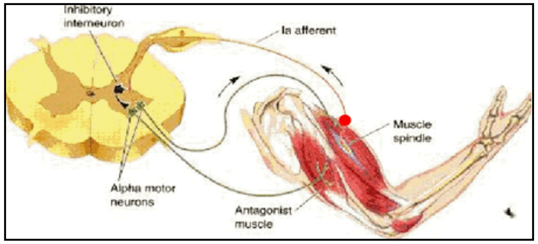
Haptic Shared Control -
using haptics to augment reality



Presenter

- David Abbink, PhD
- Assistant Professor; BioMechanical Engineering, Faculty 3mE, Delft University of Technology

What are we doing? Devices and Humans

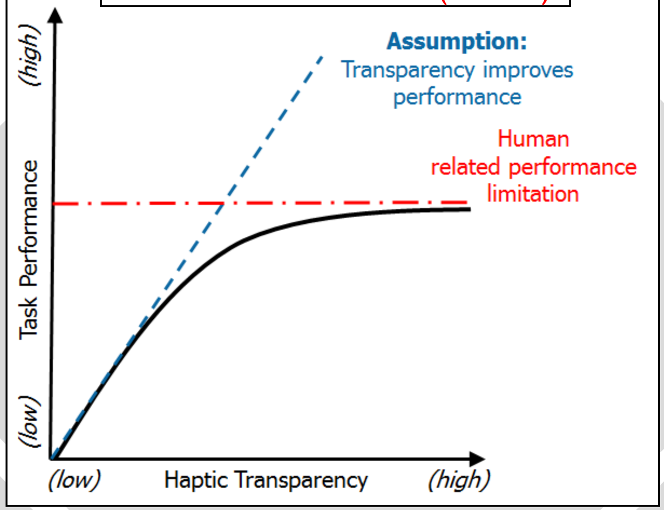
Improve Task Execution

Performance: Accuracy, speed, production

Control effort: Less control actions, reduced forces

Mental load: intuitive, situational awareness

Wildenbeest et al (2013)



The Machine

Tele-manipulator

Master Device /

Controller / Slave

The Human

controlling

a machine using

sensory feedback

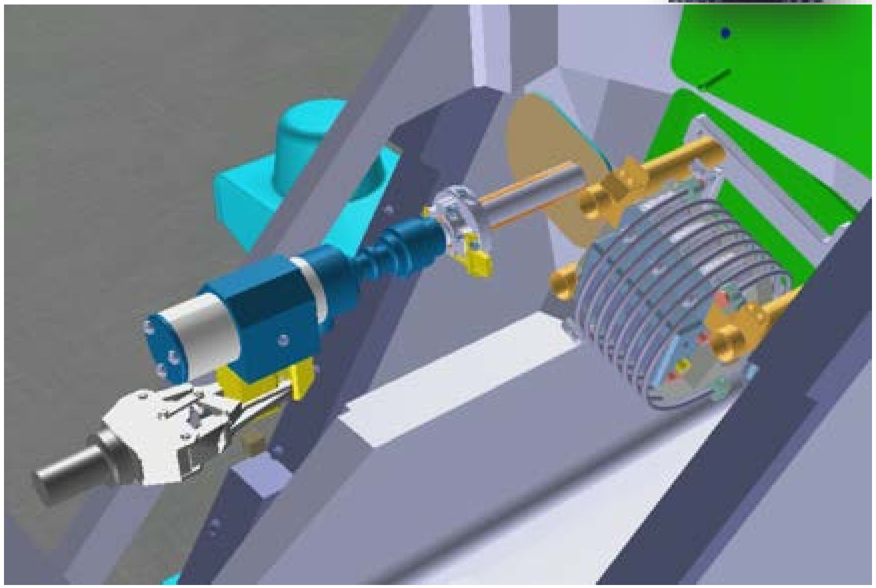
How do properties at lower level influence behavior at higher levels?

How are sensors integrated?

How do individual sensors work?

Caveat: this is very task-dependent!!

- Suppose a peg-in-hole-task
- How would you improve performance?



1. Tips & Tricks to improve performance

H: Train and select operators (e.g., ITER)

M: Design better master devices

C: Improve controller

S: Make slave a bit compliant (e.g., Christiansson)

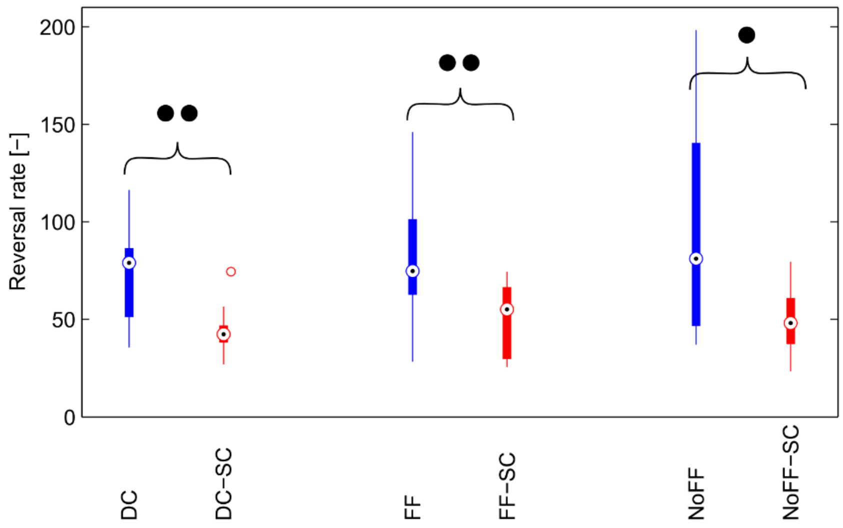
E: Structure the environment, offer many camera views (e.g., ITER)

'Tricks'

- Binary warnings
- Event-based haptics (play back a force in case of contact)
- Virtual fixtures (Rosenberg 1987)
- Haptic Shared Control (vehicle control, telemanipulation)

Using artificial forces to guide and support humans

Haptic Shared Control



Improved performance (quicker, more accurate reduced control effort)

Roseborough's Dilemma

If feedback is 100% correct, why not automate? Why have a human in the loop?

"If we understand how a man performs a function, we will have available a mathematical model which presumably should permit us to **build a physical device or program a computer to perform the function in the same way** (or in a superior manner)."

(Fitts, 1962)

What's wrong with automation?

Self-regulating devices: first automation?
- Useful to replace humans – increase efficiency

270 BC (Alexandria)

A Greek named Ktesibios in Alexandria invented a float regulator for a water clock

1100 AD (China)

a south-pointing compass was linked to the wheels of a chariot so as to keep the vehicle steered southward.

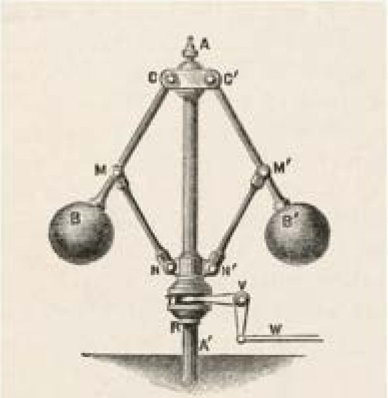


Fig. 29.—The Governor.

1600 AD (Netherlands)

Cornelis Drebbel's thermostat

1769 AD (Scotland, UK)

James Watt innovates Newcomen's steam engine by fly-ball governor

Problems with automation?

Bainbridge (1983) – Irony of automation

“The increased interest in human factors among engineers reflects the irony that the more advanced a control system is, so the more crucial may be the contribution of the human operator.”

Norman (1990)

“Problem of automation: feedback & interaction”

“ Appropriate design should:

- assume the existence of errors
- continually provide feedback
- continually interact with operators in an effective manner
- allow for the worst of situations.”

Solution? “What is needed is a soft, compliant technology, not a rigid, formal one.”

Sub-conclusions

“Human Errors”

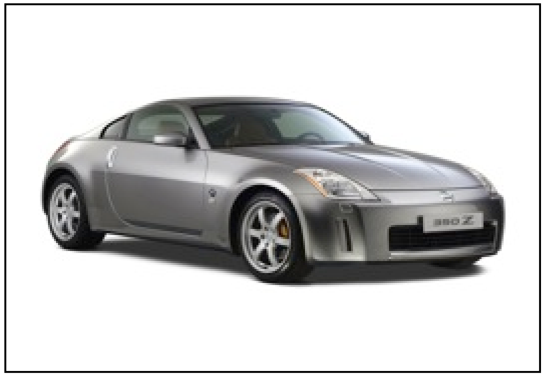
Eh... which human are we talking about?

- The operator?
- Or the designer?

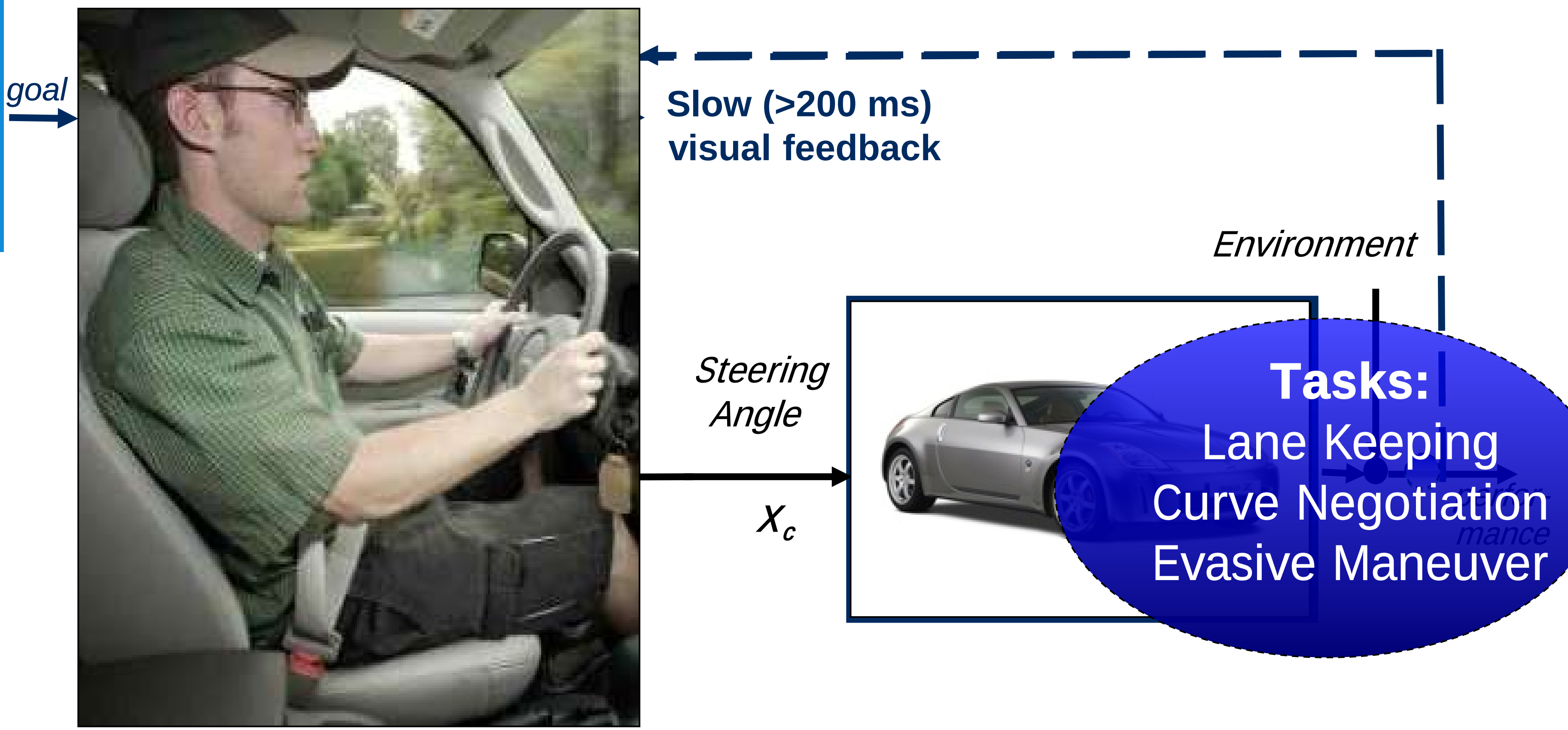
Something essential is lacking:

- ‘Magic’ Feedback, which
  - Is continuous
  - Does not annoy
  - Does not cause overload

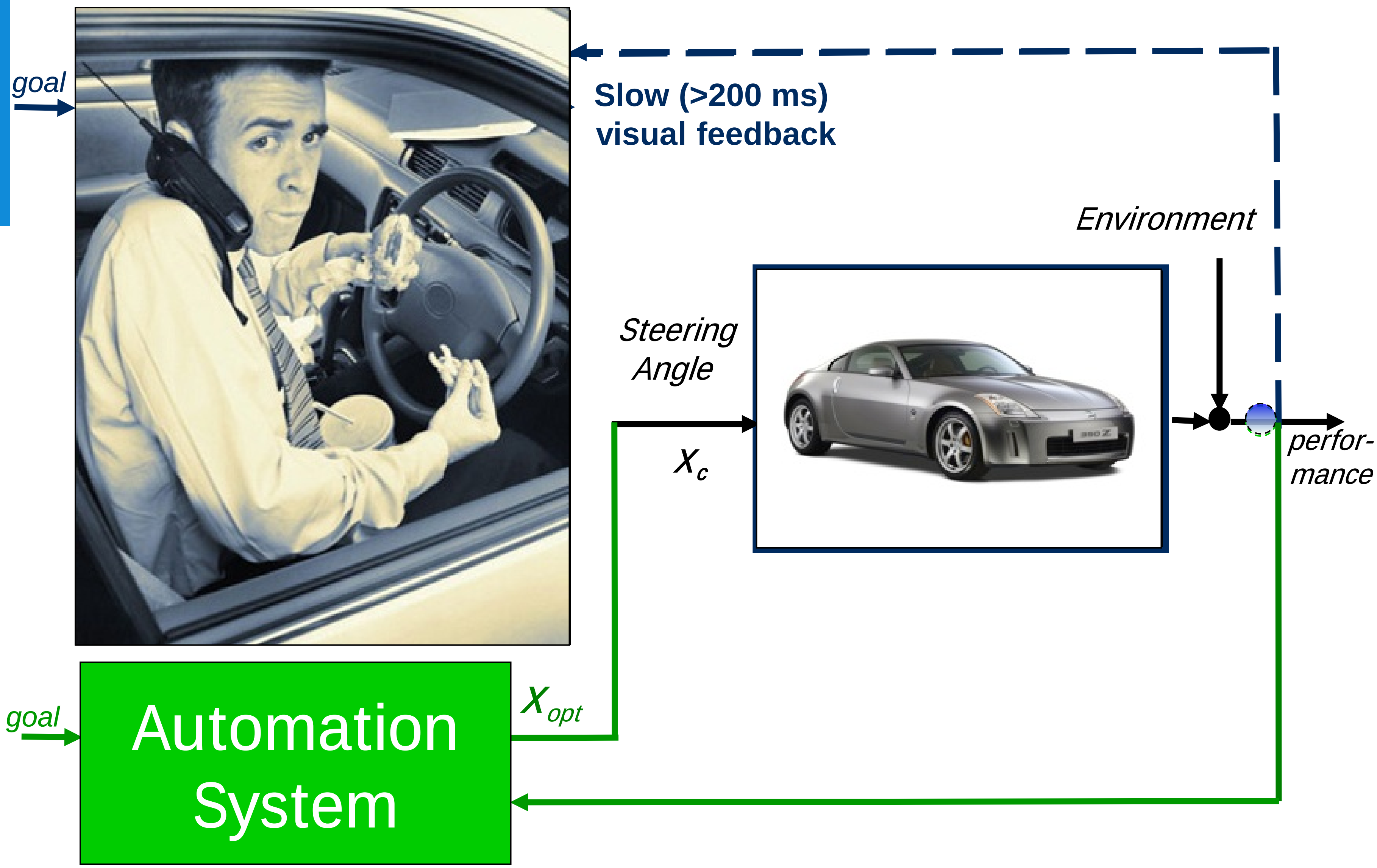
Human – Machine Interaction Possibilities



