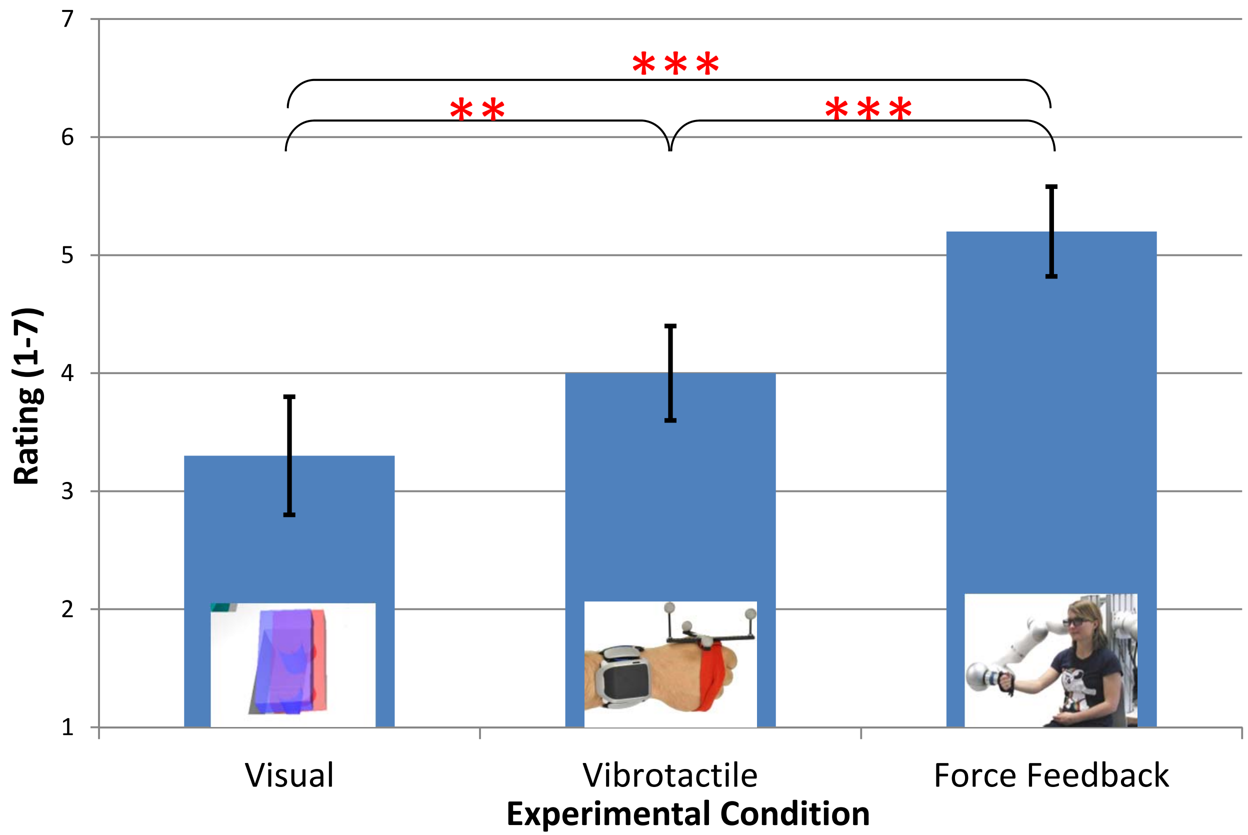
NASA-TLX weighted sum score (Hart & Staveland, 1988)



ANOVA
Main effect:
$F(2, 40) = 8.6$
$\boldsymbol{p = .001}$

Spatial Orientation

"I had a good overview of the spatial configuration, even in situations with restricted view or occlusions" (1 = "fully disagree"; 7 = "fully agree")



<u>ANOVA</u>
Main effect:
$F\,(2, 40) = 14.8$
$\boldsymbol{p < .001}$

Discussion

Visual feedback potentially **overloads the visual channel**

Vibrotactile feedback is **too difficult to distinguish**

Force feedback is **intuitive**, **easy to interpret**, allowing a **high degree of manipulation precision** and **spatial awareness**

A Meta-Analysis: Aggregating all findings in the field

The overall performance effects when using vibrotactile vs. kinesthetic force feedback

Methods

1. Literature research

→Identification of *128 primary studies* on the effect of haptic feedback in the teleoperation domains.

