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HUman behavioral Modeling for enhancing learning by Optimizing hUman-Robot interaction

HUMOUR

THEME 2: Cognitive Systems, Interaction, Robotics

Deliverable 6.2

Report on advanced studies of assisted motor learning

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1. Introduction

The goal of WP6 is to test HUMOUR concepts and technologies in the field of motor learning. The results are fed back to contribute to the development of a system which controls and supports motor learning for different groups of learners and for different types of task. Therefore the experimental work in WP6 serves to evaluate different types of robot assistance for different types of motor-learning problems. If needed, motor-learning problems are analyzed in depth to identify possible modes of assistance.

The grand challenge for WP6 is to understand whether and how haptic guidance can facilitate the acquisition of motor skills. We started with the premise that different types of motor-learning problems may profit from different types of robot assistance. In the course of the HUMOUR project we were progressively faced with the challenge to provide an answer to the question of which types of motor-learning problems do actually benefit from which types of assistance, and of which types of assistance are actually detrimental for which types of motor learning. In this Deliverable our response to the challenge is documented. It is still work in progress, which has not yet reached definite conclusions. However, the basic ingredients of the answer can be recognized and are documented in the current draft of a review paper. To the broad review we add a number of specific contributions that were instrumental in shaping our answer. Their order roughly matches the organization of the review.

2. Robot assistance of motor learning: a review

Motor learning embraces different mechanisms which result in different products, that is, different types of representations. With respect to products, a fundamental distinction is that between trajectory learning and transformation learning. With respect to mechanisms, error-based learning and imitation seem to be crucial.

Movement trajectories have spatial and dynamic (temporal) characteristics. They can be instructed by making use of different sensory modalities. They can also be instructed verbally, and they can be actively produced (with subsequent error feedback). Robot guidance provides a haptic demonstration of the target trajectory. Generally this is not superior to a visual demonstration as far as the paths (spatial characteristics) are concerned, but it might be particularly suited for timing (dynamic characteristics). Consequently there are benefits of haptic guidance for the learning of dynamic (temporal) movement characteristics, but no benefits for the learning of spatial characteristics. This pattern of results has been observed for a number of tasks. In certain tasks, in which shape and timing of the movement are tightly interrelated, benefits for timing can result in benefits for shape. Different aspects of timing are likely to profit differently from haptic guidance, with relative timing perhaps as that aspect that profits most. Subjectively relative timing corresponds to the "rhythm" of the movement.

Even though haptic guidance does not facilitate path learning, divergent force fields which drive the hand away from the known correct (and mostly straight) path do. There are two possible mechanisms which produce this effect. The first one is increased limb stiffness, which is triggered by higher accuracy demands otherwise. Here it serves to resist divergent or unpredictable forces, but at the same time it could increase accuracy in moving along a certain path. Of course this is not a mechanism of motor learning that is called upon, but a performance strategy that is induced by the force field. The second possible mechanism is error amplification, which exploits the relation between (perceived) size of error and size of the subsequent correction. Effects of this mechanism are not restricted to haptic errors, but can also be seen with visual errors.

Transformation learning can be concerned with kinematic or dynamic transformations. Learning of kinematic transformations is impeded by haptic guidance, whereas divergent force fields around the correct path of the hand leave learning unaffected as compared with a control condition. Benefits are not even observed when guided and active trials are mixed, or when the transformation is a pure time delay. The most likely reason for the absence of benefits in spite of the haptic demonstration of the correct hand movements (which in this learning task are not demonstrated visually) is a functional haptic neglect during the learning of novel kinematic transformations. Somatosensory inflow seems to be inhibited at a cortical level to avoid potential conflicts between haptic and visual spatial information. The most likely reason for the detrimental effects of haptic guidance, but not of divergent force fields, is that they largely abolish active error corrections.

Robot assistance of the learning of dynamic transformations amounts to creating a novel (joint) dynamic transformation that has to be learned. This results in benefits when robot assistance amplifies the errors that result from the (original) dynamic transformation, and it results in impediments when the errors are reduced by the robot.

In summary, there are primarily two mechanisms which produce the benefits of robot assistance:

- haptic demonstration of correct movements, provided it is superior to other modes of instruction such as visual demonstration (e.g. for dynamic, but not for spatial movement characteristics),
- error amplification, which results in stronger corrections, provided that the amplified errors are relevant for the motor-learning problem.