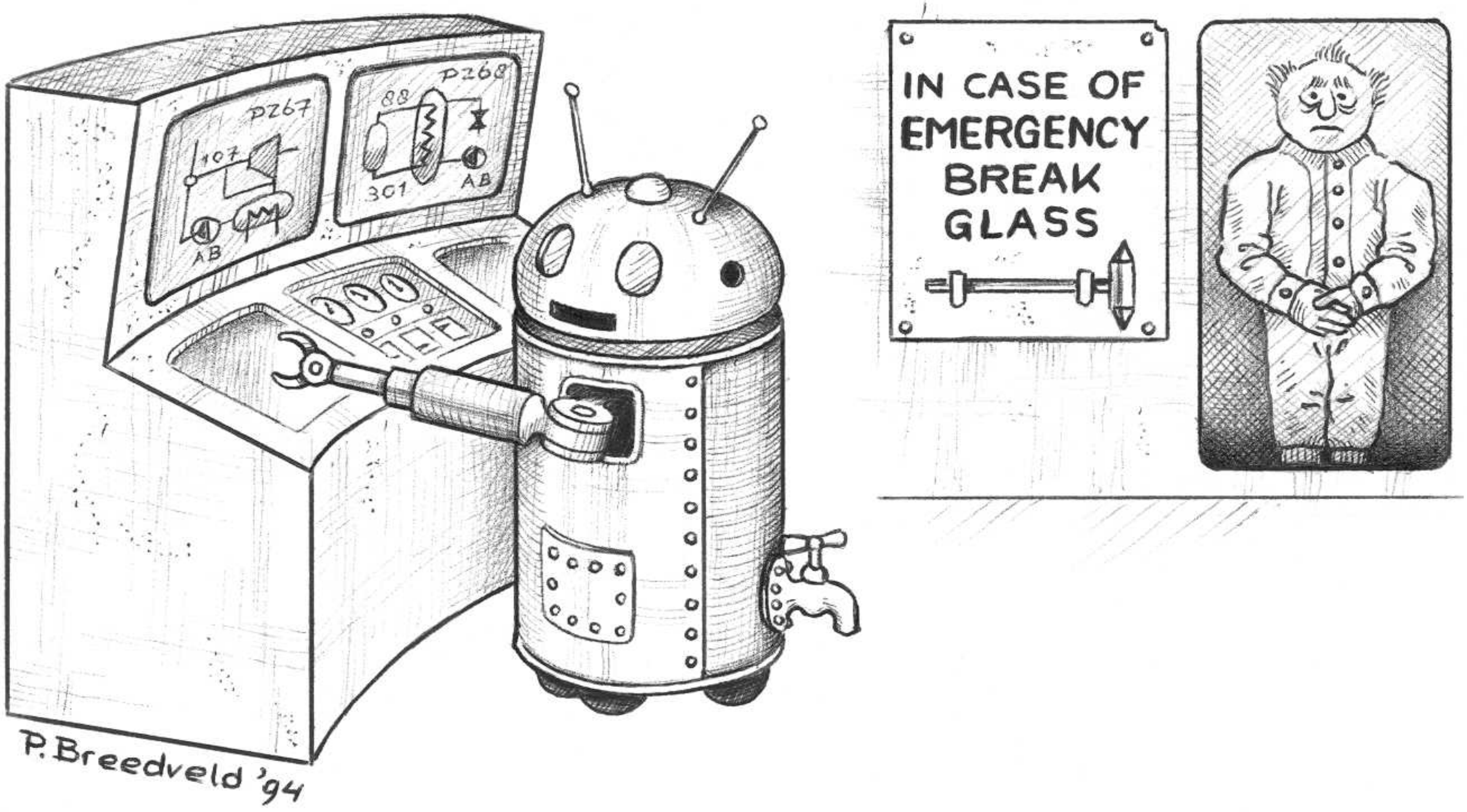
1. Manual Control



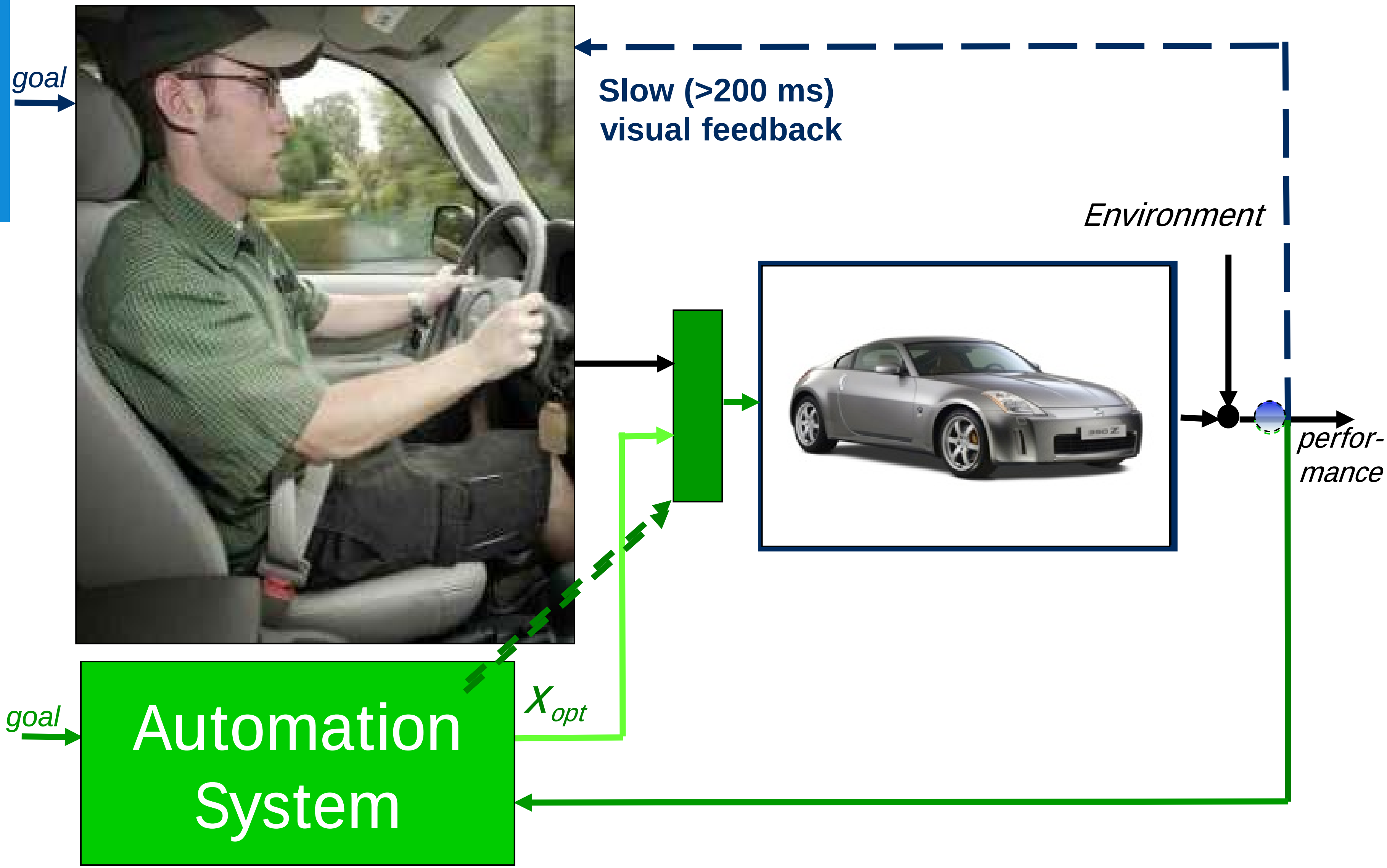
2. Full Automation



Common Solution for Human – Automation Interaction?



3. 'Blending/Mixing Input' Sharing Control



Haptic Shared Control – alternative design philosophy for human-automation interaction

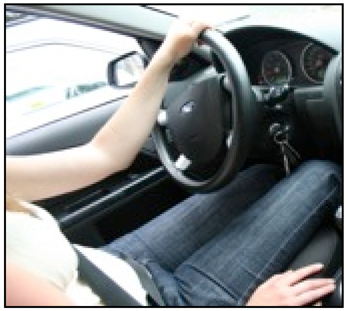
Imagine…

controlling a vehicle or operating a tool that:

- is aware of its environment
- has a good idea what you want to do in that environment
- helps you to comfortable achieve better performance or safety
- communicates its intentions, but can be easily overruled

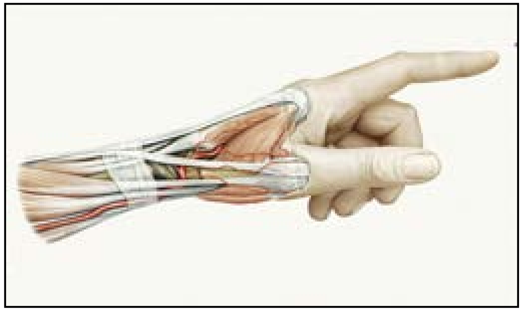
Planes

Cars



Robots

Exoskeletons / Prostheses



Human-machine interface

When human and automation share tasks…
… there is a **need** for **human-machine interfacing**
Good human-machine interface will enable lower workload, better situation awareness, better mode awareness etc…

Issue 1. Does human understand automation?

- Automation boundaries & Detected system failures

We think: *Use Haptic Shared Control (forces, stiffness) based on operator modeling and identification*

Issue 2. Does automation understand human?

- Desired trajectories, safety boundaries, strengths & limitations

We think: *Use Haptic Shared Control (forces, stiffness) based on operator modeling and identification*

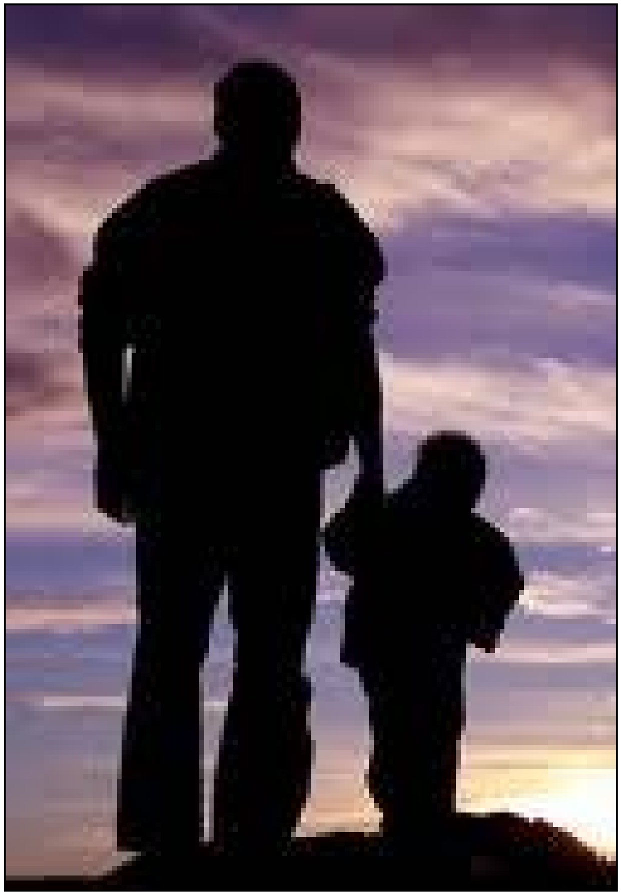
Haptic Shared Control Metaphor

“Horse Metaphor”, by Frank Flemisch & Ken Goodrich

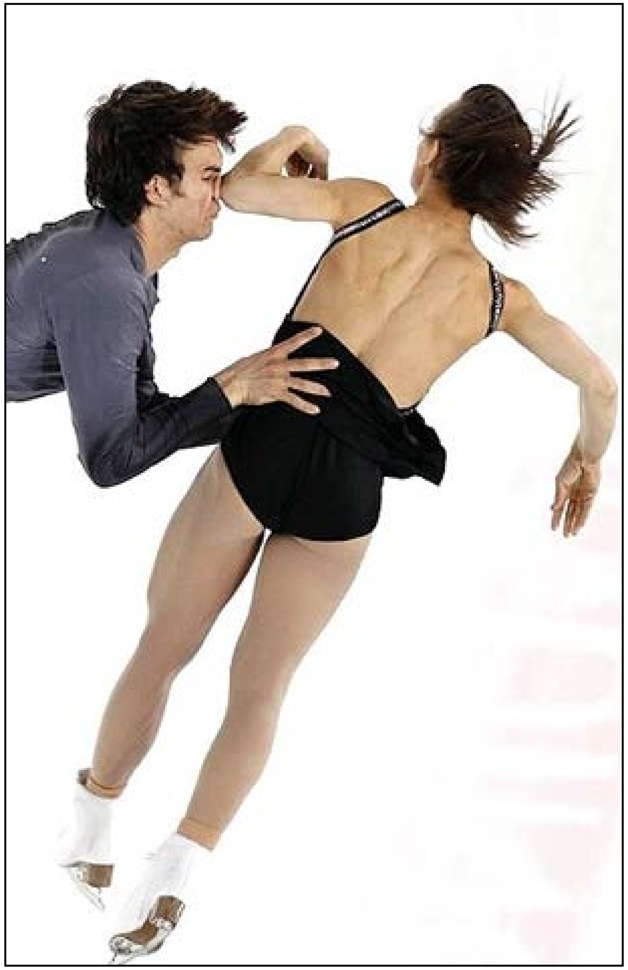
Flemisch et al. (2003). Nasa Report about the H-mode.

Goodrich et al. (2008). Piloted evaluation of the H-mode. AIAA Conference

Other Metaphors



However, design is not easy …



What do we need for design and evaluation?

Highly multi-disciplinary research: neuroscience, human factors, haptics, system identification, engineering (robotics, automotive, aviation, maritime)

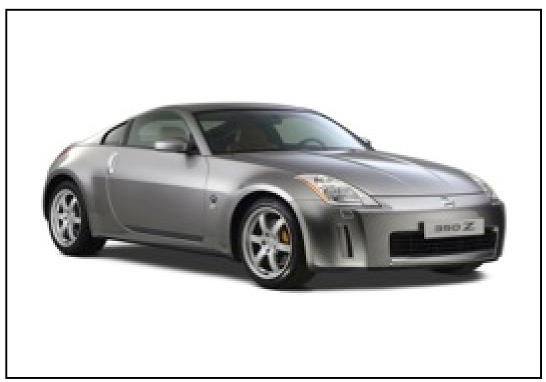
1. Design the haptic shared controller

- Mapping 1: Translating constraints of vehicle/tool in an environment to desired control input
- Mapping 2: Translate desired control input to guiding forces on the control interface
- How to deal with conflicts between human and system?
- Step away from trial-and-error design, include human in design

2. Understanding human capabilities and limitations

- Measure/model control strategies (optimal / personal)
- Measure/model response to visual and haptic cues (natural & augmented)
- Measure/model adaptation & learning