2. Inclusion criteria

Content:

- Comparison of conditions with and without haptic feedback for the same task and system (omitting studies on haptic training)

Methods:

- Basic descriptives or statistics reported
- Methodological control of time effects (e.g. counterbalancing)

→ **58 primary studies** with ***k* = 171 comparisons** and ***N* = 1104 subjects**

→ **30 VE studies**

Methods

3. Effect Size Calculation

- *Outcome Variables*
  1. Task success (task-dependent, e.g. collisions avoided)
  2. Task accuracy (task-dependent, e.g. tissue damage)
  3. Average and peak forces
  4. Completion times

- *Calculation of Effect Sizes*

Hedges's $g = \frac{\bar{x}_{No\ Haptics} - \bar{x}_{Haptics}}{S\ pooled}$

- *Effect Size Classification*

  g > .20 = small; ***g*** > .50 = medium; ***g*** > .80 = large effect

Effect Size Aggregation – Force Feedback in All Setups

Outcome Variable	*k*	*Effect Size (g)*	95% CI (*g*)	*Q*
Task Success	45	**0.75*****	0.64 – 0.85	200.4***
Task Accuracy	26	**0.69*****	0.53 – 0.85	46.4**
Detection Rates	5	**0.62*****	0.32 – 0.92	21.5***
Average Force	19	**0.78*****	0.60 – 0.96	169.2***
Peak Force	22	**0.64*****	0.46 – 0.82	132.9***
Completion Time	79	**0.22*****	0.13 – 0.30	331.0***

Note. ***p* <. 01; ****p* <. 001

g > .20 = small; ***g*** > .50 = medium; ***g*** > .80 = large effect

Effect Size Aggregation - Force Feedback in VE Setups

Outcome Variable	*k*	*Effect Size (g)*	95% CI (*g*)	*Q*
Task Success	38	**0.68*** **	0.57 – 0.80	187.3***
Task Accuracy	12	**0.67*** **	0.47 – 0.87	19.6
Detection Rates	--	---	---	---
Average Force	--	---	---	---
Peak Force	--	---	---	---
Completion Time	52	**0.18*** **	0.09 – 0.28	246.4***

Note. $^{**}p < .01$; $^{***}p < .001$

g > .20 = small; ***g*** > .50 = medium; ***g*** > .80 = large effect

Differences between Force Feedback and Vibrotactile Substitution?

Results – Feedback Modality Moderation

Outcome Variable	Q_b	*k*	*g*	95% CI (*g*)	*Q*
Task Accuracy					
Force Feedback	**34.2*** **	45	**0.75*** **	0.64-0.85	200.4***
Vibrotactile Feedback		19	**0.21** **	0.07-0.36	33.6*
Average Force					
Force Feedback	**29.3*** **	19	**0.78*** **	0.60 - 0.96	169.2***
Vibrotactile Feedback		13	-0.13	-0.41-0.15	105.3***
Peak Force					
Force Feedback	0.1	22	**0.64*** **	0.46 - 0.82	132.9***
Vibrotactile Feedback		5	**0.60*** **	0.31- 0.89	11.3**
Completion Time					
Force Feedback	**4.8* **	79	**0.22*** **	0.13- 0.30	331***
Vibrotactile Feedback		18	0.03	-0.11- 0.18	85.4***

Note. *p <. 05; **p <. 01; ***p <. 001

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Discussion

- **Substantial overall effects** of additional force feedback on task performance and force application