In addition to these modulations of motor learning, performance can be improved when external forces induce a long-term increase of limb stiffness during performance of certain tasks.

The beneficial mechanisms are accompanied by at least one mechanism which produces detrimental effects of robot assistance:

- error reduction or prevention of active error corrections, which interferes with error-based learning.

manuscript in preparation:

NN: Robot assistance of motor learning.

3 Robot assistance of motor learning: specific contributions

3.1 Learning different types of movement trajectories

In two experiments we examined the role of haptic guidance for the learning of movement trajectories. In the first experiment the task was to draw shapes of different complexity. Guidance was in the format of path guidance (or haptic tunnel) so that the hand was pulled toward the correct path. Performance was assessed by the deviations of the movement trajectory from the target. In test trials without haptic guidance after the end of practice no benefits could be observed, but a tendency toward a disadvantage of robot assistance, in particular for the simpler shapes. The observations suggest that haptic guidance creates a novel task so that costs should be expected for tasks that are already practiced to some degree.

proceedings paper:

Kostic, M.D., Kovacevic, P.S., & Popovic, D.B. (2011). Is the haptic tunnel effective tool for motor learning? IFMBE Proceedings, 37, 761-764

In the second experiment the task was more complex and took the form of a computer game. A virtual stylus was visible on the monitor and was controlled by the participants by way of moving the stylus of a Phantom Omni haptic device. A virtual ball was attached to the tip of the stylus via a spring. The ball had to be thrown into a goal frame; it was automatically disconnected from the stylus at a pre-defined spatial boundary. Guidance was in terms of an attractive force toward the release point, based on recordings of expert performance. Performance was assessed in terms of spatial variables such as the smallest distance between the trajectory of the ball and the goal frame. Learning was compared between novice players of the task and trained players. In trained players robot assistance turned out to act as a disturbance.

proceedings paper:

Dosen, S., Andresen, A.H., Kannik, K.E., Klausen, C.S., Nielsen, L., Wojtowicz, J., & Popovic, D.B. (2010). “Assistive” forces for the acquisition of a motor skill: Do they assist or disturb motor learning? Proceedings of the 1st International Conference on Applied Bionics and Biomechanics ICABB-2010, Venice, Italy

3.2 Learning different types of motor timing

Different types of motor timing have been distinguished in the literature. The first distinction is between implicit or emergent timing and explicit or event-based timing. The second distinction is between absolute and relative timing. A task suggested for the study of implicit timing is continuous circle drawing, whereas for the study of explicit timing intermittent circle drawing has been suggested. In intermittent circle drawing, drawing a circle and pausing for the same duration alternate. In this task the relative timing of circle and pause is generally incorrect. In spite of instructing (and pacing) same durations, pauses tend to be shorter than the time spent with drawing a circle. In a synchronization-continuation paradigm with auditory and auditory-plus-haptic guidance we examined the effects of haptic guidance on both absolute and relative timing.

Robot assistance had an immediate beneficial effect on performance. However, in the continuation phases (without auditory and haptic guidance) the group differences disappeared for the implicit-timing task. For the explicit-timing task, relative timing became poorer than in the synchronization phase, but it remained superior to relative timing in the control group. Absolute timing was assessed by the mean and variability of the cycle durations. A cycle consisted of drawing two successive circles in the implicit-timing task and of drawing a circle and pausing in the explicit-timing task. Only for explicit timing, but not for implicit timing, the precision of absolute timing was worse after haptically guided practice than in the control group. This finding, however, is likely a by-product of the enhanced relative timing which goes along with longer pauses and an associated increase of the variable error. According to these results, relative timing is enhanced by robot-assisted training, perhaps because haptic guidance is a better means to communicate the target pattern than visual (or other) modes of presentation.

Submitted manuscript:

Lüttgen, J. & Heuer, H.: The influence of robotic guidance on different types of motor timing

3.3 Robot-assisted putting: redundancy and variability

While robots are widely used to promote the neuromotor recovery of stroke survivors, there is some con- troversy as to whether robots might be useful to facilitate the acquisition of novel motor skills. Robots could be used to guide a trainee to experiment the correct movements and/or by preventing him/her from performing incorrect ones (the guidance hypothesis). We investigate whether and on what circumstances physical interaction with a robot may facilitate the acquisition of a novel motor skill.