Examples from automotive domain



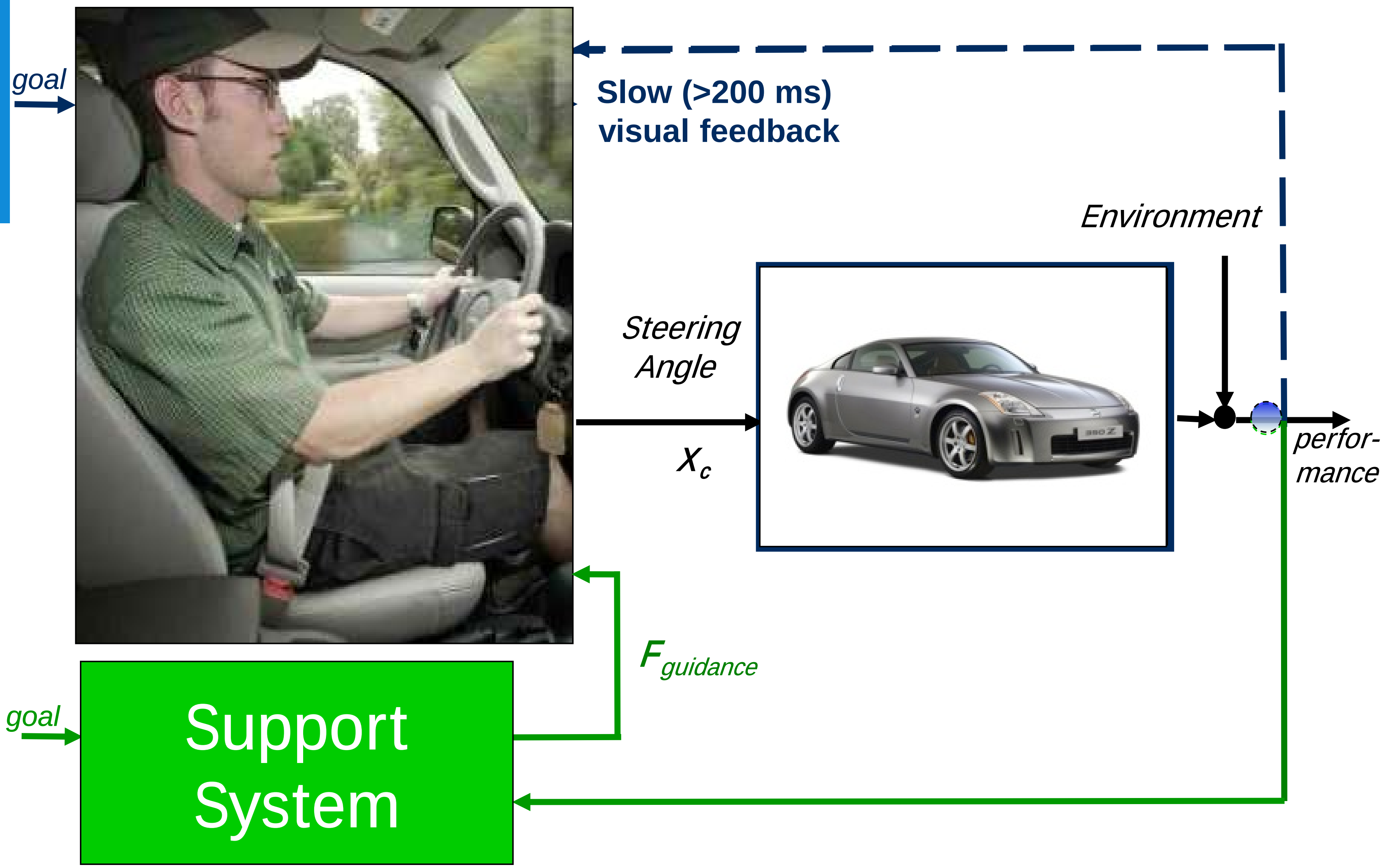
1A. Haptic Shared Control for Car-Following

2002-2006 Nissan Project: Design Force Feedback Gas Pedal & Evaluation using Neuromuscular Analysis

International collaboration with 30 scientists at universities in USA, Canada and Japan

2008 Market launch by Nissan in Japan and USA as 'Distance Control Assist'

1B. Haptic Shared Control for Steering

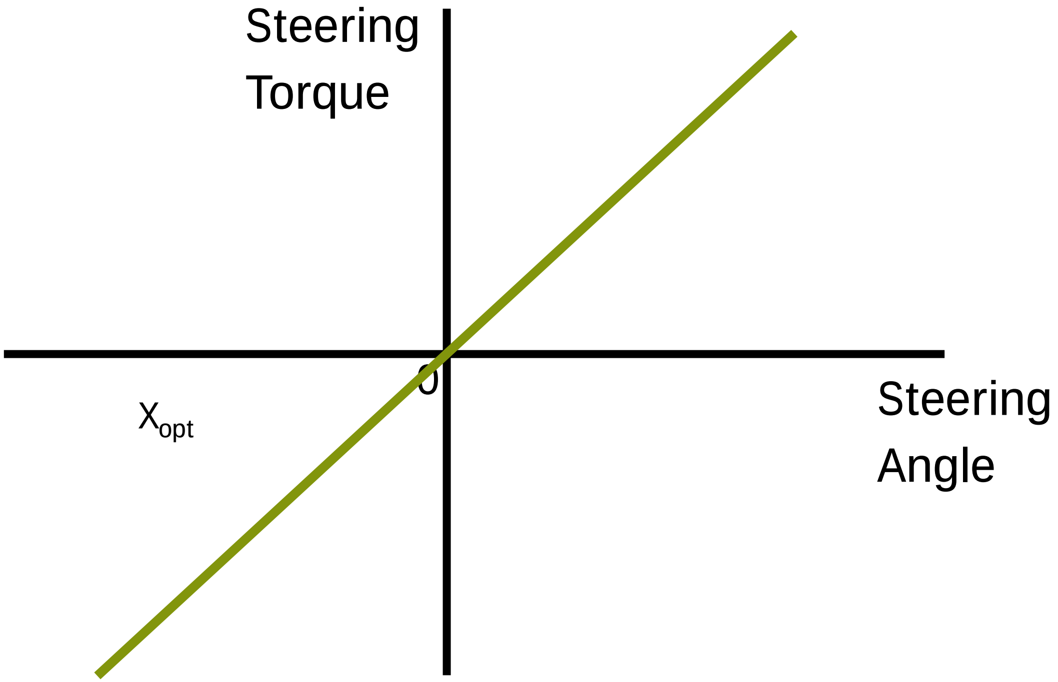


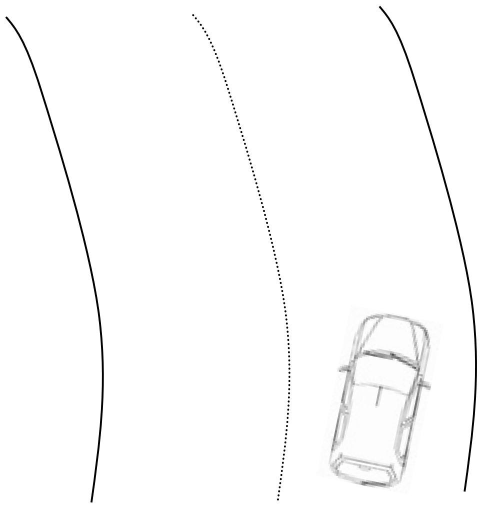
1B. Haptic Shared Control for Steering

Steering Wheel

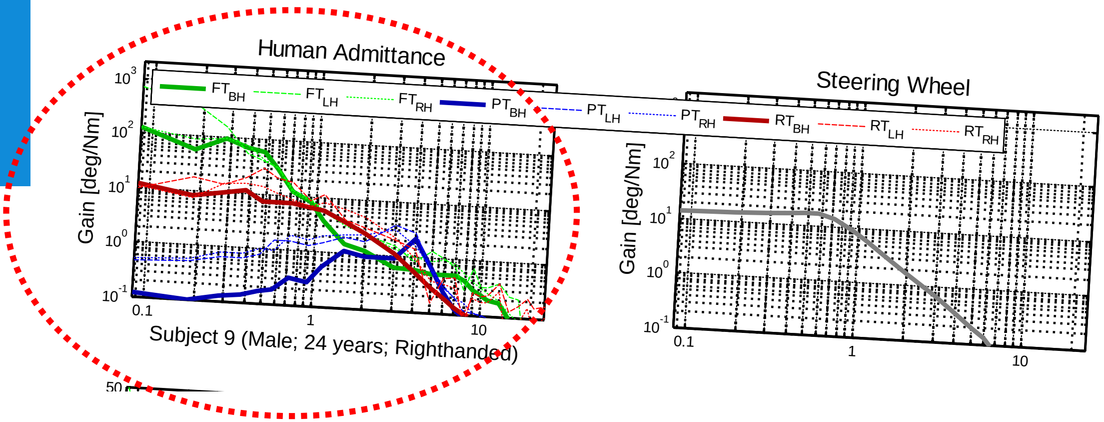
Can generate feedback forces

but: driver can relax, resist or give way



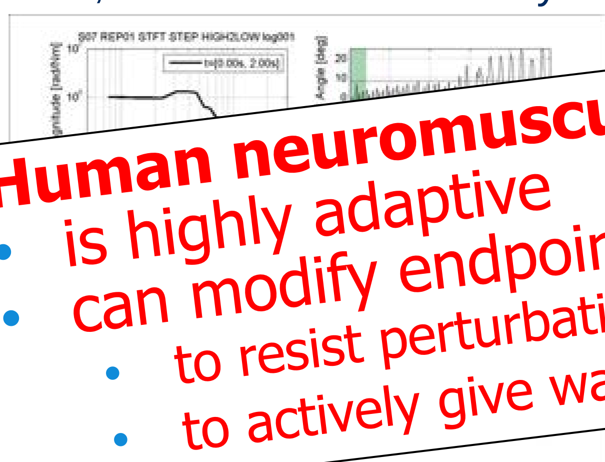


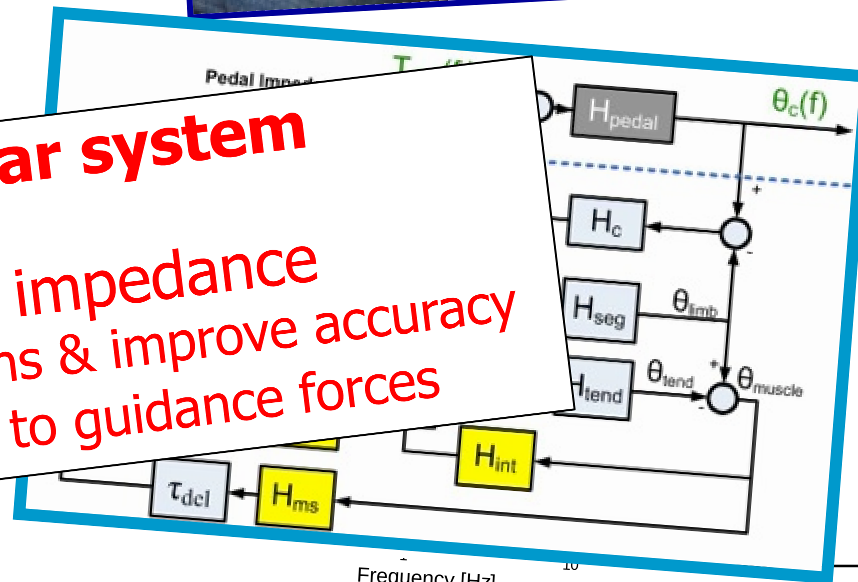
Measuring and modeling the human for (funded Nissan and Boeing)



Closed-loop system identification to estimate neuromuscular system, visual and vestibular system

EMG analys

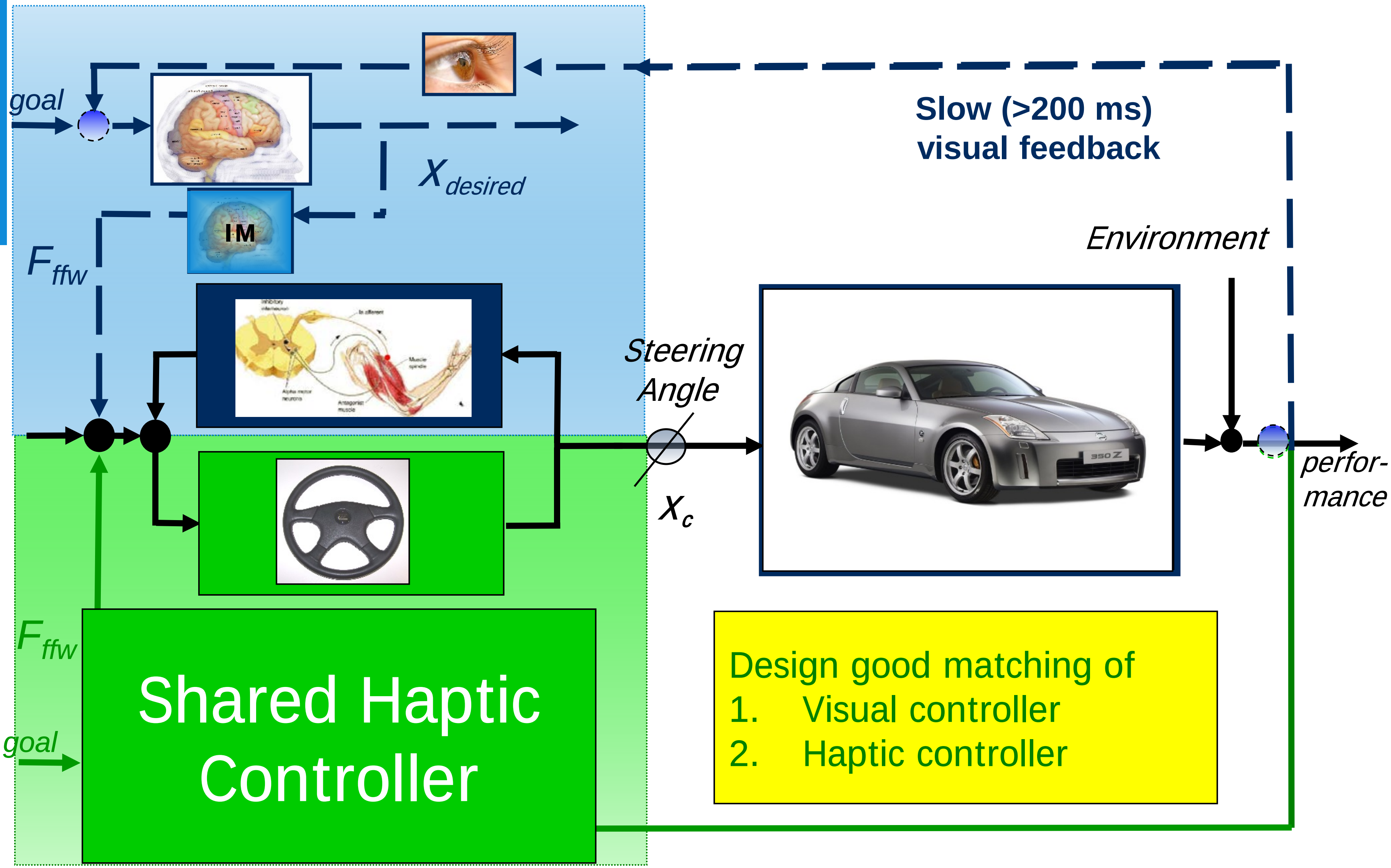




Human neuromuscular system

- is highly adaptive
- can modify endpoint impedance
  - to resist perturbations & improve accuracy
  - to actively give way to guidance forces

Design of Haptic Shared Control: 2 steps



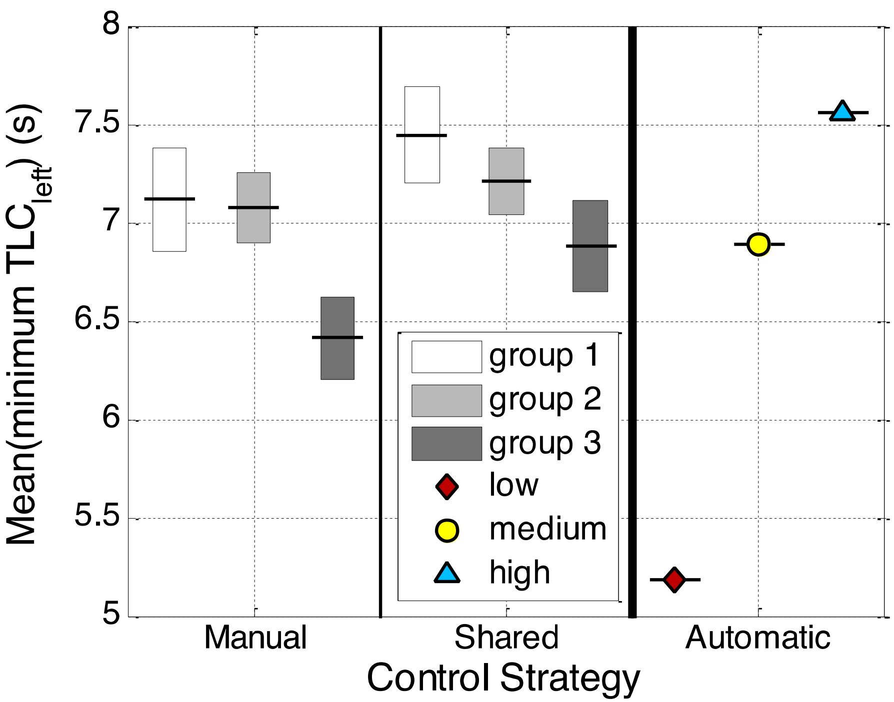
Design good matching of
1. Visual controller
2. Haptic controller

State of the art

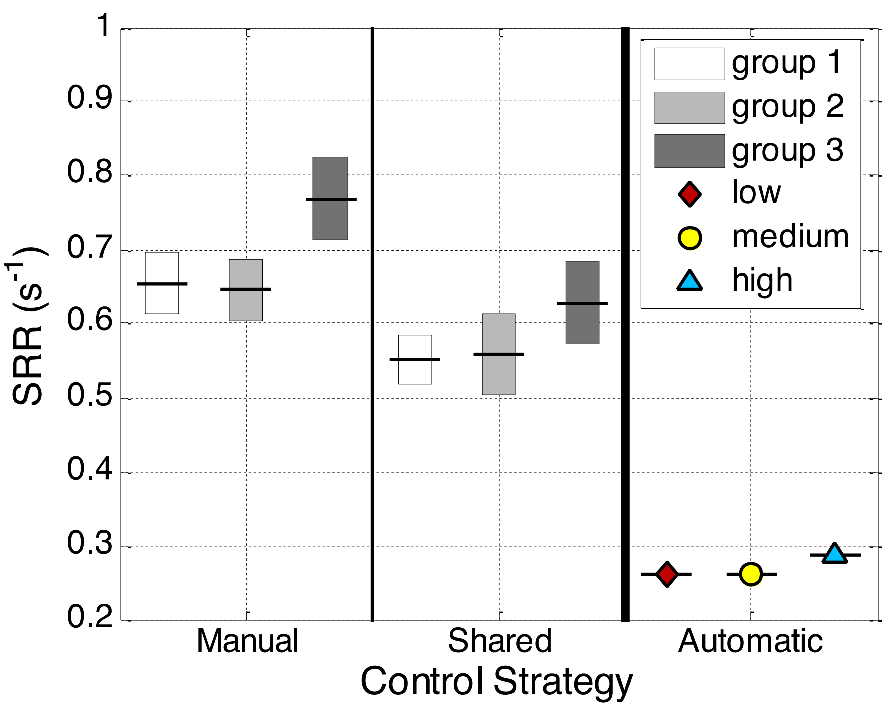
Mulder, Abbink & Boer (2012) - *Sharing Control with Haptics - Seamless Driver Support from Manual to Automatic Control* – Human Factors

Tested 3 driver groups (from young and unexperienced, to old and experienced), during curve negotiation in a fixed-base driving simulator. The goal was to compare manual control, to shared control, to full automation.