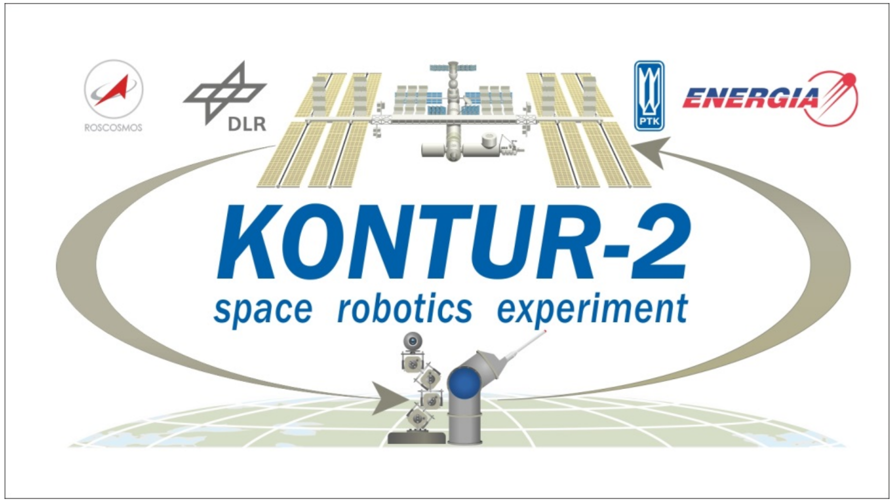
- The benefits of force feedback are **attenuated when force feedback is substantiated with vibrotactile stimuli**

  → Still a positive, small effect on task accuracy
  → Vibrotactile information as a warning function