We explored this issue in the context of a simulated putting task, consisting of gently hitting an object (e.g. a ball) by means of a tool (the pad, e.g. the golf putter) to move it to a desired final position. Successful performance is determined by an accurate adjustment of pad velocity and acceleration at impact. Putting is a redundant task, in the sense that the same final position of the ball can be obtained by different combinations of pad velocity, acceleration and point of impact.

In particular, we investigated the way subjects improve their performance with exercise, with and without the assistance of a robot. A virtual environment, involving a planar robot manipulandum and a computer screen was used to simulate the physics of the ball and the force impulse delivered to the pad during impact. In one subjects group (control group), the robot generated no assistance. In another group of subjects, the robot generated assistive forces, aimed at directing pad movements toward a target position and velocity at impact (assisted group). In both groups, we looked at the subjects performance - and its evolution with exercise - at several levels of description, namely: (i) final error (distance between final ball position and center of the target area); (ii) ball velocity just after impact; and (iii) hand position and velocity just before impact. In all cases, we looked at both mean value and variability (variance).

We found that guidance is helpful in improving longitudinal error (a matter of speed accuracy), but not directional error (a matter of position accuracy). These results are consistent with the notion that guidance can help with the dynamic, but not the geometric components of a task.

Submitted manuscript:

I. Tamagnone, A. Basteris and V. Sanguineti. Robot-assisted acquisition of a motor skill: evolution of performance and effort

3.4 Vision and proprioception in force-field adaptation

Learning of many novel skills requires integration of different sensory modalities, in particular vision and proprioception. This is also the case when learning is supported by haptic guidance. Of particular importance is the issue whether the need for haptic guidance can be partly avoided by using purely visual information. In previous experiments Melendez-Calderon et al. (2011) showed that it is possible to learn a viscous curl force field (VF) without proprioceptive error to drive adaptation, by providing visual information about the position error. This suggests that in many situations proprioceptive (or haptic) information might not actually add to visual information.

In the experiments presented here, we investigate how providing visual feedback of the estimated hand position – by means of processing the force applied to haptic channel sides – affects the learned behaviour in a real environment. Our results highlight the role of visual feedback on retaining learned dynamics. Subjects who learned a VF in a real environment and then successively performed the task constrained by a haptic channel and associated visual feedback of hand trajectory did not exhibit de-adaptation after re-exposure to the real environment. Contrarily, those subjects performing the task with no feedback of hand position exhibited a fast decay rate of the value of the force along the lateral walls of the haptic channel. In addition, subjects who experienced visual feedback only showed a slower de-adaptation rate than those who experienced both visual and proprioceptive error information. We show that a unified Bayesian framework for sensory-motor adaptation can reproduce and explain our experimental results.

unpublished report:

Melendez, A. & Burdet, E.: Persistence of motor adaptation after virtual environments

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3.5 Functional haptic neglect in transformation learning

Adaptation to a visuo-motor rotation has been shown to suffer from haptic guidance during practice. Only with a divergent force field around the correct path of the hand, adaptation is as good as in a control condition without robot assistance. The detrimental effects of robot assistance for this motor-learning problem are hard to accept. For example, robot assistance provides information on the correct direction of hand movements (which is rotated relative to the direction of the target), and in principle it should be straightforward to reproduce these movements actively. To facilitate such a demonstration-reproduction cycle, we mixed guided trials and active trials in two experiments. In the first experiment we used trajectory guidance with the position-time curve of correct movements of each individual participant (moving his hand in the correct direction in the absence of the visuo-motor rotation). Guided and active trials were mixed randomly. In the second experiment we used a divergent force field which does not reduce active error corrections, but also provides information on the correct directions of hand movements. In addition there was a strict alternation of assisted and active trials with the same target. In both experiments there was no advantage of robot assistance as compared with adaptation in a control group without assistance.

In a third experiment the visuo-motor transformation was a pure time delay of 300 ms in a discrete tracking task with preview. We chose this type of transformation because timing seems to profit from haptic guidance in general. However, for this temporal transformation haptic guidance again produced no benefits for adaptation as compared to a control group.