Performance increased



Control effort decreased



Delft Approach to Haptic Shared Control

Abbink & Mulder (2009) – Exploring the dimensions of haptic feedback support in manual control

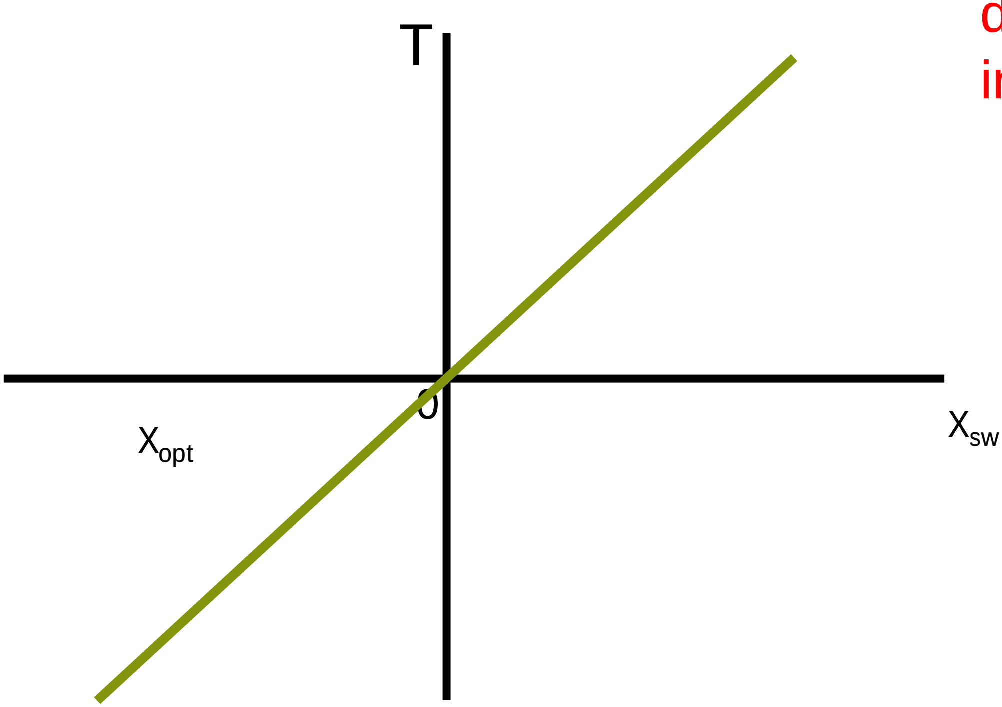
Joint patent with Nissan (2008)

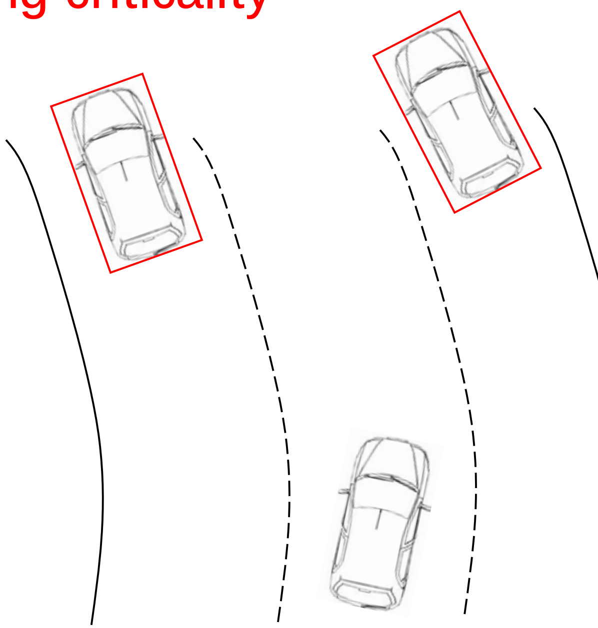
Steering Wheel

Can generate feedback forces

Can modify impedance

dynamically shift authority
in changing criticality





Design Philosophy for Automation

Abbink & Mulder (2010) – Neuromuscular Analysis as a guideline in designing haptic shared control

Haptic Shared Control is a unified approach

- **Continuous sharing of control authority** through forces
  - No more binary switches (on/off), but smooth shifting
- Driver is **better aware** of changing criticality of situation, as well as of the functionality and intent of the system
- Drivers can **always overrule** the system
- Can be **based on any automation system** that generates 'optimal steering inputs' (*visual controller*)
- Allows driver to **use fast reflexes** and neuromuscular adaptation (low-level *neuromuscular controller*)

What would be limitations of this approach?

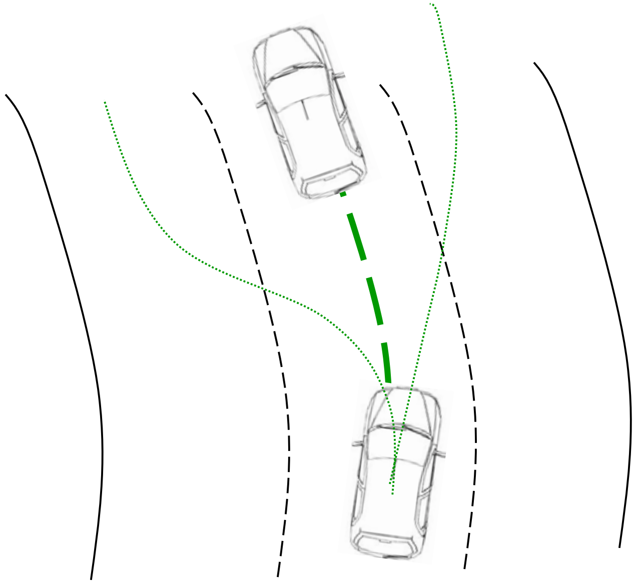
What happens in case of multiple choices?

Single path vs Multiple Paths

State of the Art: Support only one path

Problem: How to support multiple paths?

- How to support lane changes?
  - *Tsoi et al. (2010) IEEE SMC Conference*
- How to support multiple evasive paths?
  - *Della Penna et al. (2010) IEEE SMC Conference*
  - Ideally, human should make the choice
    - Creative solutions may be needed
    - Liability

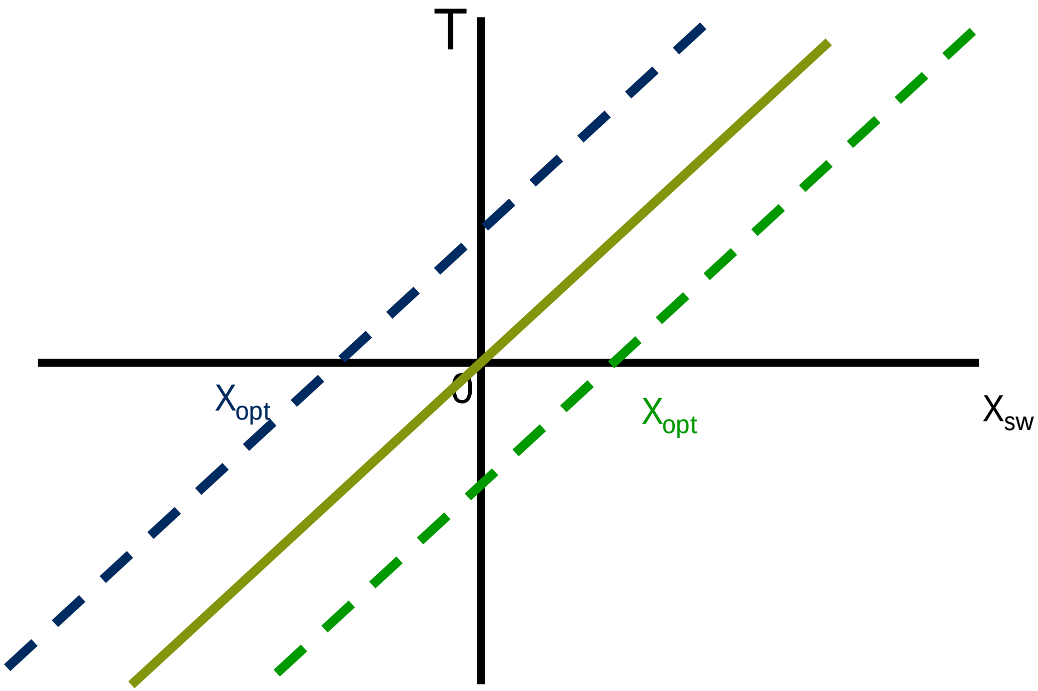


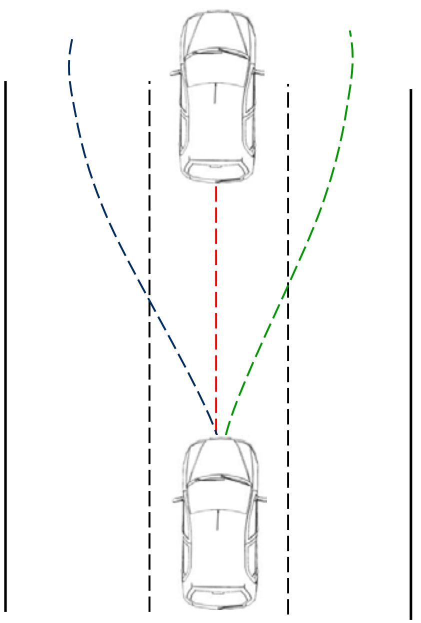
1. Design Concept: Reducing Stiffness

Idea

Reduce stiffness

- criticality will be felt when trying to steer
- easier to steer left or right



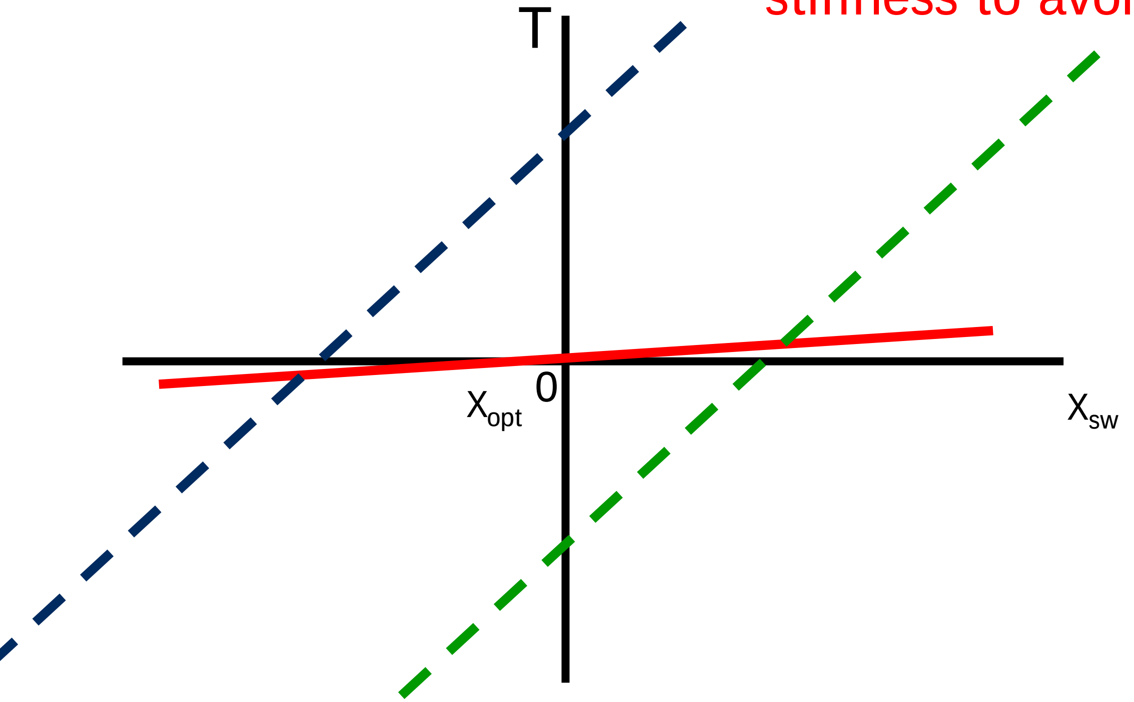


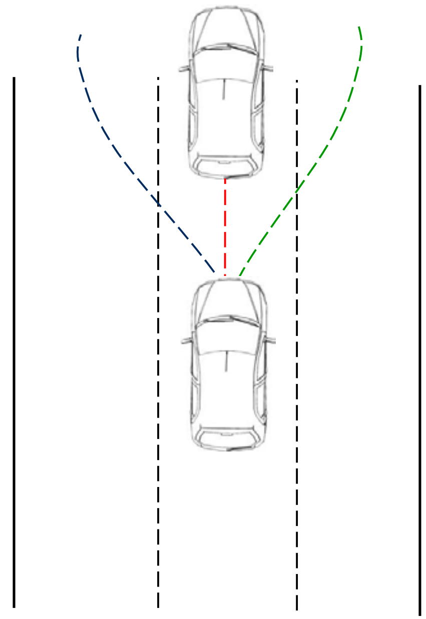
1. Design Concept: Reducing Stiffness

Stiffness

Can become negative in extreme cases

- a choosing human is supported to avoid obstacle, and is then "caught" by the support
- a stubborn human needs to increase own stiffness to avoid steering left or right





Question

What is the right level of automation?

What happens in case of support that fails at a critical moment?

How to test human-automation issues?