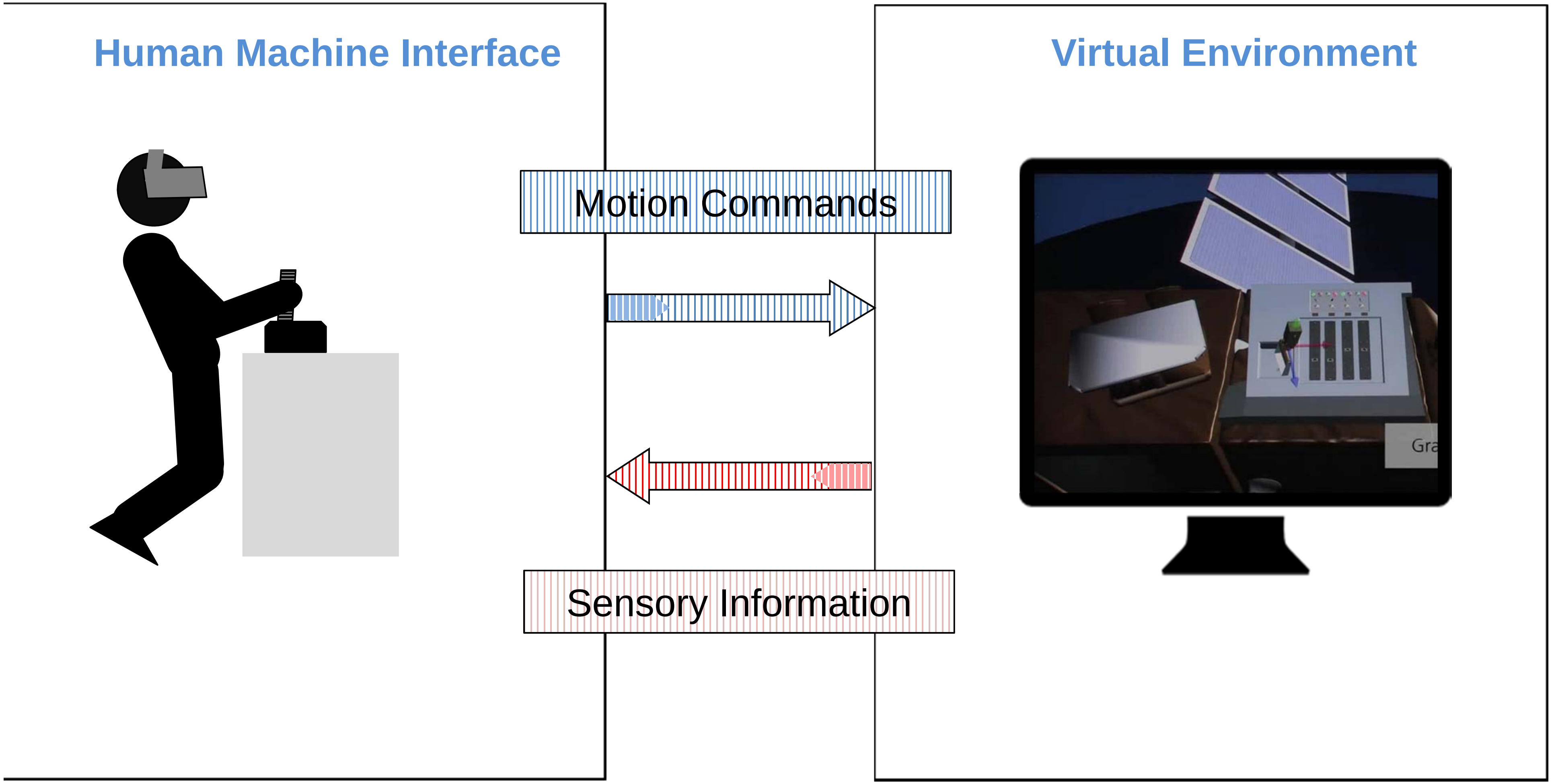
Outlook: VE and Teleoperation in Space

Human performance when using

passive force feedback (e.g. spring stiffness) in space



Outlook: VE and Teleoperation in Space



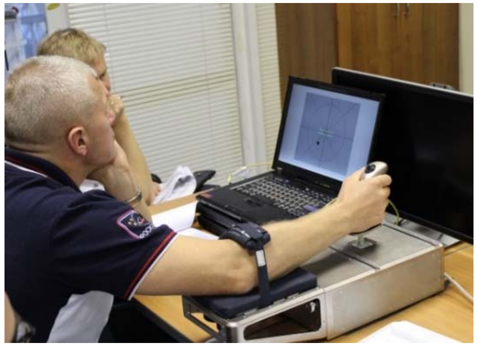
Outlook: VE and Teleoperation in Space

Main Research Question:

What are the optimal mechanical parameters (stiffness, damping, mass) of a Force Feedback Joystick under terrestrial conditions and microgravity?

Sample:

N = 3 cosmonauts

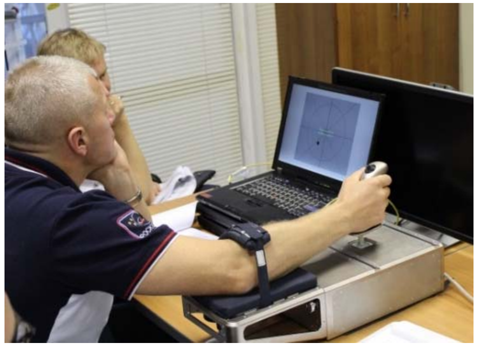


Pre-Mission Session

2 months before launch

3 Mission Sessions

2, 4, 6 weeks in space



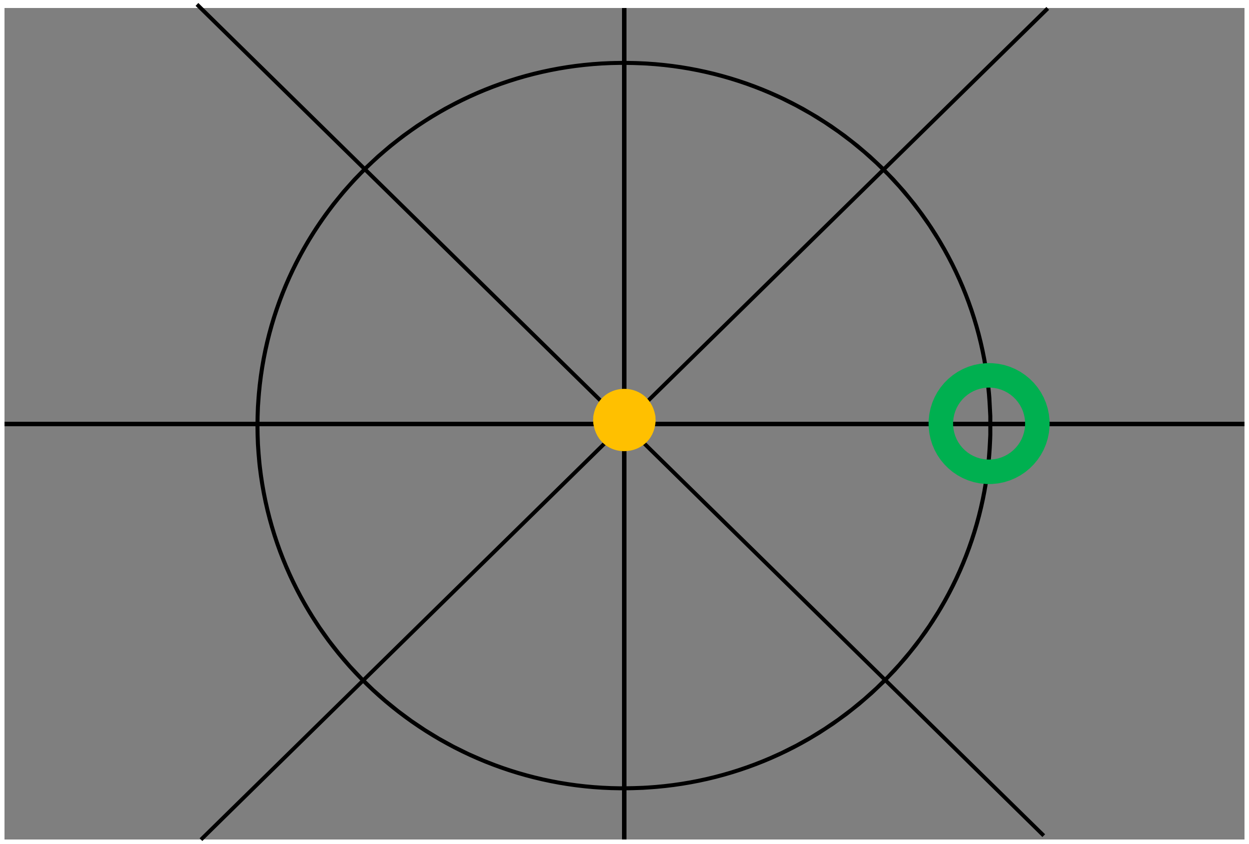
2 Post-Mission Session(s)

1) 12 days after landing

2) + 6 months (after reha.)