The consistent failures to find benefits of haptic guidance for adaptation to visuo-motor transformations provides further evidence of functional haptic neglect during this task. Such a hypothesis is consistent with findings on the effects of degraded somatosensory information on performance with and adaptation to visuo-motor transformations. Functional haptic neglect could serve to avoid potential conflicts between different sources of spatial information.

manuscript in press:

Heuer, H. & Rapp, K.: Adaptation to novel visuo-motor transformations: further evidence of functional haptic neglect.
Experimental Brain Research

3.6 Strategy learning

The goal is to investigate how humans learn to become skilled users of a Virtual Underactuated, Bimanual Manipulandum (VUBM) in an unstable environment. VUBM, which is simulated by a bimanual haptic manipulandum with four degrees of freedom, consists of a mass, affected by a saddle-like force field, and two non-linear elastic linkages, whose terminal points are grabbed by the user. The research is articulated in three activities:

1. Identification of two different stabilization strategies, which exploit in different manners the non-linearity of the elastic linkages;
2. Strategy switching in expert users;
3. Robot assistance to become an expert user.

The first activity is terminated and has produced the following publications:

Saha D, Morasso P (2010) Bimanual Control of an Unstable Task: Stiffness versus Intermittent Control Strategy. Proceed. 19th IEEE International Symposium on Robot and Human Interactive Communication (IEEE RO-MAN2010), pp. 832-837, Principe di Piemonte - Viareggio, Italy, Sept. 12-15, 2010.

Saha D, Morasso P (2010) Stiffness versus intermittent control in an unstable bimanual task. Neuroscience2010, San Diego Calif, November 13-17, 2010.

Saha D, Morasso P (2011) Stabilization strategies for unstable dynamics. PLOS One, *in press*.

The second activity is almost terminated and is producing the following publications:

Zenzeri J, Morasso P, Saha D (2011) Expert Strategy Switching in the Control of a Bimanual Manipulandum with an Unstable Task. 33rd Annual International IEEE EMBS Conference, Aug 30- Sep 3, 2010, Boston, MA, USA.

Zenzeri J, Morasso P (2011) Expert performance and generalization in bimanual unstable tasks. Neuroscience2011, Washington DC, November 12-16, 2011.

Zenzeri J, Morasso P (2012) Strategy Switching in the Control of an Underactuated, Compliant Tool used in an Unstable Task. Frontiers in Humans Neuroscience, *in preparation*.

The third activity has been pursued at the modeling level, producing a novel computational model of robot assistance, whose efficacy is in the course of being evaluated.

unpublished report:

Morasso, P., Saha, D., & Zenzeri,J. : Learning to control a virtual underactuated, bimanual manipulandum (VUBM) in an unstable task

3.7 Interactive robot assistance in a tracking task

In this experiment we tested an assistive scheme that was interactive, presumably similar to possible human-human interaction. Human participants interacted in a tracking task with a simple model such that the effectors of the human and the model attracted each other. The hand of the participant was driven toward the effector position of the model with a force that was proportional to the distance. Similarly the effector of the model was driven toward the position of the human hand. A critical characteristic of the scheme was the selective compliance of the model: compliance was high when the model effector was driven in the direction of the target, and it was low when it was driven away from the target. Consequently the forces experienced by the human participant varied. On average they were stronger when human performance was poorer and weaker when performance was better. Thus, the level of force was performance-related and its experience could support learning. In addition the scheme tends to amplify small errors and to reduce large errors, a condition that has been found to be beneficial for learning.

Performance of a robot-assisted group was compared with that of a control group. In the robot-assisted group assisted trials were mixed with unassisted test trials. If assistance were beneficial for motor learning, tracking errors should be smaller in the test trials of the robot-assisted group than in the control group; in the assisted trials of the assisted group tracking errors should be even smaller and less variable. It turned out that indeed mean and variable tracking errors were smaller in the assisted trials than in the test trials of the robot-assisted group. However, performance in the test trials of the robot-assisted group was worse - instead of better – than in the control group. Thus, in terms of unassisted performance, the effects of the particular assistance scheme were detrimental.

unpublished report:

Heuer, H. & Rapp, K.: Interactive robot assistance in a tracking task.