Over – reliance

Skill – loss

Reduced Situation Awareness

Real life

- Wait until an accident happens, analyze it

Simulator world

- Usually with one surprise trial
- Usually long tests before that surprise trial

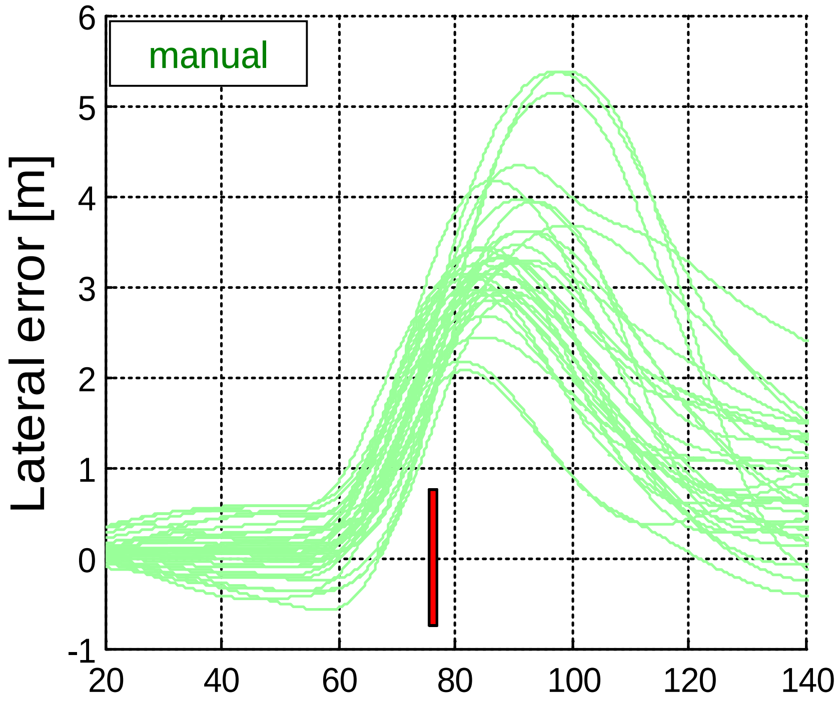
Manual Control vs Perfect Shared Control

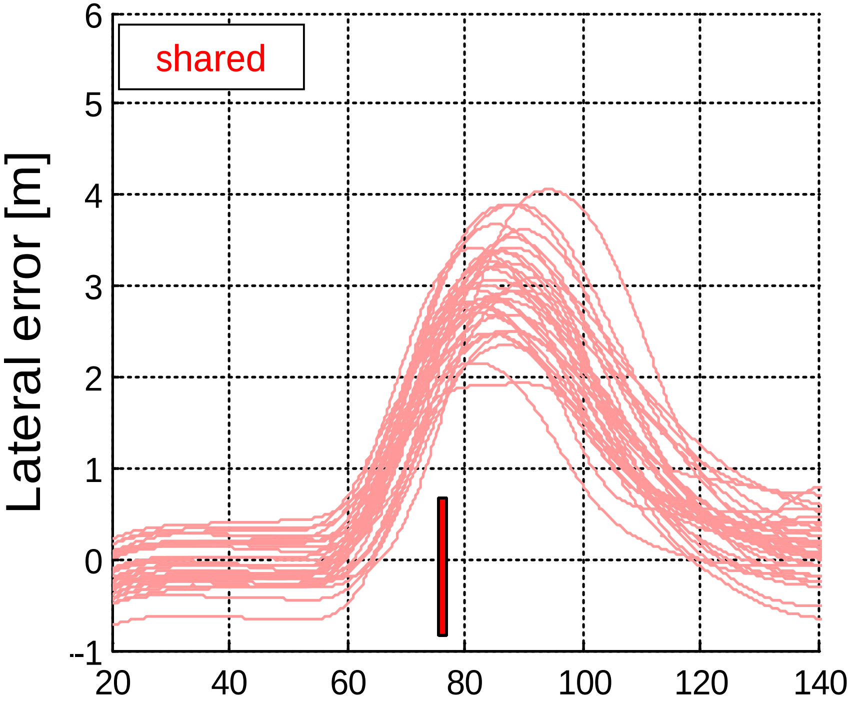
Mulder & Abbink (2011)

Obstacle hit rate at TTC = 1.4s:

21.2% manual vs 15.2% shared

more overshoot and variability in trajectory of manual control



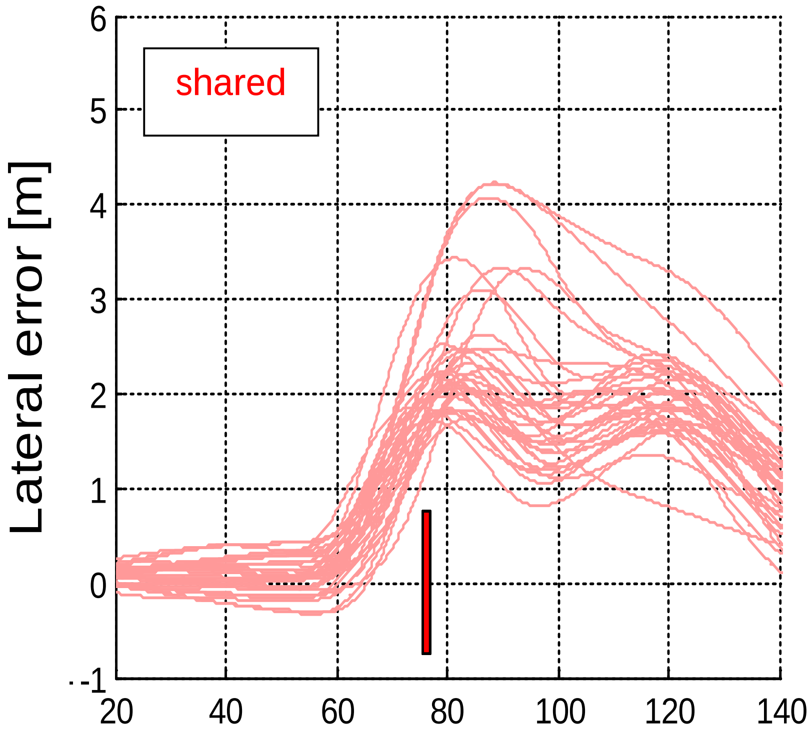


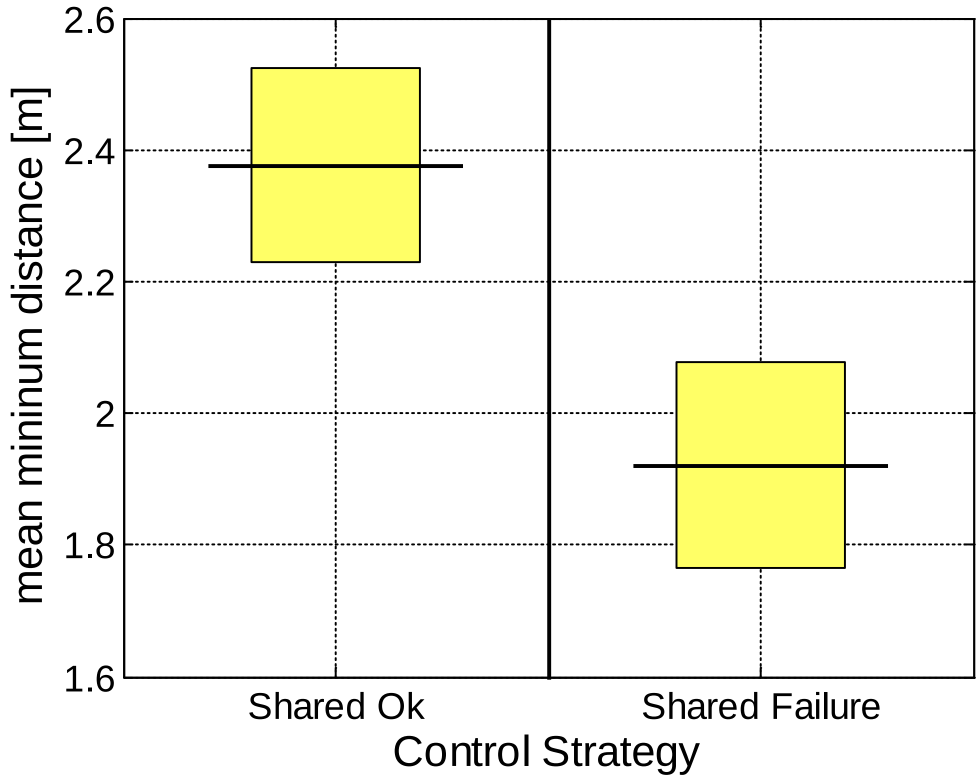
Manual Control vs IMperfect Shared Control

Mulder & Abbink (2011)

Obstacle hit rate with faulty shared control: 64.7% (up from 15.2%)

But what would have happened with full automation?





Automation with override vs Shared Control

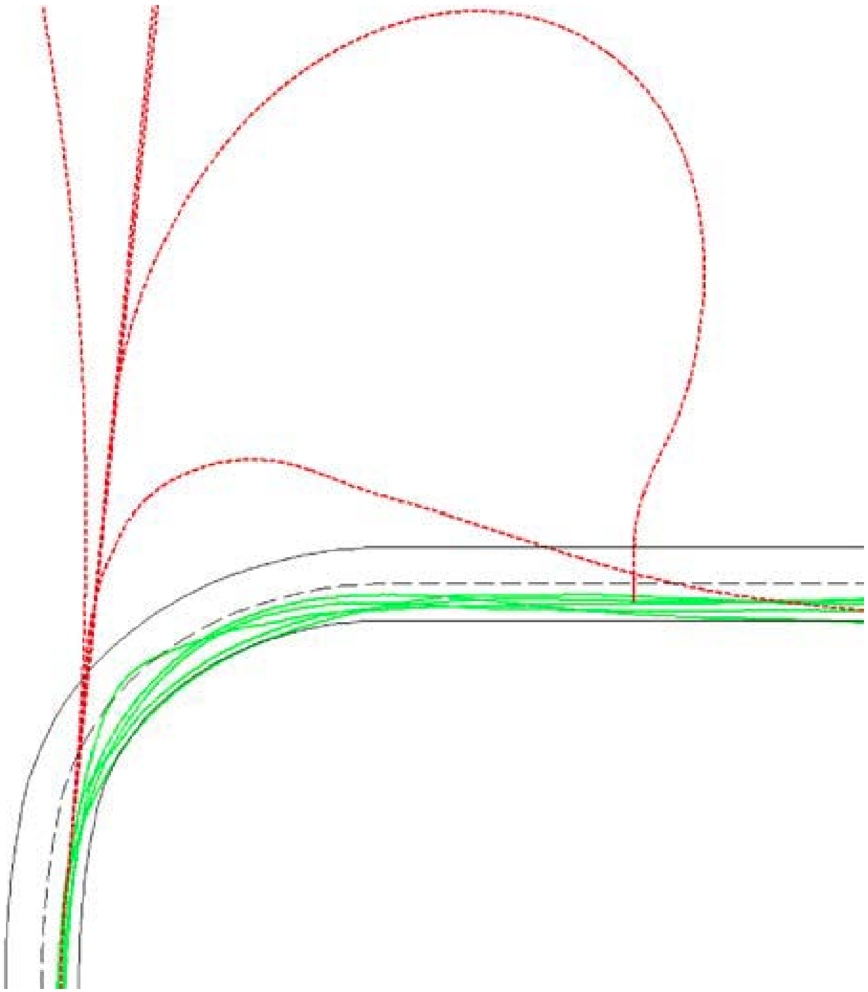
Flemisch et al (2008)

Method: Test automation errors of a curve negotiation support system that would fail just before the onset of a sharp curve

Conditions

with full automation (red lines) that allowed manual override

with haptic shared control (green lines)



How bad is over-reliance, and what can we do to solve it?

Long-term effects of shared control

Guidance hypothesis

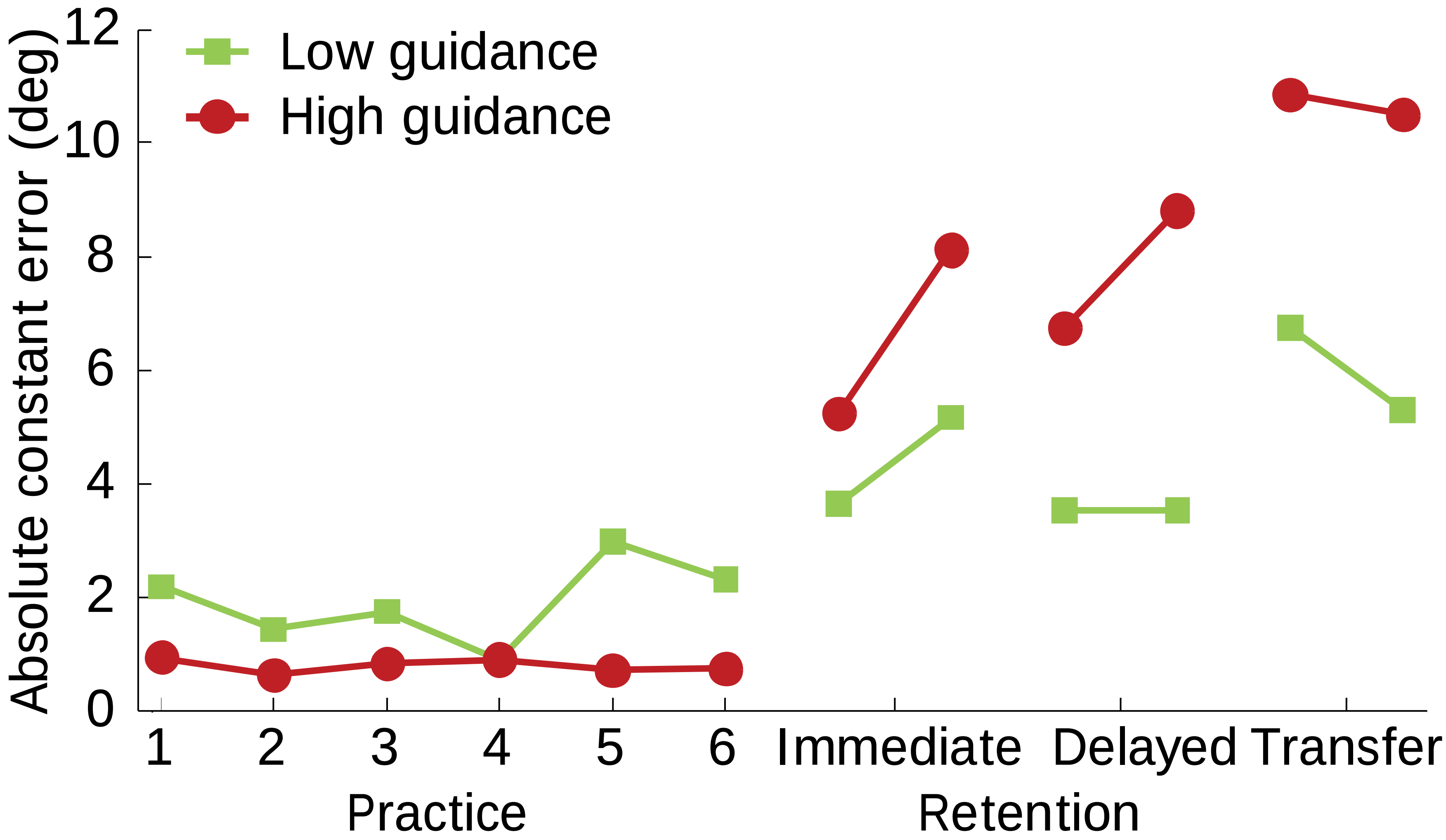
"Augmented feedback ... facilitates performance when provided, but leads to deteriorated performance after feedback is withdrawn."