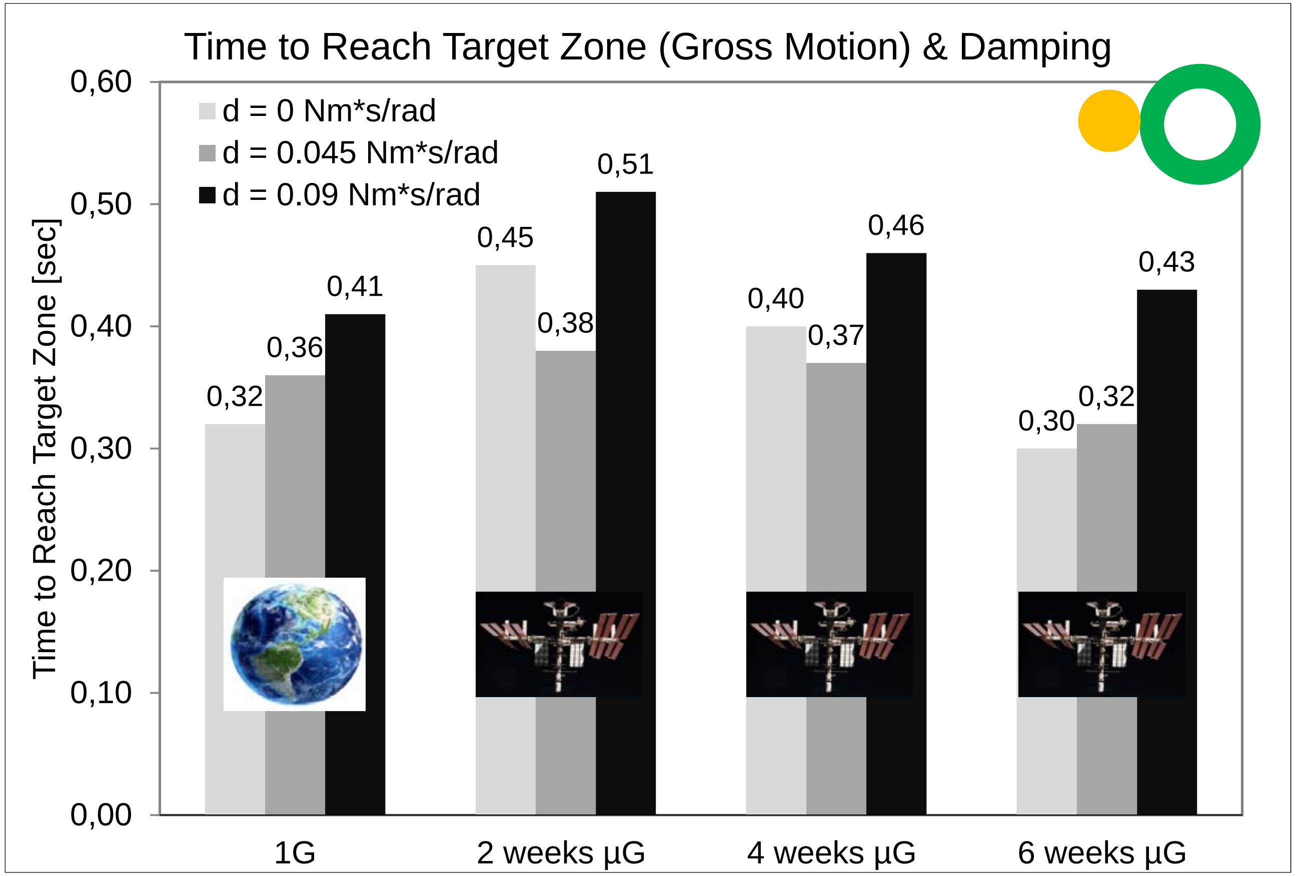
Experimental Aiming Task

„Match static target ring as quickly as possible“



ISS Sessions November + December 2016

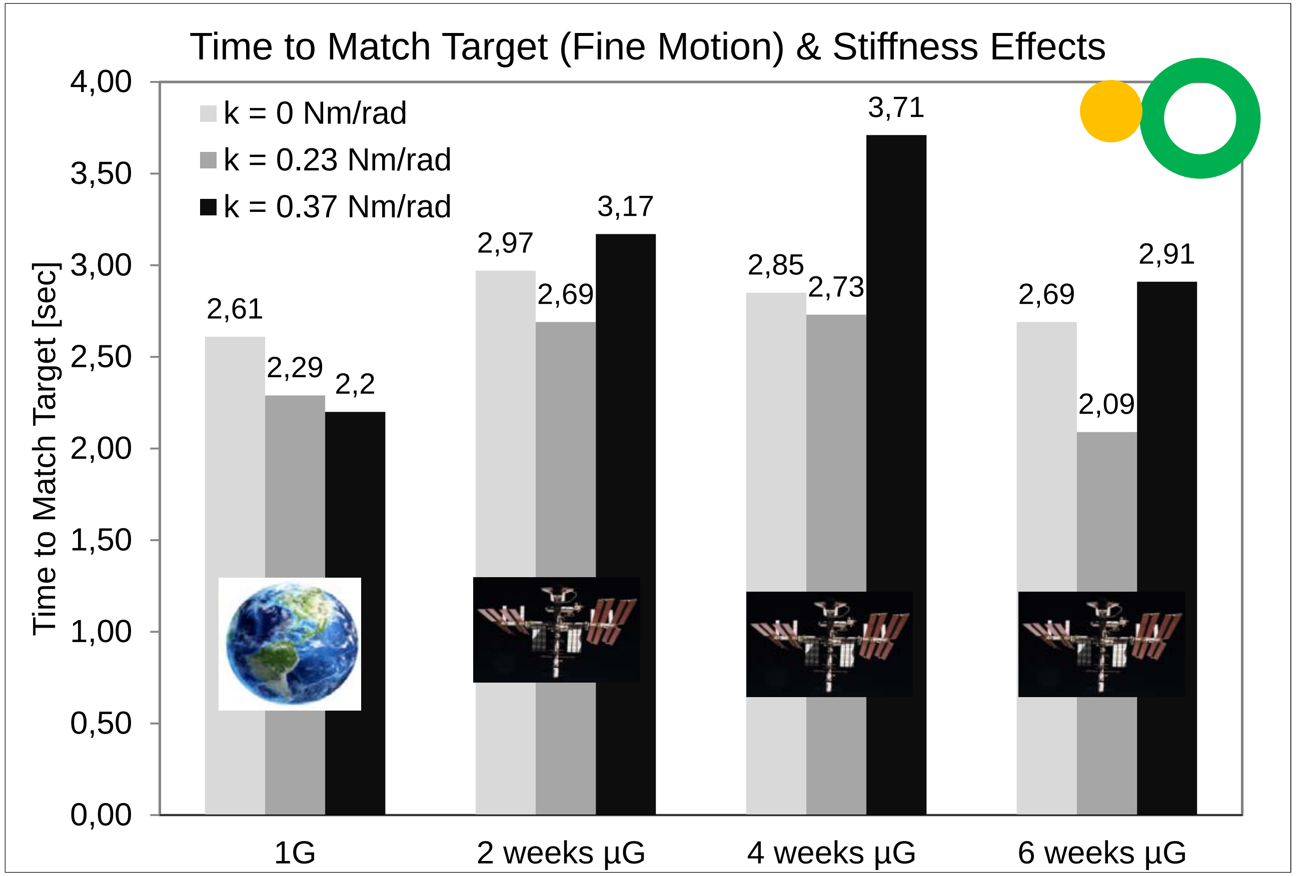
The Effects of Damping on Gross Motion Time



There are **different optimal damping values for 1G and µG in the first weeks**!

→ Moderate damping supports gross motion in µG (speed information)

The Effects of Stiffness on Fine Motion Time



There are **different optimal stiffness values for 1G and µG**!

→ Stiffness has to be reduced in µG

Summary

Degraded human performance in space:

Slower, more sluggish movement profiles when matching a **static target**, probably due to **distorted proprioception**

→ Specific mechanical properties **provide crucial kinematic information,** allowing for more precise and faster movements

→ There are **optimal mechnical configurations for space** (moderate damping, moderate stiffness)

General Discussion

- **Kinesthetic Force Feedback is indispensable** for teleoperation/ VE setups:
  → substantially improved accuracy, better force regulation (***g***s > .60)
  → small effects on completion time
  → lower workload, better spatial orientation

- **Vibrotactile substitution** still has a positive effect on task performance, but is better suited **for warning/ collision detection**

- **Haptic assistance** seems to be **indispensable** for maintaining **high task performance in space**

Thanks a lot for your attention!

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