(Schmidt & Wulf, 1997)

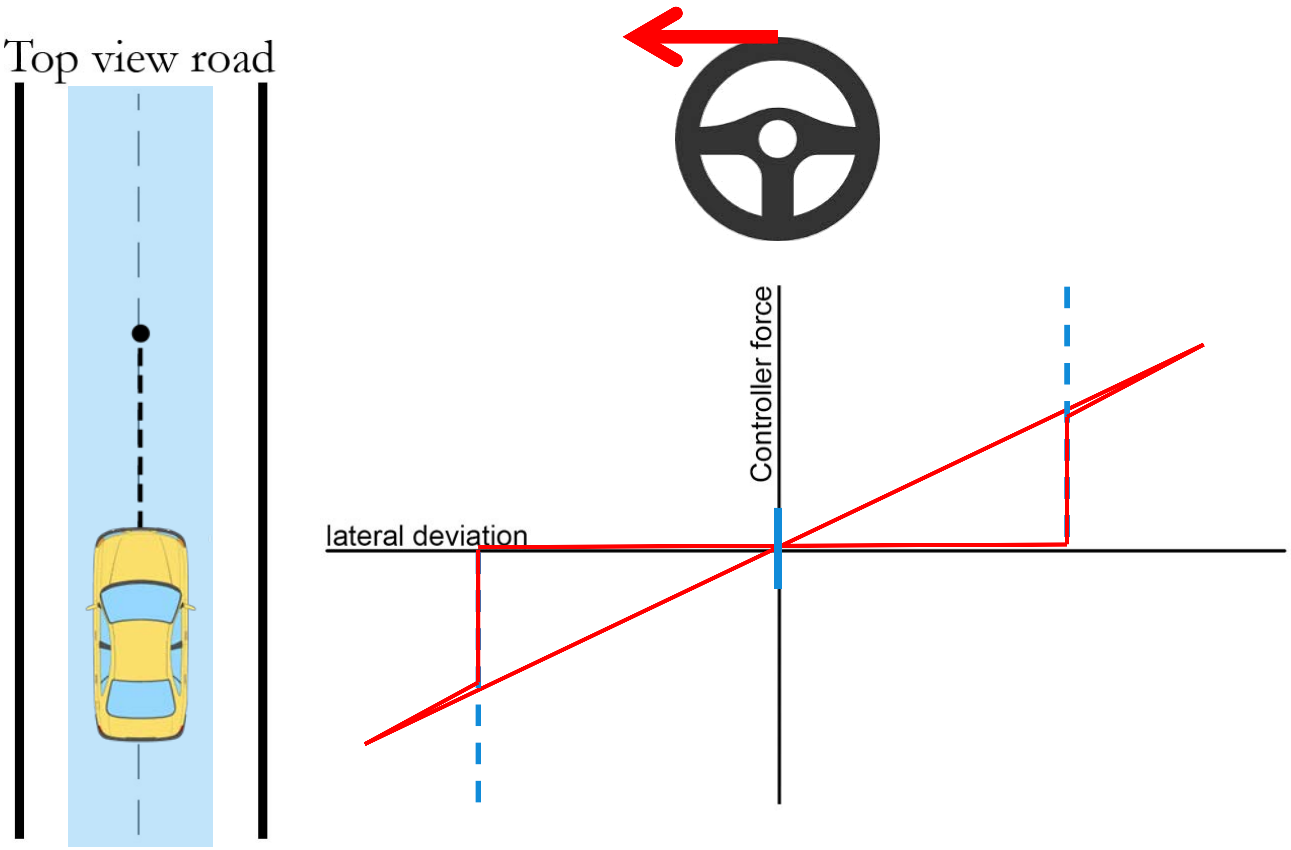
"Feedback that is relatively more guiding would be expected to have greater detrimental effects on motor learning"

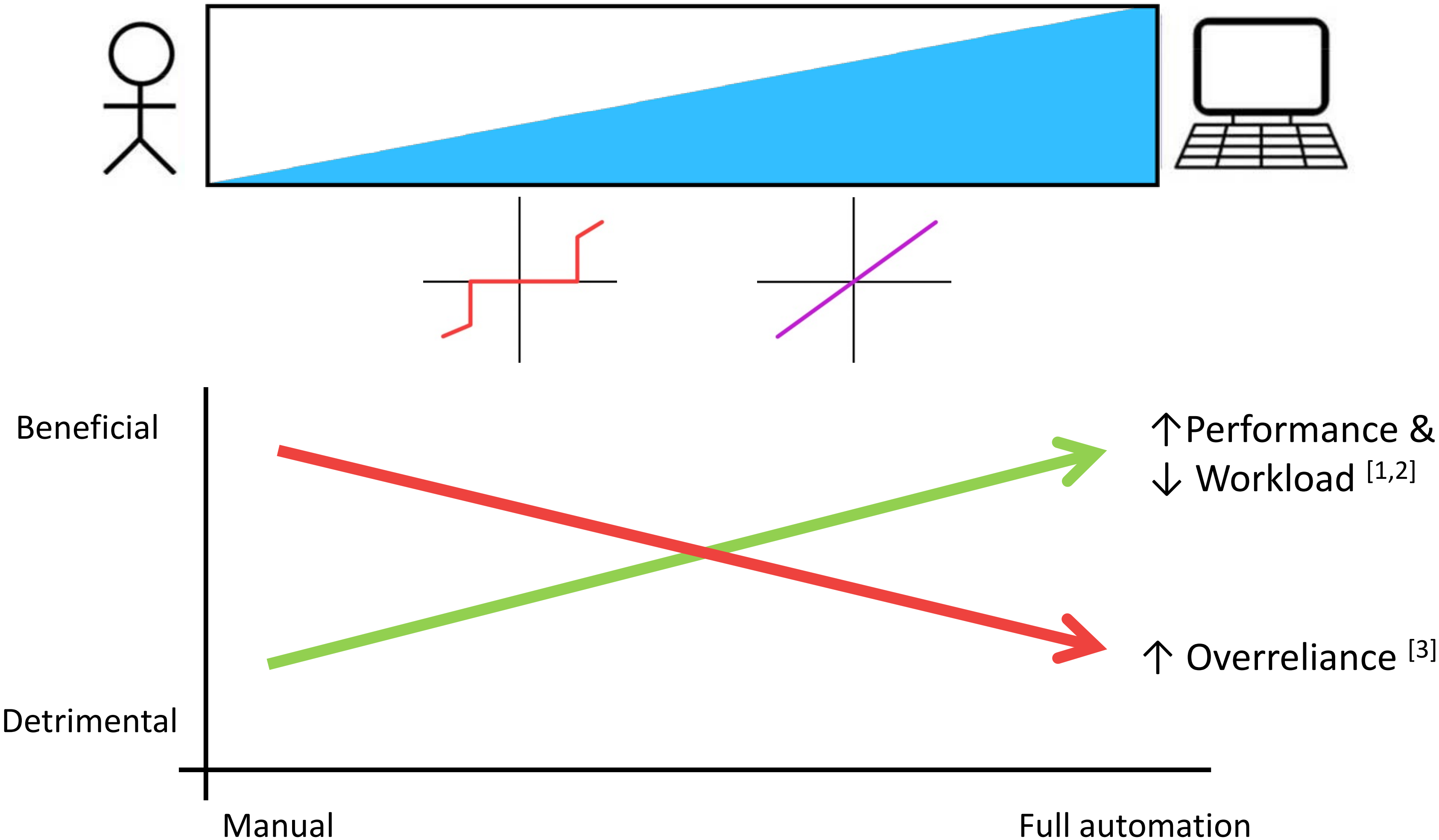
(Winstein et al., 1994)

Long-term effects of shared control

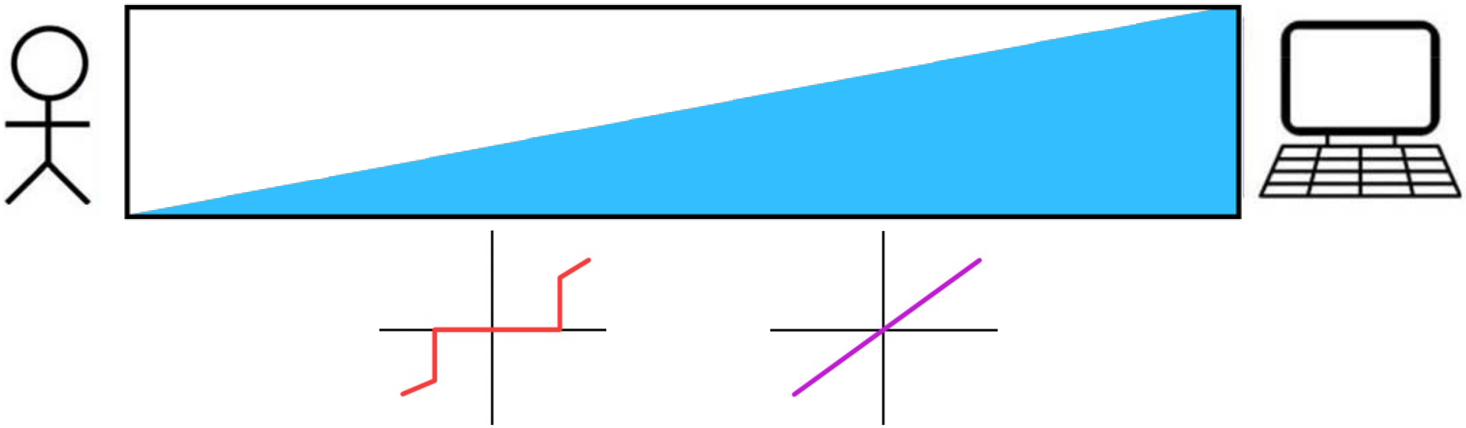


How does bandwidth feedback work?





[1] Flemisch et al. 2008, [2] Mulder et al. 2012, [3] De Winter & Dodou 2011



More feedback will result in:

- better **performance**
- a decreased **workload**
- stronger **aftereffects**

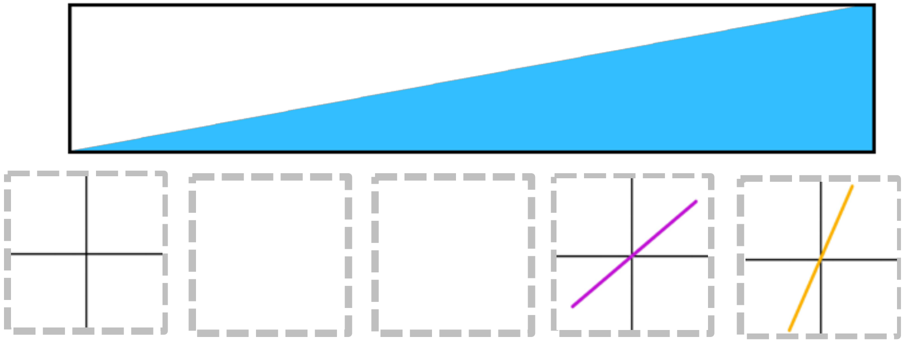
Bandwidth feedback will result in less driver **satisfaction**

Simulator

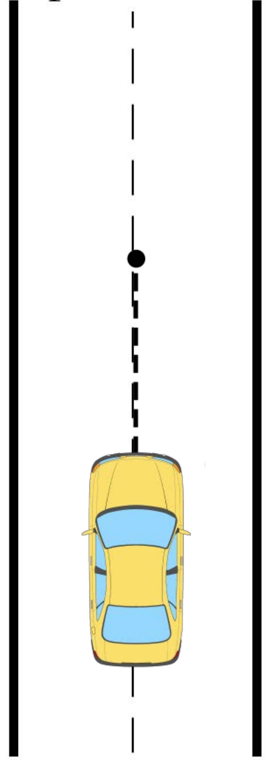
32 participants:

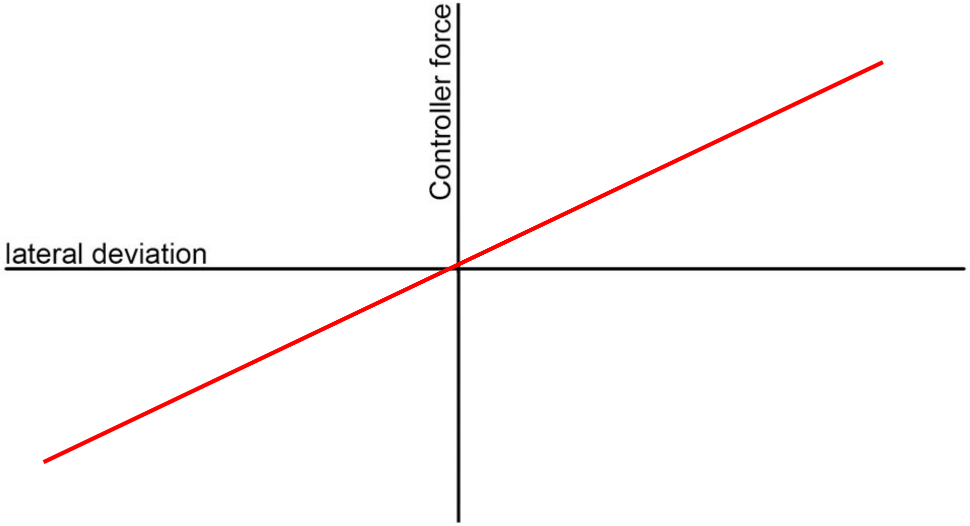
- Between 18 – 38 years old
- At least 1 years licensed to drive

Continuous feedback

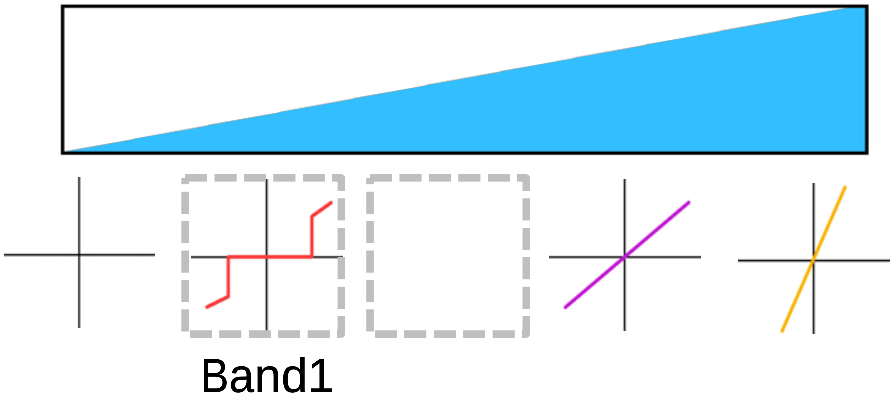


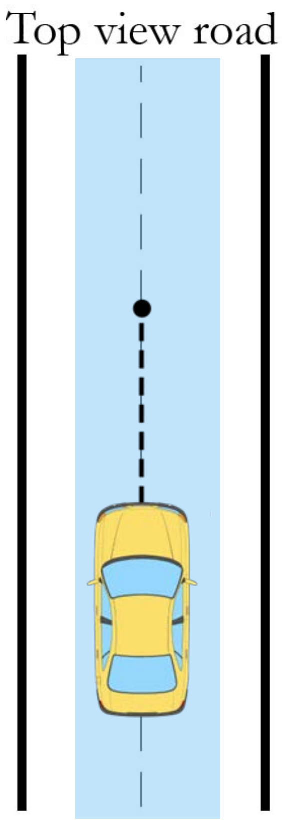
Top view road

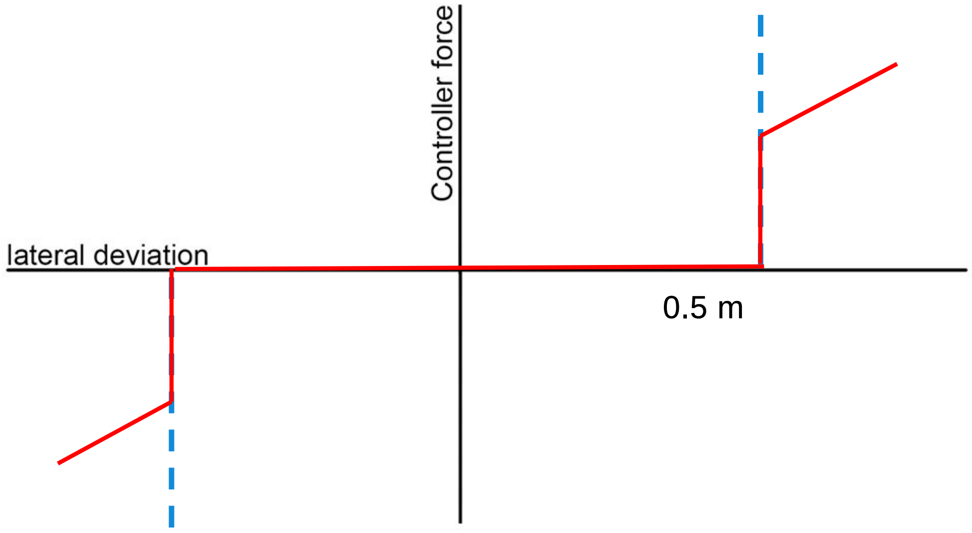


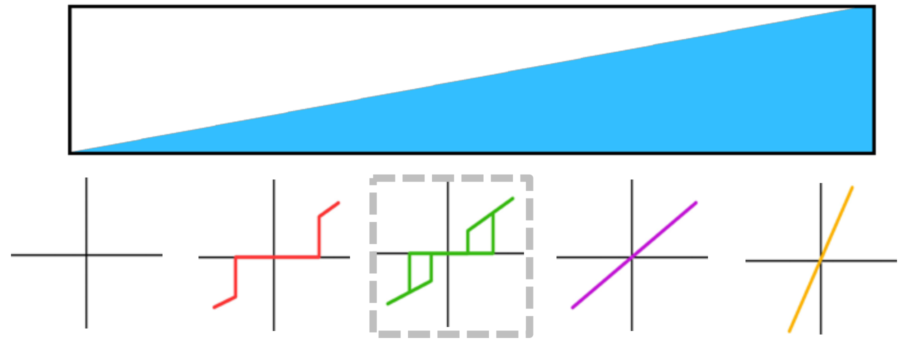


Bandwidth feedback 1



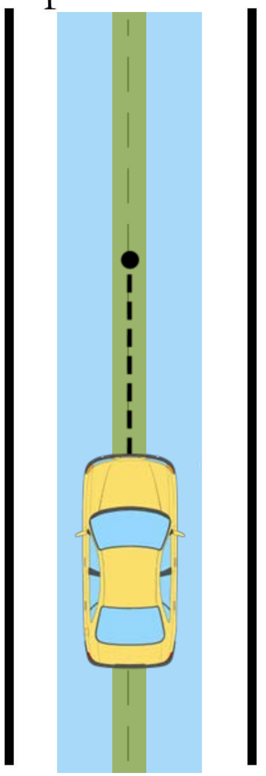


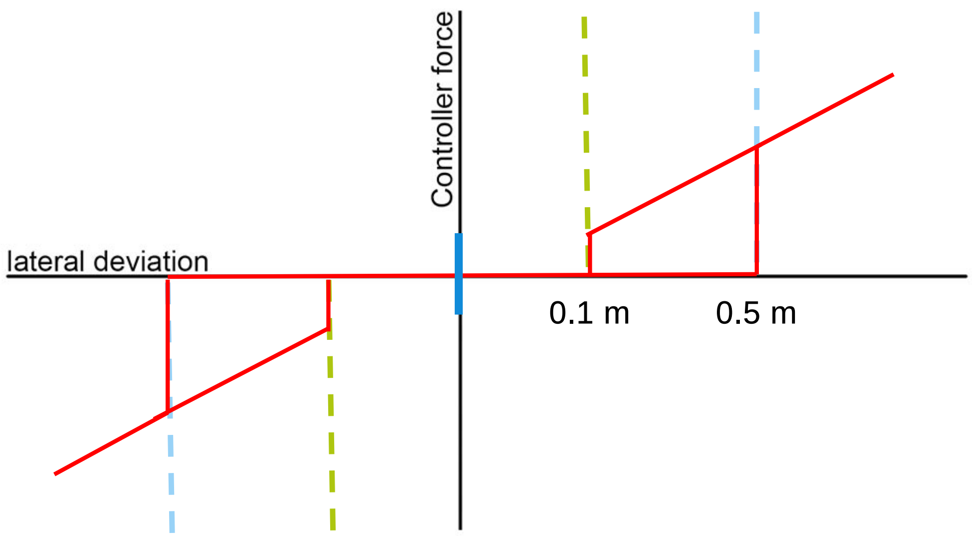




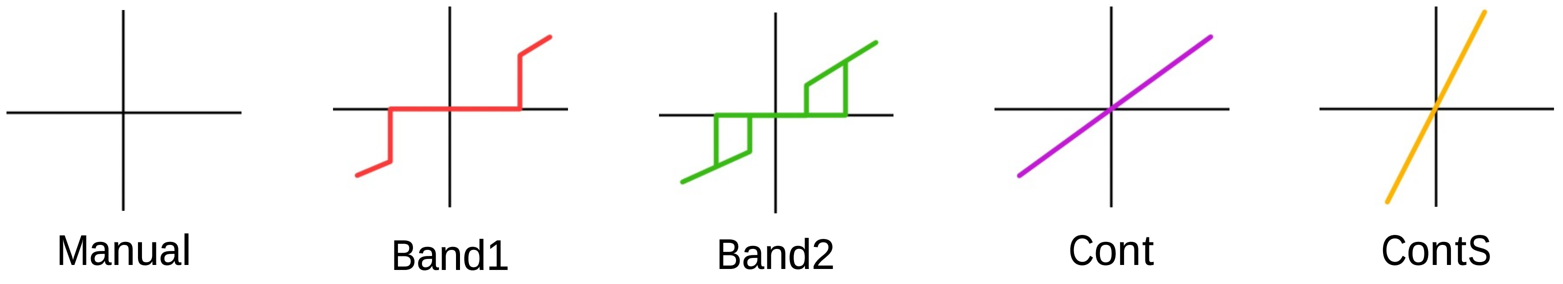
Bandwidth feedback 2

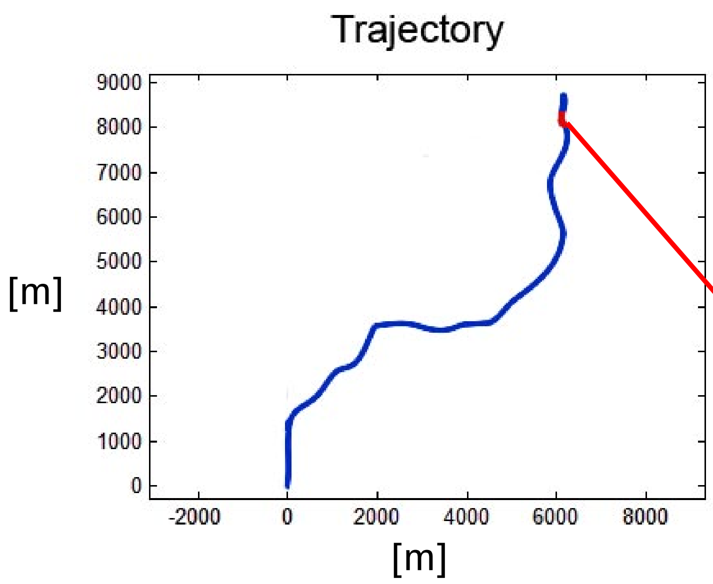
Top view road

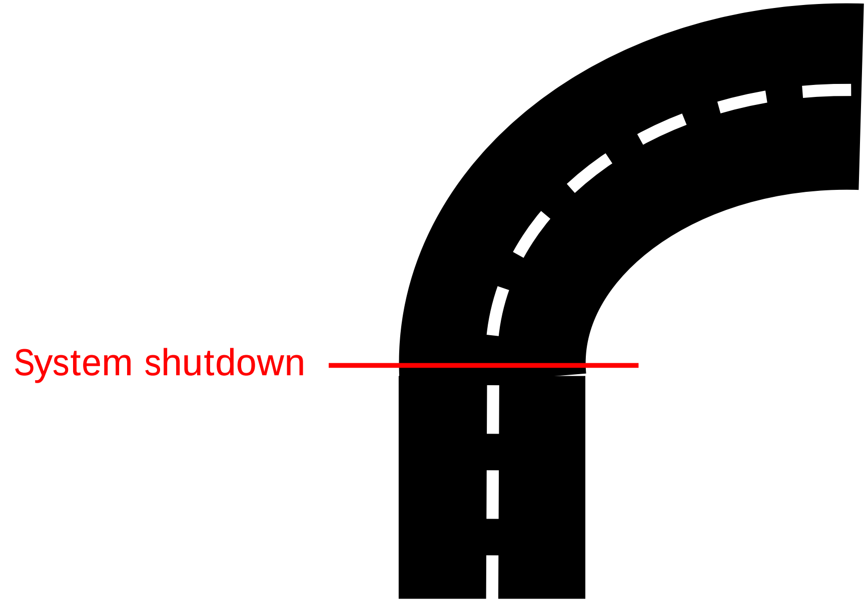




Condition 1	Condition 2	Condition 3	Condition 4	Condition 5





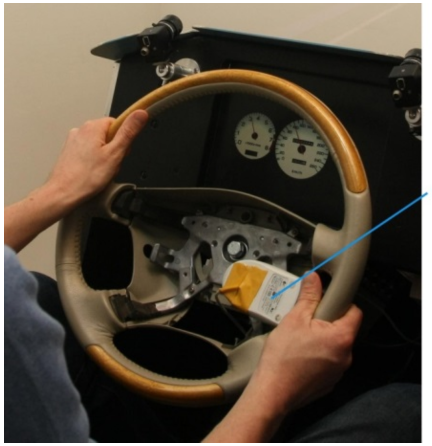


Task :

- Drive in the centre
- Peripheral detection task

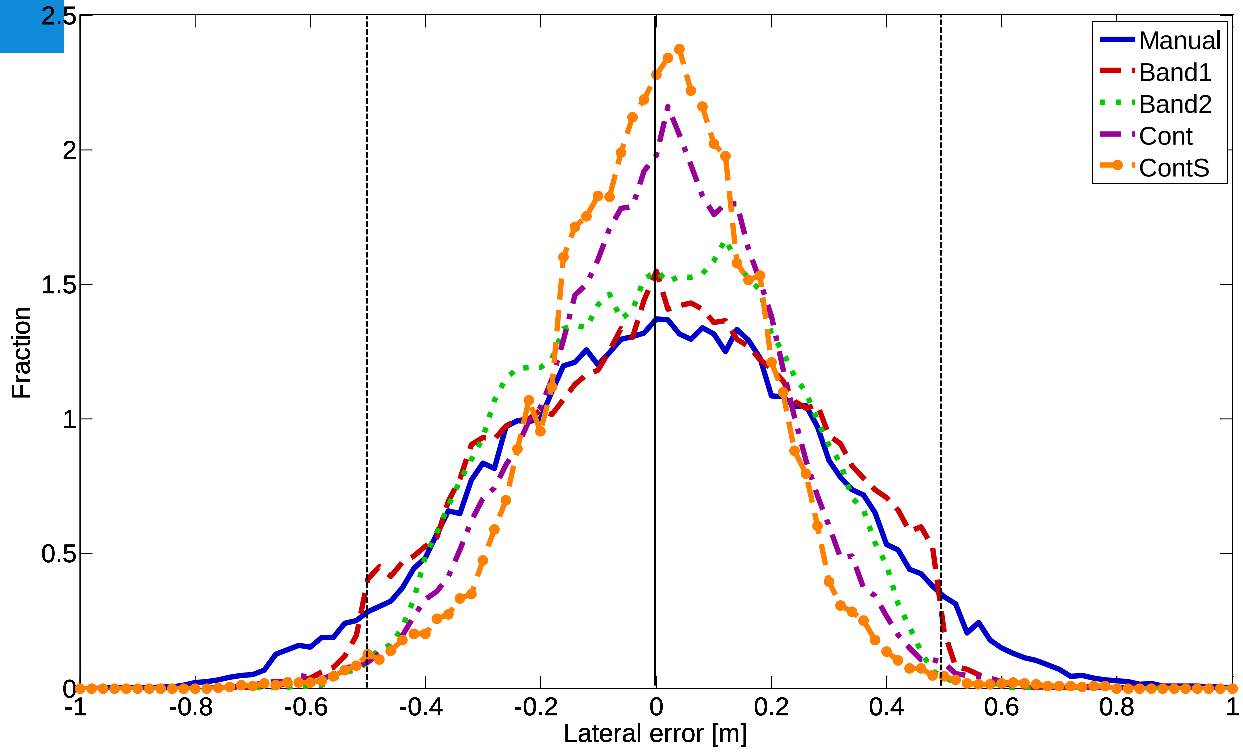
Questionnaires:

- NASA-TLX (Workload)
- Vanderlaan (Driver's satisfaction)



Performance

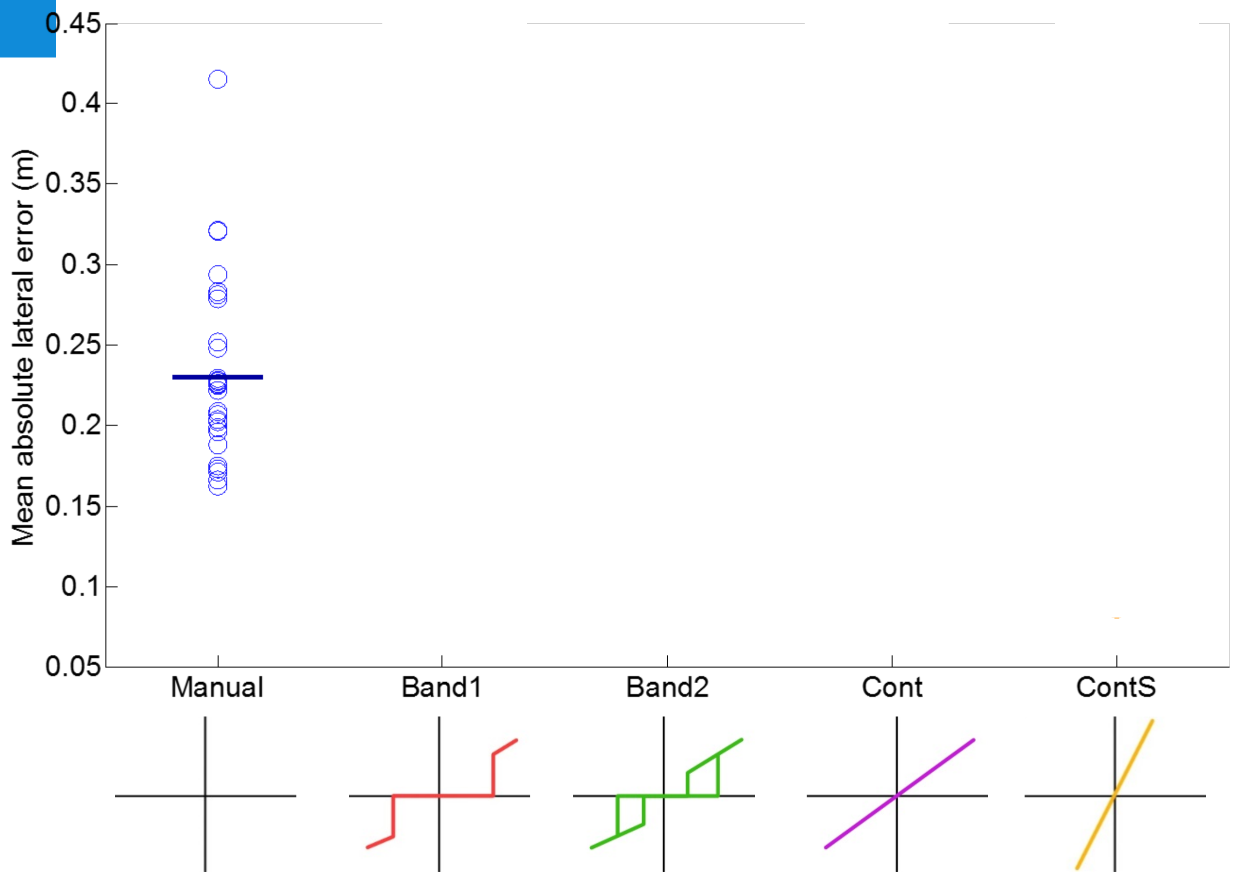
Distribution lateral error



- Bandwidth feedback prevents large lateral errors
- Continuous feedback yields better performance

Performance

Mean absolute lateral error

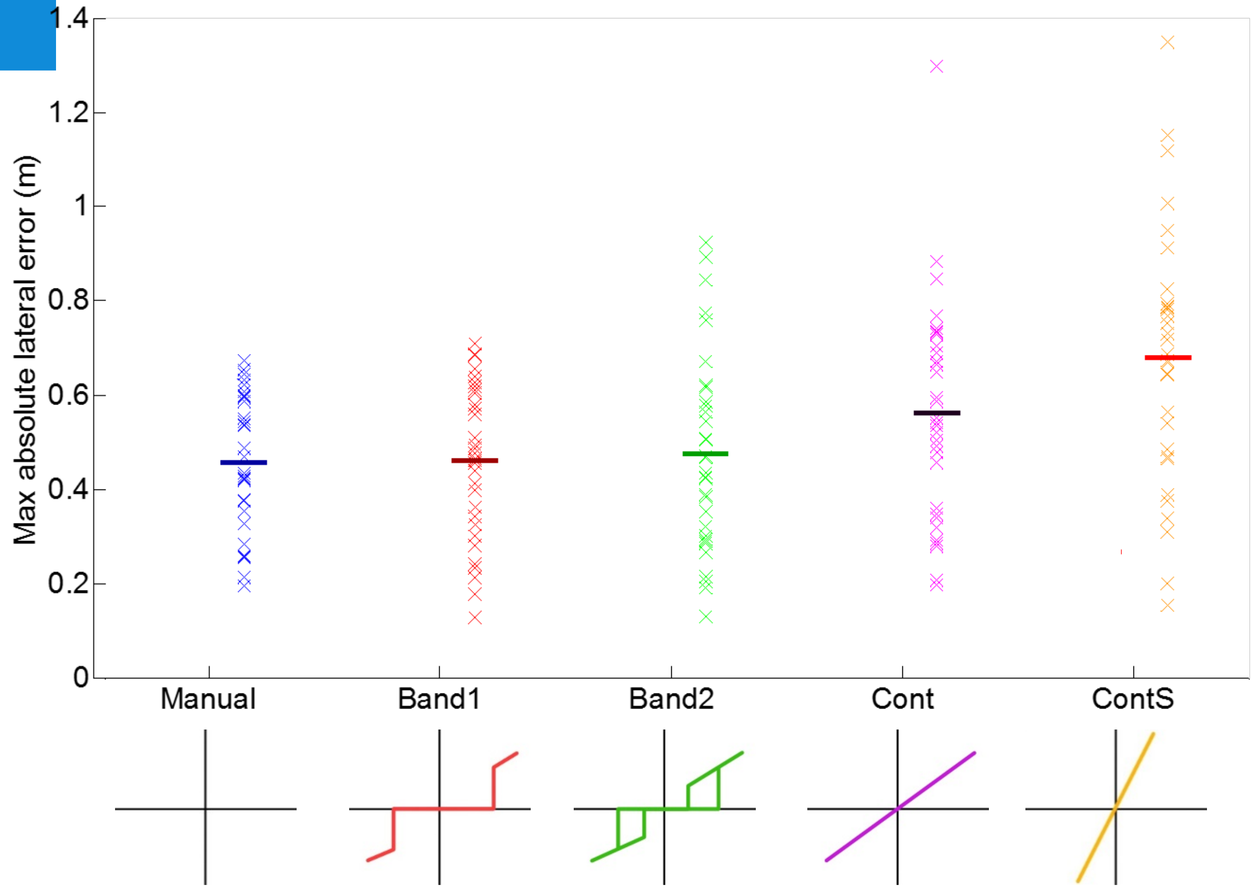


- Performance increases with more feedback
- Confirms results from the literature

F(4,124) = 60.3, p = $3.38*10^{-28}$

Results

Maximum lateral error – before/after

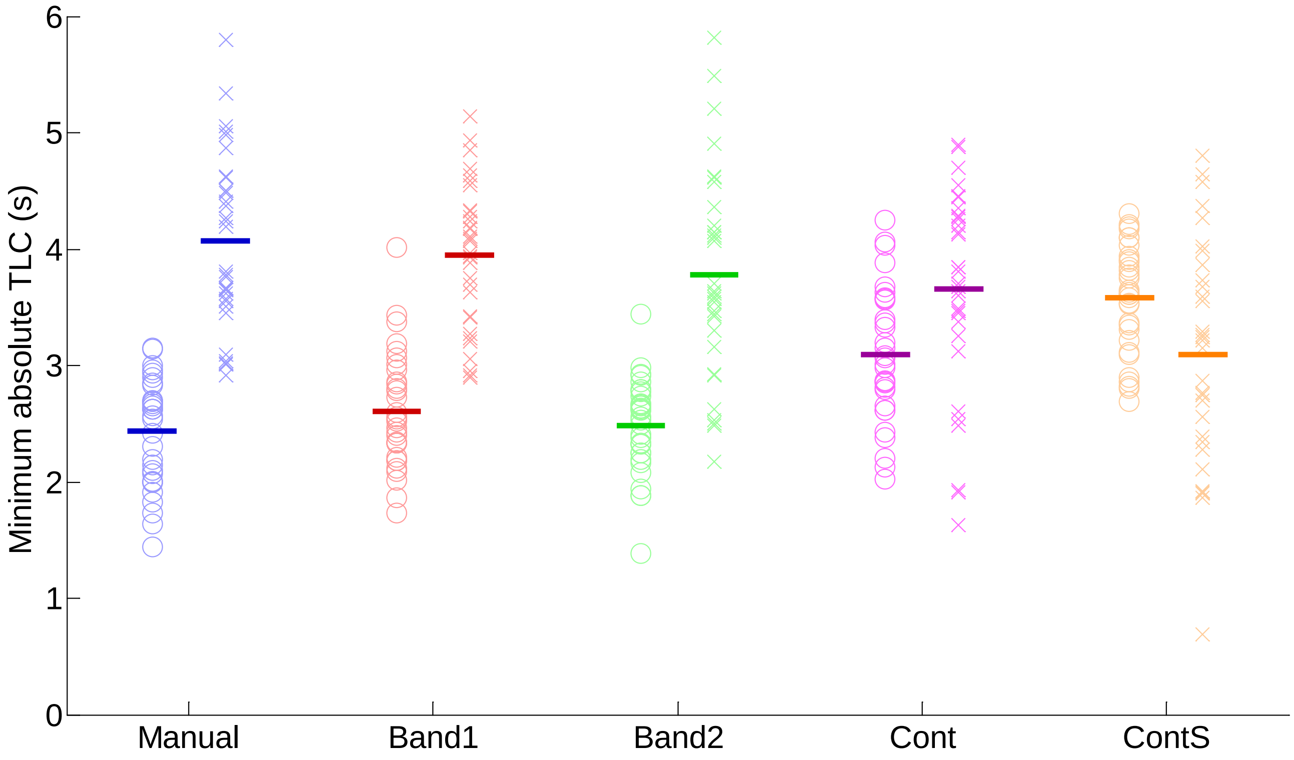


- Continuous feedback yields aftereffects
- Only ContS is significantly higher than manual and bandwidth

$F(124,4) = 9.78$, $p = 6.61*10^{-7}$

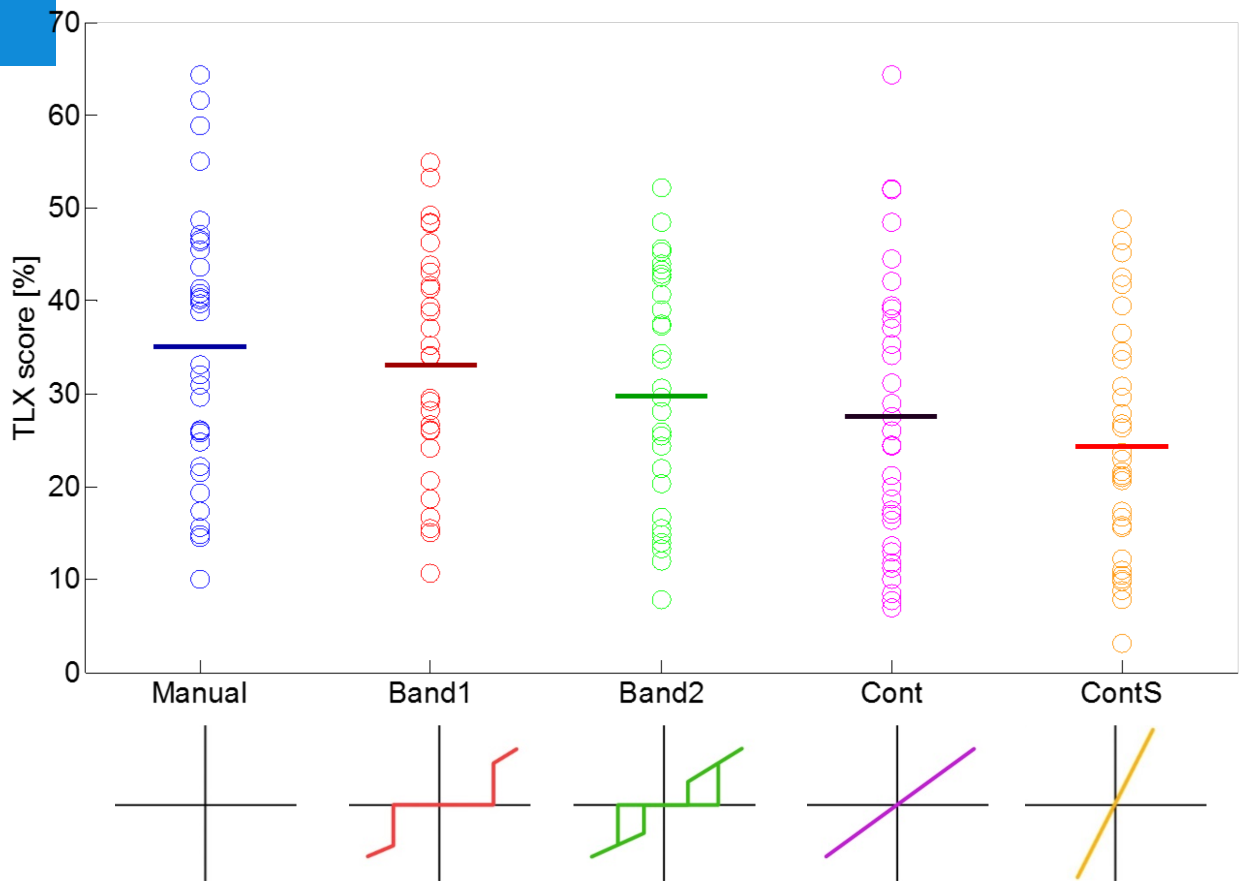
Results

Time-to-lane crossing (available time to respond before you leave the lane)



Workload

NASA TLX



- Continuous feedback yields lower workload than manual

$F(124,4) = 5.91$, $p = 2.19 \cdot 10^{-4}$

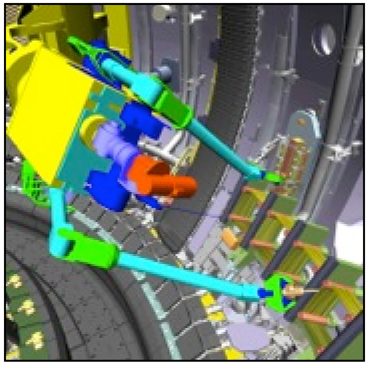
Conclusions

The more the guidance, the more benefits of automation is inherited (increased performance, decreased workload)

The more the guidance, the more downsides of automation is inherited (increased reliance, after-effects)

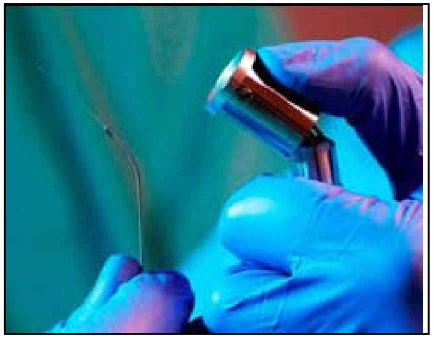
Future Work

2011 – 2016 STW Perspectief Programma Human-centered Haptics



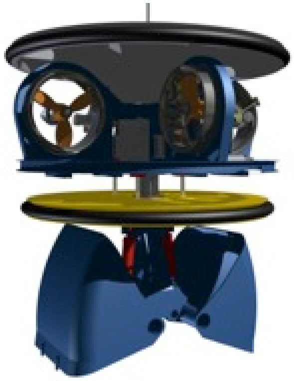
Nuclear fusion reactor

Funding: 4,800,000 euro
from STW + companies

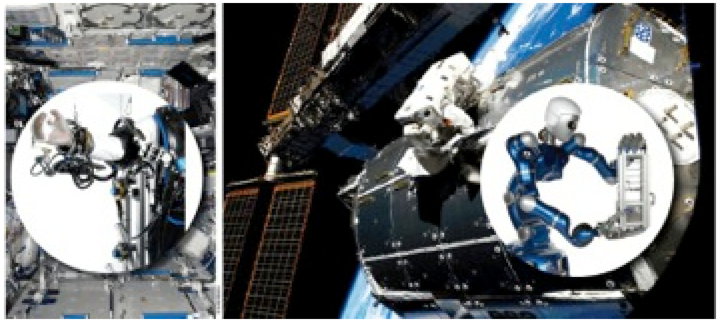


Steerable needles in humans

Goal: Extend concept of Haptic Shared control to tele-operation



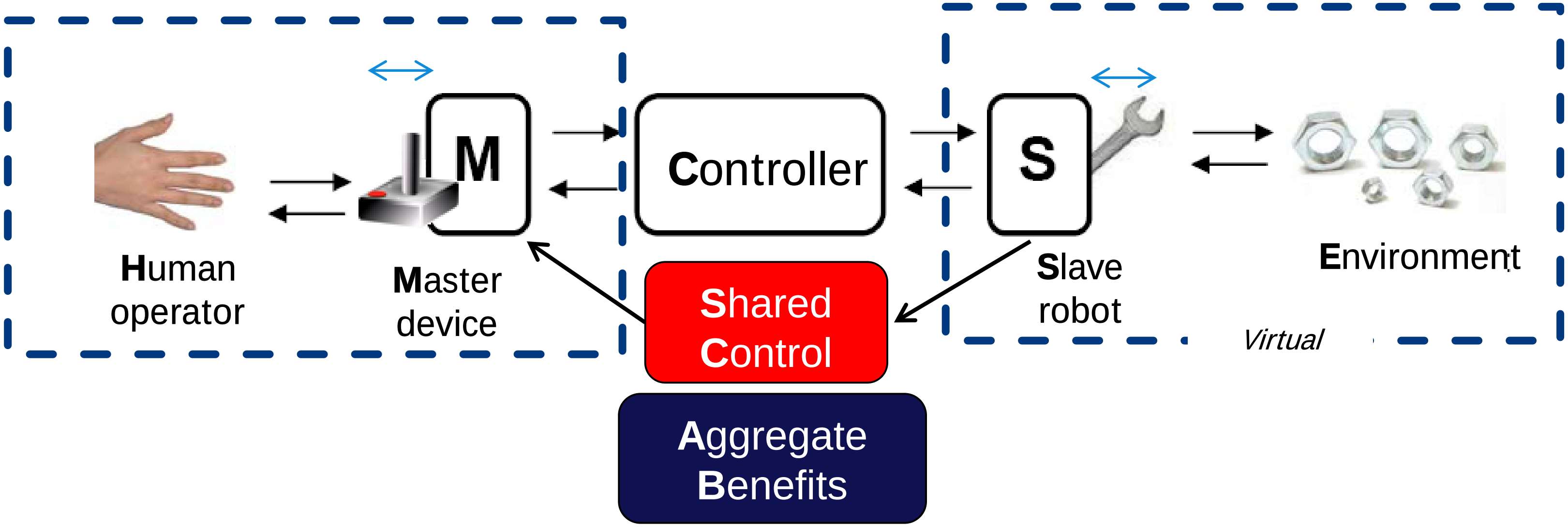
Deep sea mining



Space robotics

Lifting aid for care and industry

"What is the impact of each element on total benefit for the end user?" (H M C S E SC AB)



Guidelines for design and evaluation

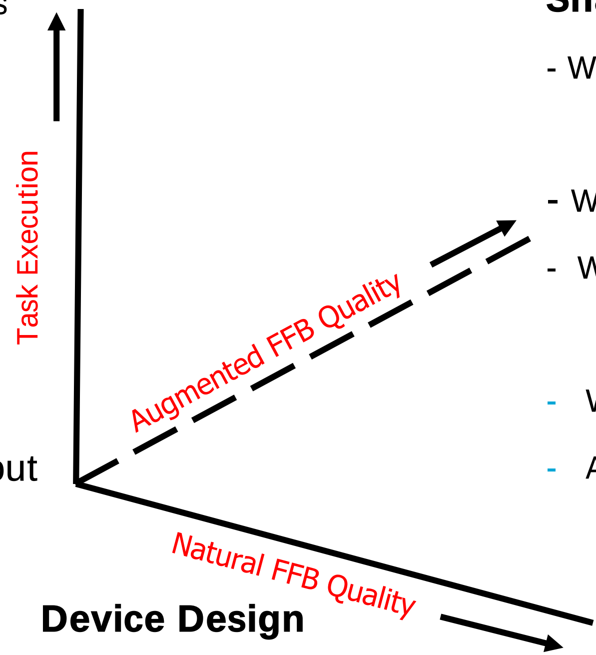
Develop fundamental understanding & practical guidelines

Task Execution

- What (sub)task?
  - Abstract vs realistic tasks
  - Force tasks
  - Static vs dynamic
- Environment
  - Constraints, time delays
- Criticality?
- What metric to look at?
- How do humans think about performance and effort?

Shared Control Design

- What controller is behind the force generation?
  Human-centered? Preview needed?
- Which task is supported, which not?
- Which environmental information needs to be sensed?
- What (shifts in) Level of Haptic Authority?
- Augmented visuals/tactile/auditory as well?



Device Design

- Fidelity of signals (‘transparency level’)
- Impact of Master / Slave / Controller Design
- Endpoint VS exoskeleton control

Take Home Messages

I hope I have been able to demonstrate:

- That improved tool design (master-controller-slave) is not ‘holy’, other ways exist to improve task execution
- That haptic shared control allows for an integrated framework to support humans during vehicular control and telemanipulated control
- The haptic shared control lies in between manual control and automation, inheriting benefits but also limitations of each!
- That a solid understanding of human multi-sensory feedback and control is required to engineer and evaluate such novel solutions

Questions?

www.DelftHapticsLab.nl

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